MONASH University

MODULAR CONSTRUCTION CODES BOARD

HANDBOOK FOR THE DESIGN OF MODULAR STRUCTURES

Handbook for the Design of Modular Structures
Published by Monash University

The Modular Construction Codes Board (MCCB) was founded by Prof. James Murray-Parkes and Dr Yu Bai from Monash University in Melbourne, Australia, in early 2013.

Prof. Murray-Parkes cited the lack of cohesion and availability in technical references as the key drivers for this project, as he struggled to find adequate support material to reference modern forms of construction design.

Monash University's support was instrumental in gaining momentum, and ultimately a Steering Committee, led initially by Bai and Murray-Parkes, with support from Prof. Martin Buoncristiani and shortly thereafter by Mr. Angus McFarlane, was soon established with McFarlane seated as the Committee's honorary chair.

Many other contributors joined and/or supported the Steering Committee, they include Mr. Adam Styles, Dr Matthew Davey, Mr. Goh Hoo, Ms. Angela Wang, Mr. Brendon McNiven, Mr. Justin Pearce, Mr. John Lucchetti, Dr Ben Forbes and Mr. George Konstandakos.

The committee's work, spanning a 3 year period, came to an end in January 2017, when the current Advisory Committee was formed to deliver the Committee's new technical handbook.

In May 2017, the first edition of the new Handbook for the Design of Modular Structures was realised. The delivery of this new handbook was led by the board's current Advisory Committee Chair Mr. John Lucchetti, Director Dr Ben Forbes, Mr. Phillip Gardiner and original founders Bai & Murray-Parkes.

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Handbook for the Design of Modular Structures

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Foreword

Buildings expend about 30% of the world's resources in construction, consume approximately 40% of global energy and produce approximately 40% of total greenhouse gas emissions (Green Building Council of Australia 2008). Maximising the use of modular construction in efficient factory conditions minimises the environmental impacts of construction and also improves safety and quality control. Today almost all types of industry are being advanced with automated processes to speed up, optimise and economise production. The construction industry has been slow to adopt these processes and there is little guidance available for their inclusion in a regulated way. This Handbook is the first comprehensive publication to address this issue in a holistic way. The use of more efficient off-site manufacturing techniques in construction has the potential to improve economic and social outcomes through more efficient use of our limited resources and the ability to deliver more affordable, well designed and durable housing. Well-regulated modular construction will be a key contributor to the realisation of this potential.

Aims of the Handbook

The Handbook is a project by the Modular Construction Codes Board (MCCB) to provide guidance to the industry on the design and construction of modular structures.

The aim of the Handbook is to share the experience and knowledge advances in modular manufacturing and construction for improving safety, productivity and quality in industrial practices. This document is expected to provide integrated solutions and experiences to industry, government and the community including:

i. Design for performance.
ii. Design for Manufacture and Assembly (DfMA).
iii. Regulatory compliance.

It is intended that this Handbook be an evolving document, to be reviewed by a larger community of technical professionals and organizations, both in Australia and world-wide.

A Collaborative Project

The Handbook is a collaborative project that has been prepared with support from the Department of Economic Development, Jobs, Transport and Resources, within the State Government of Victoria, Australia and a range of industrial and university partners through the Manufacturing Productivity Networks program.

This Handbook was an Activity within a larger project as agreed between the Victorian State Government, Monash University and other MCCB members during 2015–2018, "Best Practice and Integrated Solutions for Module Manufacturing and Construction" under the Manufacturing Productivity Network (MPN) program.

Partners

The work on this project is supported by the following organizations.

Instigators

Council on Tall Buildings and Urban Habitat
MONASH University
MODULAR CONSTRUCTION CODES BOARD
VICTORIA State Government
AUSTRALIAN STEEL INSTITUTE
ENGINEERS AUSTRALIA
prefabAUS

Principal Partners (Tier 1)

CIVMEC
MULTIPLEX
Engineering Innovations Group
LAING O'ROURKE
lendlease

Supply Chain Partners (Tier 2)

onesteel
westkon
PRECAST
WÜRTH
BLUESCOPE
Dulux
WOOD & GRIEVE ENGINEERS
AUSCO
MODULAR

Supporting Partners (Tier 3)

RobertBirdGroup
tbs precision construction.
ARUP
Ennesty energy
ausungroup.

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Founding Committee

The early development of this Handbook was driven by a committee of experienced figures in industry and academia who shared the common goal of encouraging innovation in the construction industry.

Angus McFarlane (Chair)	Laing O'Rourke
Prof. James Murray-Parkes (Vice-Chair – Industry)	Multiplex
A/Prof. Yu Bai (Vice-Chair – Academia)	Monash University
George Konstandakos	Timber Building Systems
Brendon McNiven	Arup
John Lucchetti	Wood & Grieve Engineers

The MCCB acknowledges the valuable role played by Engineers Australia in endorsing the project and enabling the collaboration to move forward with Government support.

Advisory Committee

In 2017, with the project well underway and the Handbook nearing completion, the management team has comprised the following members of the Advisory Committee:

John Lucchetti (Chair)	Wood & Grieve Engineers
Prof. James Murray-Parkes (Vice-Chair – Industry)	Multiplex
A/Prof. Yu Bai (Vice-Chair – Academia)	Monash University
Dr Ben Forbes (Director)	Monash University

Modular Construction Codes Board Members

The professional, financial and intellectual support of the MCCB members is appreciatively acknowledged. Membership of the MCCB includes (in alphabetical order):

i. Arup
ii. Ausco Modular
iii. Australian Steel Institute
iv. Ausun Modular
v. BlueScope
vi. Multiplex
vii. Civmec
viii. Dulux
ix. Engineers Australia
x. Ennesty Energy
xi. Laing O'Rourke
xii. Lendlease
xiii. Monash University
xiv. OneSteel
xv. Robert Bird Group
xvi. Timber Building Systems
xvii. Victorian State Government
xviii. Westkon
xix. Wood & Grieve Engineers
xx. Würth

The MCCB also acknowledges the support and input received from others in the construction industry.

Contributors and Reviewers

The following people are acknowledged for their contributions to the Handbook:

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Nigel O’Neill	Laing O’Rourke
Angela Wang	Multiplex

How to Read and Reference this Handbook

This document may be cited as the *Handbook for the Design of Modular Structures*, or shortened to *Modular Construction Handbook*.

The technical content of this Handbook is divided into Chapters (A, B, C and so on). These are preceded by a comprehensive list of Definitions. Words so defined, when they are used throughout the technical text, are shown in italics. For example:

> The *Builder* should ensure that all necessary and Regulatory controls are used on site so that construction activity is without *risks* to health and safety.

In this paragraph, *Builder* and *risks* have a specific definition in the context of this Handbook.

Each Chapter is then further subdivided by up to three nested levels of numbered headings. For example:

A1.1.1 Wind Actions
H3 Transportation

Each section of technical text is referenced by an Item number having four fields, even under higher levels of heading subdivision. For example:

H3.0.0.2
H3.1.0.2
H3.1.1.1

Where lists are embedded within the text each point may be referenced as a suffix. For example:

E1.0.0.1(iii)
F5.0.0.2(ii)(b)

Tables, Figures and Equations are numbered sequentially throughout each Chapter and shown in bold where cited in the text. For example:

Table J1
Figure H3

External documents are referenced in square brackets, for example:

Refer to [2.4]

The details of each reference can be found in the References and are grouped for convenience.

Although this Handbook has no regulatory status with respect to legislation, it proposes guidance for recommended practice and matters to be considered. Where the word “should” is used it indicates a recommended course of action.

Where information contained within the body of the document is less a direct recommendation and more commentary for background context and reference, such commentary material is displayed within shading as shown here.

Assorted unreferenced illustrations are shown throughout for descriptive purposes.

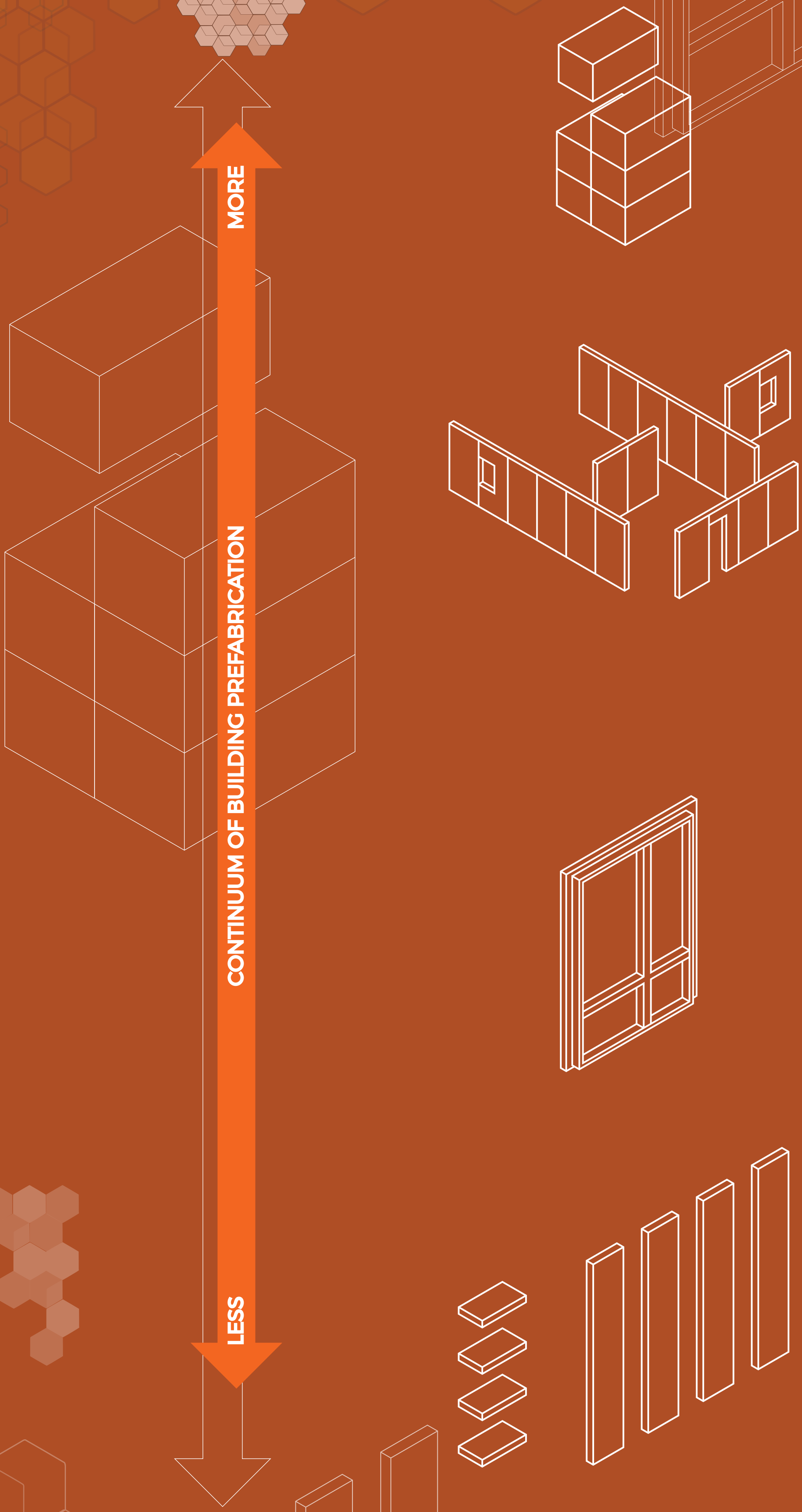


Figure i — Continuum of prefabrication degree

Introduction

What is modular construction?

The term “Modular Construction” refers to one of several methods of construction (applicable to Buildings and Civil works) all of which ultimately configure required materials on a site to create a built environment in compliance with a specification.

Modular Construction seeks to maximise the off-site prefabrication content (including framing, cladding, services, fittings and finishes assembled in factory conditions), minimise the on-site building activity/ use of trades, and minimise the potential for rework on site. The optimum mix and degree of these objectives varies from project to project. Where this concept is maximised to deliver structurally complete building units to site it is described as volumetric (or three-dimensional) Modular Construction. Other forms employing a lesser degree of completeness but which may be efficient options are variously described as Flat Pack, or Panelised Elements, or Prefabricated Components. Modular Construction concepts include but are not limited to residential building works. Any method where on-site work is minimised and prefabrication is maximised is considered Modular Construction. Traditional construction methods bring many raw materials to the site for processing, combination and assembly via suitably competent tradespeople.

Prefabrication of materials prior to site arrival may occur and has been used in varying degrees throughout history. Prior to site placement raw clay is used to manufacture bricks, raw concrete can be formed into blocks and precast reinforced concrete, and even raw timber is almost universally seasoned/ dressed to size and often prefabricated into frames. Common elements such as windows and doors (and even their frames) are typically brought to site complete for fitting into the structural fabric. These descriptions of degrees of prefabrication are illustrated in **Figure i**.

Even at its most basic application the potential benefits of prefabrication have been known and sought for centuries. The difficulty (and consequent safety risk, process risk, and cost) of arranging raw materials on site in their intended positions for a specified performance is usually greater than for creating sub-assemblies (i.e. smaller assembled units) from processed materials under simpler and more predictable conditions (e.g. at a factory) and then connecting them on site into the same intended positions.

As with other construction forms, Modular Construction needs to be intentional and planned, and by definition it cannot simply be worked out on site but involves the coordination of significant sub-assemblies and program precedents. These need to be designed in advance with Modular concepts in mind. The maximised extent of prefabrication for predictable assembly on site requires a high degree of design process and input. Achieving the ultimate outcome of Modular Construction therefore derives from the overarching philosophy of Design for Manufacture and Assembly, commonly abbreviated to DfMA.

Design for Manufacture and Assembly

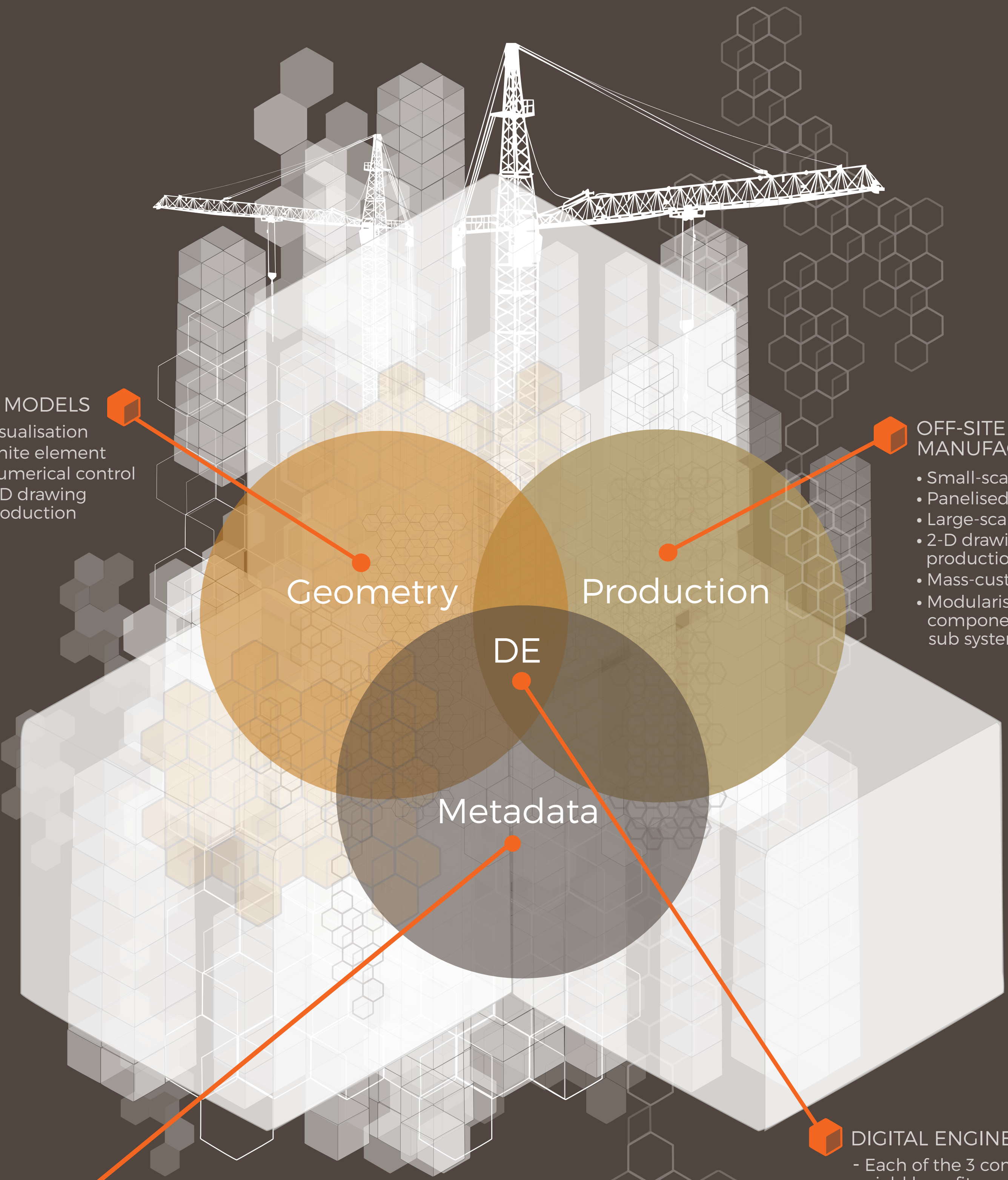
DfMA is a design philosophy that stresses a holistic view of the design process. In this overarching view, the Designer will consider not just the design of the individual elements and the completed structure composed thereof, but also the design of the assembly process. An increased focus is placed on how the individual parts are to be fabricated and connected as part of the design process, rather than an after-thought. This is particularly important in Modular Construction, where the design of an individual module will depend sensitively on the requirements of the assembly process (e.g. built-in mechanisms for attaching modules together). Modular Construction should therefore not extend to “modular thinking” (i.e. restricting one’s attention to one module at a time), but rather should consider how the **whole** completed structure could be sensibly **manufactured** in modular components. Modular Construction may be held back by the temptation to concentrate too closely on individual modules, and will only make significant inroads in the construction industry when the DfMA philosophy is embraced. The DfMA “envelope”, comprising some of the key elements of the DfMA approach to construction, is illustrated in **Figure ii**.

Why modular construction?

Buildings expend about 30% of the world’s resources in construction, consume approximately 40% of global energy and produce approximately 40% of total greenhouse gas emissions (Green Building Council of Australia 2008). This is mainly because such structures are still built on-site using traditional craft-based labour-intensive methodology. This results in ever-increasing costs and unacceptable consequences regarding quality, safety and environmental impact. Today, almost all types of industry are being advanced with automated processes to speed up, optimise and economize production.

Furthermore, we currently face a crisis in the availability of affordable, high-performance and durable housing. This impacts our society through an increasing rate of homelessness, reduced living standards and the inefficient use of our limited resources. Resolving or ameliorating these problems

What is DfMA?



3D MODELS
- Visualisation
- Finite element
- Numerical control
- 2-D drawing production

OFF-SITE MANUFACTURE
- Small-scale items
- Panelised systems
- Large-scale
- 2-D drawing production
- Mass-customisation
- Modularised components & sub systems

DIGITAL ENGINEERING
- Each of the 3 components yield benefits
- Greatest benefits are achieved in overlapping DE portion
- The DFMA envelope delivers optimum solutions

BUILDING INFORMATION META DATA (BIM)
BUILDING INFORMATION MODEL
- Programme (time & costs)
- Quality & performance
- Safety & maintenance
- Environmental impacts: noise pollution, carbon footprint, disruption to business & residents

Figure ii – The DfMA envelope

will require innovation in many areas, particularly in construction.

Modular Construction offers exceptional advantages over traditional construction methods, as evidenced by growing demand. These advantages include:

i. Efficiency gains through faster construction schedules, less material wastage, greater precision via controlled manufacture, lean manufacturing practices, reduced site progress risk from bad weather, reduced site-space demand for workers, traffic, material storage and safety improvement via site activity reduction.
ii. Increased productivity and suitability for high volume automation-content (particularly for buildings due to dimensional ranges of modules for human use and road transport) leading to structural standardisation.
iii. Flexibility for Designers regarding mass customisation and suitability for the growing trend toward Building Information Modelling (BIM) methods
iv. Less requirement for large construction sites and less disruption to neighbouring environs.
v. Potential for demand via more affordable housing as efficiencies are passed on to consumers.
vi. Potential for removability and reuse of modules.

Why this Handbook?

This Handbook is intended to form a Guide for Modular Construction and DfMA in relation to the considerations and expectations required of the various stakeholders – the Developer, the Designer, the Manufacturer, the Materials Supplier, the Builder. In so doing, each stakeholder can have confidence of successfully delivering results of specified quality with managed risk to provide an acceptable product that meets customer expectations and complies with applicable Regulations.

Modular construction has, as of 2017, not yet achieved in Australia the success that it has seen elsewhere in the world. Although the benefits can be significant in terms of cost and build time reductions, the uptake has been hindered by the technical complexities and regulatory uncertainties of the prefabricated and modular construction process. The modular industry has also suffered from a reputation of poor quality modular structures built both locally and overseas. This has left many financial institutions reluctant to support the finance of modular structures.

This Handbook for the Design of Modular Structures seeks to provide technical guidance to promote the uptake of safe and high quality modular and prefabricated structures. This is not a statutory document and cannot of itself hold any Regulatory status but it proposes best practice and integrated solutions for module manufacturing and construction. It offers a basis for reference to existing building regulation through consistency, in Australia, with the National Construction Code (NCC) and standardisation of engineering practices in the context of relevant Workplace Health and Safety (WHS) requirements. It offers guidance to competent technical professionals about the salient matters to be considered rather than simplified prescription of standard details.

Regarding DfMA this Handbook stresses designing for the detailed construction phase of modular building (including manufacture and erection). It also deals with how the design process must account for this as part of the total performance life, as well as for the long-term behaviour of the completed building (when all the modules act together as one structure). Due to the typical compartmentation of some buildings for human use (e.g. residential, hotels), they have relatively dense framing, with a higher degree of structural redundancy, and typically without excessive spans. This makes them more suitable for consideration with DfMA regarding maximised off-site manufacture and minimised on-site construction. Conversely larger factory-type buildings may continue to be better suited for on-site assembly of large structural framing elements and subsequent fit-out but the challenge remains to maximise off-site manufactured content.

The goal for this document regarding Modular Construction is to provide guidance which may:

i. Prevent adverse outcomes concerning health and safety, regulatory compliance, building performance and product quality.
ii. Advance the building construction industry to embrace appropriate and mature manufacturing and design concepts.
iii. Respond to existing market and societal demands to stimulate industry growth and improve productivity.
iv. Propose a process framework to build and sustain stakeholder confidence.
v. Further stimulate innovation to explore difference and improvement to conventional construction culture.
vi. Develop standardisation of engineering practices for design and Compliance verification.

Applicability within Australia and abroad

This Handbook has been detailed in the context of Australian conditions – regarding both compliance with relevant Regulations and known industry best-practice. The overarching principles of Building law and Workplace Safety law (to protect and regulate the public interest) and the natural laws of physics (which govern applied engineering) should enable this Code of Practice to be relevant and useful outside Australia once the contextual variations are accounted for.

References to the National Construction Code (NCC) in text should be taken as referring to that for Australia, which may differ from that in other countries.

Design fundamentals

This Code of Practice provides guidance to assist users to demonstrate Compliance with applicable Regulatory controls (e.g. refer **Chapter J** regarding Building Regulations) and to achieve acceptable quality requirements for safety, serviceability, and durability when building with Modular Construction principles. Achievement of acceptable safety, serviceability and durability extends through the life cycle phases of manufacture, transport, construction, operation, maintenance and demolition.

Regulatory compliance is mandatory and those Australian regulations applicable to Modular Construction are performance based. This places the burden of accountability upon decision-makers to determine and record the basis of compliance. The key areas of regulated practice relate to:

i. Buildings
ii. Work health and safety
iii. Transport safety

Aside from the primacy of personal safety these regulations also seek to encourage efficiency and productivity. Beyond simple compliance with legal requirements the culture of design and practice ought to support these principles.

Inherent to current acceptable building practice are the achievement of specified Reliability and Robustness measures in design. These have related regulatory provisions in the NCC.

A further overarching principle in this Handbook is that of verification, given that there needs to be documented assurance that anything which has been specified has actually been produced. This not only applies to verifying that the delivered construction matches the design intent but also verification that the design itself is in compliance with Regulatory controls and meets acceptable technical standards. Refer to Chapter K for matters relating to Verification.

Consideration should be given to the design and construction of modules while they form a Workplace during manufacture, construction and demolition. In this regard provisions of Workplace Health and Safety Regulations apply.

The Regulatory structural provisions in the NCC apply to “A building or structure, during construction and use…”[1] [6.2] so there is no less obligation on the Designer to account for safe behaviour of works in progress prior to completion.

It is also highlighted that the purpose and practice of design generally (be it in the DfMA process or for anything else) is about accounting for what is foreseeable – practically and with regard to any liability. If conditions of actions/circumstances and the properties of materials supporting them are foreseeable then there is an obligation on practitioners who ought to foresee them. The concept of “Safety in Design” is now being promoted throughout industry wherein the Designer has a duty in relation to reasonably foreseeable aspects of safety for the necessary construction and operational/maintenance phases of the building being designed. In the DfMA process these foreseeable circumstances also include the necessary manufacturing (off site), transportation and handling (in transit) and assembly (erecting/connecting on site) phases as well as any design aspects to enable appropriate verification measures for construction compliance with the design intent.

This covers not only the structural framing elements but also building fabric otherwise considered non-structural (such as claddings, partitions and services) that are fully installed within modules. Therefore in many aspects the modular forms may need to be more substantial to meet Performance Requirements arising from their short-term life being transported/handled by various vehicles than from their long-term life in a completed structure on the project site.

Chapters A and **J** include guidance about design when relying upon the testing of materials and systems proposed.

Handbook Management Plan

It is anticipated that this Handbook will periodically require updating and maintenance, to keep it up to date with the latest developments in codes and standards as well as in the state of the art of the Modular Construction industry. The Handbook is supported by the Modular Construction Codes Board operating with support from the Victorian Government out of Monash University, Australia. The Advisory Committee includes members with a wide range of backgrounds in the construction industry and academia, all of whom have an interest in

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[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

ensuring that this Handbook continues to serve well into the future as a guiding light in promoting Modular Construction in Australia and beyond.

Outline of the document

This document is divided into a number of chapters, roughly along content lines. In some cases a particular topic may appear in multiple chapters, when it is a multi-faceted topic which falls under multiple broadly defined umbrellas. A broad overview of the chapters is given below, with the intention that the reader may wish to concentrate their attention on some particular areas of interest.

The Structure chapter is the largest single chapter; it is after all the structural integrity of an element or an assembly of elements that differentiates it from a pile of raw materials. The chapter covers a broad range of topics relating to the loads which may be subjected to an element or structure, and the factors which the Designer must consider to ensure that the structure is both reasonably unlikely to fail and can reasonably fulfil its intended purpose. The chapter is subdivided into a number of sections: Loads, which details the range of loads that the Designer must take into consideration for the completed structure as well as for the individual components during the overall construction process; Element Design, which lays out considerations for the design of the elements comprising the individual modules; and Structural Analysis, which covers a range of topics taking an in-depth look at the underlying structural mechanisms. This chapter will be of interest primarily to structural engineers; the content is generally quite technical, although some effort has been made in each section to lay out clearly the relevance of the content.

The next chapter covers Building Services, Fire, Acoustics and Sustainable Thermal Regulation. This is of particular relevance in Modular Construction as many of the advantages of this form of construction stem from the ability to pre-install services into modules, with minimal work necessary on site. Fire Resistance in this chapter covers chiefly the aspect of smoke detectors and sprinkler systems. This chapter will be of interest to services engineers and safety and compliance personnel.

The Facades chapter covers considerations which should be taken into account regarding the exterior (generally non-structural) building elements.

The Architecture chapter makes some statements regarding the interplay between construction methodology and architecture, as well as design of the modular components.

The Materials and Manufacturing chapter details a number of considerations that arise when manufacturing materials for use in a building. This includes quality, tolerance and certification issues. The increased importance of off-site manufacture in Modular Construction means that this chapter will be of interest to a wide audience including the Designer, structural engineers, manufacturing facility workers, on-site personnel, etc.

The Durability chapter explores the idea that the performance capacity of a structure is time-dependent; changes in material properties may mean that the structure can only meet its performance requirements for a finite duration, or design life. Corrosion is particularly important in this topic, with UV degradation also playing a part.

The Safety chapter covers best practices necessary for ensuring safety throughout the construction process and lifetime of the complete structure. This is a wide-reaching topic which has relevance for almost everyone involved in a construction project.

The Transportation, Erection and Temporary Works chapter covers important topics relating to Modular Construction, due to the tendency towards off-site manufacture of potentially large and massive component modules which must get from the manufacturing facility to ultimately be assembled into the complete structure, with an extended logistical chain in between; storage, transportation and lifting become even more involved in this type of construction. The audience for this chapter will include more than just those personnel directly involved in logistics: the Designers and structural engineers must anticipate that the modules will be subjected to a variety of conditions before becoming part of the complete building; and the Builder must account for the arrival of modules and materials onto site, as well as the erection process.

The chapters covering Compliance, Inspection and Verification, Traceability and Documentation deal with a range of issues essentially relating to what procedures and practices are recommended, or required by law, throughout a construction project to ensure that the completed building performs as intended. Furthermore, these laws aim to ensure that the logistical and construction processes are themselves conducted in a rigorous, verified and well-documented manner.

The chapters on Disassembly and Recyclability, Simplified Low-Rise Guidance and Relocatable Modular Structures cover a few supplemental topics on some further possibilities and considerations in Modular Construction.

The final chapter on DfMA, Digital Engineering and Lean Manufacturing takes a detailed look at some principles which underlie modular construction.

Definitions

Accidental action: An *accidental action* is any unforeseen action arising from events not considered in the design brief, for example an impact from a vehicle or other object or an internal explosion

Typically an *accidental action* is important in the design of structures when considering *Robustness* as these actions, as equivalent static or dynamic actions, may cause the localised failure of a structural element. Additionally, *probabilistic models* of these actions play a key role in determining the *Reliability* index of a component when *risk* analysis is the appropriate design methodology when considering the *Robustness* of a structure.

Accuracy: the degree of minimisation of actual error from an exact specified property.

Anchor: for building engineering, a manufactured device that connects a fixture to a base material/substrate for load transfer, usually by some mechanism of embedded geometric interlock, friction or adhesion between the *anchor* and substrate. For example, a steel bolt cast into concrete.

Axial shortening: a particular case of significant material deformation typically in the vertical direction due to weight response and related to tall building behaviour. The differential vertical deformation of adjoining materials is a potential cause for distress in related connections. It is contributed to by the cumulative responses (linear and non-linear) of materials to stress levels and, in the case of a material such as concrete, susceptibility to additional time-dependent effects such as shrinkage, creep and variable stiffness. Behaviour compatibility between loaded structural framing and supported building services can become problematic. The elastic compressive response to accumulated weight can be exacerbated by wind-induced bending and differential thermal expansion effects, both of which are accentuated by tall building slenderness.

BCA: Building Code of Australia, as volumes 1 & 2 of the *NCC* – for Buildings. It is a uniform set of technical provisions for design and construction.

BIM: Building Information Modelling – a process involving the generation and management of digital representations of physical and functional characteristics of a build environment.

Builder: a *Competent person* who controls construction activities on the project site (including procurement and supply of materials in any degree of prefabrication) to implement and comply with the design specification and with relevant Regulation, and who offers works for verification processes.

Capacity reduction factor: the ratio of design capacity to nominal capacity

Centre of Gravity/CoG: a point from which the weight of a body may be considered to act. A practical outworking of this requires that the CoG of a body being lifted from a single point will rest vertically below the point of suspension.

Certifier: a *Competent person* who independently verifies that the design specification and/or constructed works and/or a specified testable claim generally will satisfy a nominated standard or claim. The *Certifier* must not have any conflict of interest with the *Designer* or *Builder* or *Construction compliance supervisor.*

Certification: a document produced by a *certifier* which includes:

i. A unique documentary identifier
ii. Identification and contact details of the *Certifier*
iii. Verifiable competence or authority of the *Certifier* to issue the *certification*
iv. The scope of what has been certified, including any time limitation
v. The standard or claim against which an assessment has been made
vi A statement of conformance, including any validity period.

Chain of responsibility: a term used in conjunction with complex activities involving multiple entities each relying upon the performance of others before completing their work for the use of another. It is a widespread tool generally for managing accountability and is reflected directly in some Regulation.

Characteristic value: the 5% fractile value from a population of test measurements for a given property. That is, a value that will be exceeded in 95% of all tests.

Competent person: a person who is appropriately skilled, as evidenced by qualifications, and experienced to perform a task. Where required the *Competent person* must be registered under applicable Regulations.

Complexing works: the manner in which each module interfaces and connects with other modules and with the building as a whole.

Compliance: verification that something has been assessed as meeting a specified Regulatory requirement, as evidenced by the record of a *Competent person*. Refer also to distinction of meaning between *non-conforming building products* and *non-compliant building products*.

Construction compliance supervisor: a *Competent person* who verifies that the intent of the design specification is complied with.

Design service life: the duration for which a structure, as designed, is assumed to perform for its intended purpose with expected maintenance but without major structural repair being necessary.

Design for Manufacture and Assembly (DfMA): the combination of two methodologies – Design for Manufacture (design for efficiency to manufacture components of a larger product) and Design for Assembly (design for efficiency to assemble those components as the product). In the context of building construction, the modules are the manufactured components and building project (on site) is the product.

Designer: a *Competent person* who specifies the requirements of what is to be constructed, ensuring that relevant regulatory controls are satisfied, and in a manner to allow for verification of construction *compliance*, and of specified durability.

DfMA: see *Design for manufacture and assembly*

Fire Resistance Level (FRL): the grading period in minutes from prescribed fire performance testing for the criteria:

i. Structural adequacy
ii. Integrity
iii. Insulation

Freight container: (informally "sea container") an article of transport equipment that is of a permanent character designed for repeated use by & securing to one or other modes of transport without intermediate reloading. As approved by the International Convention for Safe Containers (ICSC) 1972. It is one type of Cargo Transport Unit.

Hazard: something in, or that may be in, the work environment that has the potential to cause harm (injury, illness, including psychological illness, or death) to a person

Importance Level (IL): a grading of the level of consequences (primarily loss of life) in the event of a building failure. It allows also for buildings required to fulfil essential functions in post-disaster recovery.

IFD: Intensity, Frequency, Duration – used as a descriptor when specifying certain dynamic or chaotic action effects (e.g. wind and vibration)

Induction (structural): an indirect structural behaviour as a consequence of a direct action, the effects of which may be significant. Refer following examples:

i. Consider the robustness analysis of the removal of a short column element supporting a floor above and supporting further levels of column and floor above that. The floor immediately above the removed column element would not only directly respond to the increased span as beam action between neighbouring supports but also, by induction, would act as a catenary tension member.
ii. Consider the wind action on a tall building which will cause it to deflect in direct response but the building also may by induction move through elliptical oscillations. This may arise due to interactions between the building geometry and its relationship to the incident wind direction, and the building façade conditions. A further induction effect of torsional rotation about the vertical axis may also arise.
iii. Consider the effects in a tall building of differential axial shortening where the centroid of shortening/resisting forces does not coincide with the structural vertical centroid for bending behaviour. By induction the differential axial shortening may produce bending in the vertical cantilever and thus progressively greater horizontal displacements of floors up the building.

Lean construction: an approach to design and construction, and desirable adjunct to *DfMA*, in which systems of production aim to minimise waste of materials, time and effort in order to generate the maximum value. There is an emphasis on managing variation, *reliability* of work flow and quality (*precision*) so as to minimise errors and need for rework. It is an open process of review and improvement beyond the solving of immediate work flow problems.

Limit state: A state beyond which the structure no longer satisfies the design criteria

Load-bearing: in relation to a structural element the design intention of resisting vertical forces in addition to those due to its own self-weight

Modular Construction: an approach to construction which aims to maximise the degree of prefabrication of materials for the project off-site and minimise construction activity on-site. The goal is to maximise sustainable efficiency while meeting specified quality and Regulatory requirements. It gives rise to enabling complementary approaches of *DfMA* and *Lean construction*.

National Construction Code (NCC): the governing Regulatory control adopted by State legislatures for on-site construction technical requirements in Australia. Volumes 1 and 2 relate to Buildings.

Non-compliant building products: (refer [6.17])- products that are used in situations where they do not comply with the regulatory requirements of the *NCC*. For example, a building product that is combustible, and described as such, but is used in a situation where a non-combustible product is required under the *NCC*, is not fit for purpose and thus is *non-compliant*.

The use of compliant building products is primarily the responsibility of the *Designer* regarding specification and of the *Builder* regarding building construction. Refer to Building Regulation.

A building product can be both *non-conforming* and *non-compliant*.

Non-conforming building products: (refer [6.17]) - products and materials about which claims are made that are not true; that do not meet required standards for their intended use; or are marketed or supplied with the intent to deceive those who use them. For example, a building product that is labelled or described as being non-combustible but which is combustible is a *non-conforming* product.

The provision of conforming building products is primarily the responsibility of the Manufacturer and of the Supplier. Refer to Consumer Law.

A building product can be both *non-conforming* and *non-compliant*.

Plane of Lift: the plane defined by the points of attachment of the rigging to a lifted module. Where the *Plane of Lift* is below the module's *Centre of Gravity* there may be a *risk* of lateral instability and load shifting or tipping over during the lift.

Performance Requirement: a Regulatory term mandating a minimum level of performance or outcomes to be achieved, ultimately to reflect community expectations. In broad terms *Performance Requirements* of relevance to *Modular Construction* focus on safeguarding the wellbeing of persons and protection of property.

Precipitation: various forms of water from the atmosphere which rests on the ground or structures over it including rain, snow, hail.

Precision: the degree of minimisation of variation between multiple measurements of a property.

Prefabricated concrete: preferred term for all forms of precast concrete which are not cast in-situ. All *prefabricated concrete* requires mechanical lifting. Main subgroups are on-site *prefabricated concrete* and off-site *prefabricated concrete* which also requires vehicular transportation from the place of manufacture.

Probabilistic model: A model which defines the variation in a given property, generally resistance or action. These models will generally clarify the following properties:

i. The mean value of a property
ii. The nominal design value of a property
iii. The coefficient of variation of a property – The ratio of the standard deviation to the mean

In the case of a model of resistance, the nominal design value is typically taken as the *characteristic value*. Various distributions may be used for these models such as normal, lognormal or Weibull.

Progressive collapse (also termed Disproportionate collapse): Typically related to the lack of *robustness* of a structure, this may be defined as the global failure of a structure resulting from the progressive failure of elements. For example, *progressive collapse* may occur as the result of the local failure of a column, resulting in an increased load on nearby structural elements and thus further failures. This might also be referred to informally as the "domino effect".

Proof testing: application of testing to a structural item to determine the structural characteristics of that one item under test.

Prototype testing: application of testing to an early sample, model, or release of a product built to test a concept or process or to act as a thing to be replicated or learned from.

Reasonably practicable: qualification applied to a regulated *Workplace Health and Safety* duty. It requires weighing up all relevant matters including:

i. The likelihood of the *hazard* or the *risk* occurring
ii. The degree of harm that might result from the *hazard* or the *risk*
iii. Knowledge about the *hazard* or *risk*, and ways of eliminating or minimising the *risk*
iv. The availability and suitability of ways to eliminate or minimise the *risk*, and
v. After assessing the extent of the *risk* and the available ways of eliminating or minimising the *risk*, consideration of the cost associated with eliminating or minimising the *risk*, including whether the cost is grossly disproportionate to the *risk*

Reliability: as measured by the *Reliability* Index (β) this is the acceptably small probability of failure of a building, component or connection. That is, the acceptably small *risk* that an unlikely inadequate resistance of the structure (which may vary over time) will be exceeded by an unlikely high loading during the *design service life*. Minimum requirements for assessment and verification of *Reliability* are addressed directly by the *NCC*.

The *Reliability* Index (and thus *Reliability*) of a structure/component is related to the probability of failure of the component when a particular action is applied. This is calculated on the basis of two *probabilistic models:*

1. Model of the action considered
2. Model of resistance

The model of the action accounts for the variability of the magnitude of the action, and the model of resistance accounts for the variability in a structural system's ability to resist these actions (i.e. ultimate strength). The distributions used in the determination/development of these models will affect the final *Reliability* Index calculated and thus should be clearly stated and documented for any calculation.

The *NCC* provides guidance on limits on the *Reliability* of a structural component/assembly.

Risk: the chance (or likelihood) that a hazard will cause harm to a person, and/or significant damage to assets.

Robustness: capacity of a building once failure is initiated to perform in such a way that it will not be damaged by defined events to an extent that is disproportionate to the original cause. Minimum requirements for assessment and verification of *Robustness* are addressed directly by the *NCC*.

Robustness generally relates to the ability of a structure to resist collapse as a result of the notional removal of a structural element (as the result of an applied *accidental action*).

Robustness is closely linked with the concepts of *reliability* and ductility. Typically the *Designer* may think of designing for *robustness* as increasing the *reliability* of the structure to resist global failure due to disproportionate/*progressive collapse* assuming a defined structural failure has been initiated. That is, reducing the probability of global failure of the structure due to a *hazard*/*accidental action*. This may be achieved through many means, which includes the ductile failure of elements.

Rotational stiffness: The *rotational stiffness* of a joint is related to the rotation of the joint with respect to an applied moment (i.e. the movement of a beam with respect to its original 'neutral' position) and its ability to resist this. This resistance/stiffness is more important in the case of *Modular Construction*, where it may have a significant effect upon the overall structural response of the building.

While typical structural design often involves the treatment of joints as notionally pinned or fixed, there is possibility for joints to be treated as semi-rigid.

Seismic: relating to vibrations transmitted through the ground, including that from earthquakes, dynamic groundworks, mining, and heavy vehicle transport. For analysis of *seismic* effects on structures some definition is required of the input signal regarding intensity (amplitude and direction), frequency, speed of propagation and duration.

Serviceability Limit State (SLS): A state beyond which the specified service criteria for a structure are not met, as based on the intended use. These may include limits on deformation, vibratory response, or material degradation.

Sling: a length of load-rated rope (fibre or steel-wire), webbing or chain with connection eyes formed at each end.

So far as is reasonably practicable: a legal concept serving as the basis for management of safety *risk* under widespread *WHS* law. It is precaution-based and requires a positive demonstration of due diligence, which may be a legal defence against claims of negligence. Where it is possible to guard against a reasonable and foreseeable *risk*, due diligence requires adoption of *reasonably practicable* means to do so.

This is not the same as, and ought not be confused with, the allied concept of "as low as *reasonably practicable*".

Tester: a *competent person* who can approve a *Test Report*.

Test Report: a report document about a test which should include the following (from **AS/NZS 1170.0** App B):

- i. Scope of information required from the test data
- ii. Description of conditions that could influence the behaviour under consideration
- iii. Details of the testing arrangement and measurement methods
- iv. Details of the testing procedure (including the methods established for analysis)
- v. Environment conditions of the test
- vi. Materials tested (including number of samples and all relevant properties thereof)
- vii. Measurements of relevant properties
- viii. Results (including modes of failure if relevant)
- ix. Evaluation of the data and conclusions
- x. Any unusual aspects of the testing
- xi. The name and location of the testing laboratory or testing organisation
- xii. Citation of **AS/NZS 1170.0**

Tolerance: limit of permissible variation in a physical property without significantly affecting the required function of a system or structure.

Twist lock: a locking device with a rotating head which normally engages a corner casting on the load. As commonly used with a Cargo Transport Unit (CTU)/“sea container”.

Ultimate Limit State (ULS): A state associated with collapse or with other similar forms of structural failure. It is a strength-based limit state. For ductile materials the state where yielding occurs may also be of interest.

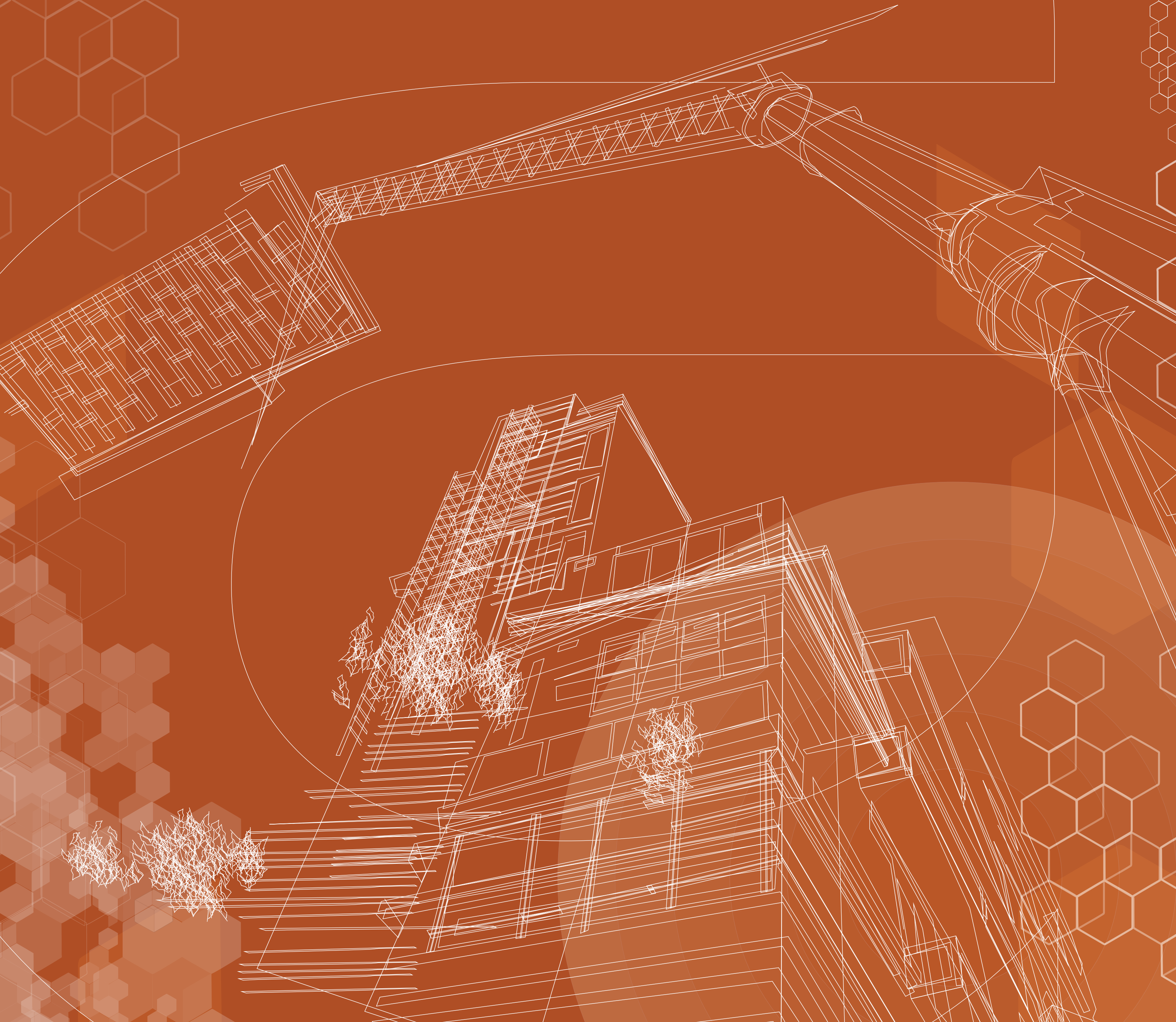
UV: ultra-violet light

Workplace Health and Safety (WHS): a defined regulatory term in various jurisdictions (may also be called Occupational Health and Safety) but also referring to generalised expectations in work practice and responsibilities.

A

Chapter

Structure



A Structure

A0.0.0.1

The primary *Performance Requirement* for any structure (during construction and use), as regulated by the *National Construction Code* (*NCC*) in Australia, is that it:

> “must perform adequately under all reasonably expected design actions”[1] (*NCC*, BP1.1 [6.2]).

Adequate performance relates to safeguarding people and protecting property – preventing loss. This includes foreseeable extreme or repeated design actions and those arising from local damage to the remaining structure. In resisting these reasonably expected actions there is also a duty to avoid causing damage to other properties.

A0.0.0.2

The *NCC* lists actions to be considered, as shown below, but this is not claimed to be exhaustive. A duty rests with the *Designer* to account for all actions as might be reasonably expected. Actions to be considered include:

i. Permanent actions (dead loads)
ii. Imposed actions (live loads)
iii. Wind action
iv. Earthquake action
v. Snow action
vi. Liquid pressure action
vii. Ground water action
viii. Rainwater action
ix. Earth pressure action
x. Differential movement
xi. Time dependent effects
xii. Thermal effects
xiii. Ground movement
xiv. Construction activity actions
xv. Termite actions

A0.0.0.3

Modular Construction by definition seeks to embody *Design for Manufacture and Assembly* (*DfMA*), where on-site labour and construction activity are to be minimised and off-site labour and manufactured content in controlled environments are maximised. For any location, local codes of practice and standards apply when considering the design of structures. The main difference in the case of modular is the mode of construction.

Considerations that may vary significantly from a typical design are:

i. Adequate performance under transportation, handling and erection.
ii. Greater impact of *tolerances*
iii. Design *certifications* and approvals.
iv. Increased likelihood that *Modular Construction* will require specialised solutions that fall under the “Performance Solution” section of the *NCC* e.g. testing and first-principle design.
v. Access in terms of buildability, safety in design and other *Work Health and Safety* (WHS) requirements.
vi. Critical importance of connections to the overall structural performance of a modular building.

It is also to be noted that for *WHS* there is accepted Regulatory definition across most jurisdictions that this applies to any structure, not just those defined as Buildings (as classified via the *NCC*).

Modular Construction typically introduces more connections and discontinuation of rigid floor diaphragms than would be expected for in-situ construction of the same building. This may apply also to aspects other than structure in any built environment (e.g. services, cladding).

A0.0.0.4

Designers are reminded that design values for loading, materials behaviour and performance of functional systems may be established by testing where controlled in an appropriate process in order to achieve *compliance* with *Performance Requirements* (see **Figure A1**). Alternatively, Prescriptive (Deemed-to-Satisfy) Solution provisions commonly reference related Australian Standards. For the completed building there are no fundamental differences in *Performance Requirements* resulting from the method of construction. The additional scenario for *Modular Construction* is that individual modules must also withstand satisfactorily the manufacture, handling, transportation and erection phases up to incorporation with the project building.

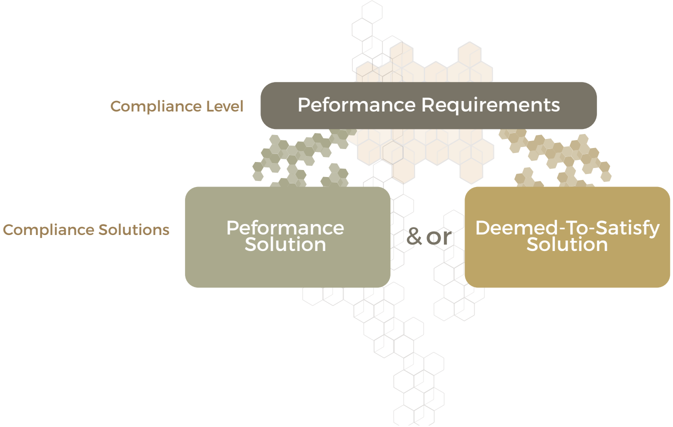


Figure A1 – Extract from NCC 2016 Vol 1 illustrating Performance Requirements and compliance solutions generally.[1]

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[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

All structures in Australia to which Building Regulations may apply in any jurisdiction (typically due to the building function being defined in terms of usage by or proximity to humans) must comply with the *NCC*, specifically the *Performance Requirements* therein. These *Requirements* must be complied with and the *Designer* must apply one of the options described. This is distinct from other structures such as civil infrastructure (e.g. bridges, drainage works, powerlines) which may not be applicable to the *NCC* , although in those cases the *Designer* still has a duty of care regarding community expectations to apply the appropriate skill and judgment they ought to have as demanded by the project in which they are engaged. This may involve using the same technical standards and design methodologies as for building works if considered appropriate.

A0.0.0.5

While the considerations that follow focus particularly on Australia, effort is made to provide enough information that *Designers* in any jurisdiction may apply the process while using load combinations, reduction factors or calculations specific to their region/jurisdiction.

A1 Loads

A1.0.0.1

Correctly describing the applicable loads on any structure requires accounting for all reasonable circumstances which generate loads. This is acceptable design competence and a regulatory requirement under principles for “Safe Design of Structures” [4.1]. This includes foreseeable loading arising from service life, operation and maintenance activities. In addition, the processes of manufacture and assembly (i.e. as a part of *DfMA*) typically demand that the built materials withstand a multiplicity of short-term loadings and possibly with varying support and load-transfer configurations.

A1.0.0.2

All cited load factors accounting for transport and handling dynamic effects are recommended minimum values. They are to be applied to the calculated loads (weight forces G) or applied to the gravity constant (g) initially. Both produce the same result for analysis.

A1.0.0.3

The *Designer* is to assess whether different values are appropriate in all cases. Load factors are not always independent of any consideration of other additional loads such as wind and/or wave actions, and thermal effects. For example, self-weight may be reduced when opposing the effects of wind uplift. An assessment may also be required of the extent to which any loads or acceleration factors may be additive and whether the design precludes any discretionary combinations. For example, limiting the wind speeds in which modules may be lifted or positioning modules on ships to limit potential pitch/roll accelerations.

A1.0.0.4

Structures can be assigned an *Importance Level* (IL) as well as a Consequence Class (CC) which act as a guide for the *Designer* in how to account for the impact of certain events on the structure. One can furthermore consider the probability that a particular event, for example wind, will exceed the magnitude accounted for in the design. **Table A1** is a summary of *Importance Levels* assigned to structures and **Table A2** shows corresponding annual probability of exceedance of the design events for *Ultimate Limit States* (*ULS*) design (see **A1.0.0.5**). These tables are drawn from **AS/NZS 1170.0 Appendix F** [5.2] for structures in Australia. For structural steelwork the Designer may also consult **AS 5131** [5.31] which introduces “Construction Categories” that are intended to be consistent in philosophy with the manner in which **AS/NZS 1170.0** categorises structures.

Table A1 – Summary of Importance Levels (IL) (from **AS/NZS 1170.0** [5.2] Table F1 – Australia) (IL) Importance Level as per **AS/NZS 1170.0**; (CC) Consequence Class as per **EN 1990** [6.8][2]

IL	CC	Description
1	1	Minor structures with low consequence for loss of human life, **small or moderate** economic, social or environmental impact
2	2	Normal structures or structures not covered by other levels with **medium** consequence for loss of human life, **considerable** economic, social or environmental consequences
3	3	Major structures with **high** consequence for loss of human life or **very great** economic, social or environmental consequences
4		Post-disaster structures (filling post disaster functions or dangerous activities) with consequences equivalent to Importance Level 3
5		Exceptional structures where reliability must be set on a case by case basis and a risk assessment should be conducted

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Table A2 – Summary of Annual probability of exceedance of design events for ULS [from **AS/NZS 1170.0** Table F2 - Australia]
(**NR**) Not required; (**nc**) non-cyclonic;
(**c**) cyclonic; (*) refer **AS/NZS1170.0** App F;
(IL) Importance Level as per **AS/NZS 1170.0**[3]

Design working life	IL	Design event & annual probability of exceedance for ULS		
		Wind	Snow	Earth-quake
Equipment e.g. props, scaffolding	2	1/100	1/50	**NR**
5 years	1	1/25	1/25	**NR**
	2	1/50	1/50	**NR**
	3	1/100	1/100	**NR**
25 years	1	1/100	1/25	**NR**
	2	1/100	1/25	1/250
	3	1/500	1/100	1/500
	4	1/1000	1/100	1/500
50 years	1	1/100**nc**	1/100	1/250
	1	1/200**c**		
	2	1/500	1/150	1/500
	3	1/100	1/200	1/1000
	4	1/2500	1/500	1/2500
100 years or more	1	1/500	1/200	1/250
	2	1/500	1/200	1/250
	3	1/2500	1/500	1/2500
	4	*	*	*

Table A3 – Strength limit state cases as per **AS/NZS 1170.0** clause 4.2.2
Refer to **A1.0.0.6** for definition of symbols.[3]

Design Action (E_d)	Description
1.35G	**Permanent** action only (does not apply to prestressing forces)
1.2G + 1.5Q	**Permanent** and **Imposed** actions
$1.2G + 1.5\psi_l Q$	**Permanent** and **Long-term Imposed** actions
$1.2G + W_u + \psi_c Q$	**Permanent, Ultimate Wind** and **Combined Imposed** actions
$0.9G + W_u + \psi_c Q$	**Permanent** and **Ultimate Wind** action (when opposed)
$G + E_u + \psi_E Q$	**Permanent, Earthquake** and **Combined Imposed** action
$1.2G + S_u + \psi_c Q$	**Permanent** actions, actions determined in accordance with **AS 1170.0** clause 4.2.3 and imposed actions

A1.0.0.5

Ultimate Limit States relate to design to ensure adequate ultimate strength. While structural design of *Modular Construction* does not introduce any additional considerations in analysis of loads for the completed structure, load combinations are repeated in **Table A3** for the convenience of the *Designer*. This is done on the basis of **AS/NZS 1170.0** (specific to conditions in Australia & New Zealand) but with a view that the *Designer* might apply appropriate load factors, combinations and procedures for their jurisdiction. Generally, load safety factors are based on level of certainty around estimation of loading, and reduction factors used when forces produce stabilising effects. Load duration reduction factors (ψ) are introduced to account for reduced likelihood of the full load being experienced over longer periods of time.

A1.0.0.6

Symbols used to describe loads are defined as follows[3]:

i. G – Permanent action
ii. Q – Imposed action
iii. ψ_l – Factor for determining quasi-permanent (long term) values of actions
iv. W_u – Ultimate wind action
v. E_u – Ultimate earthquake action
vi. ψ_C – Combination factor for imposed action
vii. ψ_E – Combination factor for earthquake actions
viii. S_u – Ultimate value of various actions appropriate for particular combinations

A1.0.0.7

Strength *Limit* states require that the design capacity (R_d) satisfies

$$R_d \geq E_d \quad \textbf{(A1)}$$

where E_d is the design action. This provides a basis by which structural performance may be assessed. Further detail may be found in **AS/NZS 1170.0 Structural Design Actions – General Principles** or similar as is applicable to the *Designer's* jurisdiction.

A1.0.0.8

If there is uncertainty, the *Designer* should, and is encouraged to, consider testing as a method of verifying that a modular component/system meets strength requirements. Refer to **Sections A2.6** and **J3** of this document for further guidance in this regard.

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A1.0.0.9

Serviceability Limit States relate to design to ensure adequate function in service conditions. In this regard, the *Designer* should determine the appropriate combination for the condition being considered. Combinations of one or a number of the following, using short- and long-term values, may be appropriate:

i. G (Permanent action)
ii. $\psi_s Q$ (Short-term Imposed action)
iii. $\psi_l Q$ (Long-term Imposed action)
iv. W_s (Serviceability Wind action), typically determined on the basis of a 1/25 annual probability of exceedance, as **AS/NZS 1170.0** Table C1 defines this as the recurrence period after which serviceability issues are typically seen
v. E_s (Serviceability Earthquake action)
vi. Serviceability values for other actions, as deemed appropriate

For further detail on *Serviceability Limit States* the *Designer* is referred to **AS/NZS 1170.0** or an appropriate standard for their region. However, when considering a *Serviceability Limit State* the *Designer* should confirm that:

$$\delta \leq \delta_l \qquad \textbf{(A2)}$$

where δ is the value of the serviceability parameter determined on the basis of the design actions (e.g. beam deflection) and δ_l is the limiting value of the parameter.

A1.0.0.10

The *Designer* should refer to appropriate Standards for values of δ_l. The Australian/New Zealand Designer may refer to Table C1 **AS/NZS 1170.0** for general guidance on suggested Serviceability criteria, with further guidance available in specific material Standards e.g. **AS 4100** [5.15] for steel structures, **AS/NZS 4600** [5.17] for cold-formed steel structures, **AS 3600** [5.16] for concrete structures, **AS 1720** for timber structures and **AS 2327** for composite structures.

The Designer should consider that for volumetric modules, the structural members are constrained within a module. As such, values given in the standards referenced above regarding limiting values of serviceability may not necessarily be suitable. Furthermore, serviceability design should also take into account the relative movement between modules.

A1.0.0.11

Given the slender/lean nature of *Modular Construction*, the *Designer* should consider human perception of acceleration. **AS/NZS 1170.2** Appendix G provides guidance on the peak acceleration due to wind, **AS 1170.4** Chapter 7 provides guidance on dynamic analysis for *seismic* design, and **AS 2670** [5.19] provides details on human comfort related to vibration and shock.

A1.1 Fully Assembled Structures

A1.1.0.1

This section describes some of the loads that are relevant to a fully assembled structure or a completed building, as opposed to the considerations specific to modules comprising a modular construction project, i.e. temporary loads. The latter will be discussed in **Section A1.2**. The guidance and calculation methods described here are specific to conditions in Australia and New Zealand, and the international *Designer* should consult the appropriate local codes and standards for their jurisdiction.

A1.1.0.2

The *Designer* should ensure that design *seismic* and wind actions have been computed in order to determine which governs the design resistance required. This will have ramifications for the final design adopted.

A1.1.1 Wind Actions

A1.1.1.1

The following guidance is offered in **AS/NZS 1170.2 – Wind Actions Section 2** for calculation of site wind speeds $V_{(\text{sit},\beta)}$:

$$V_{\text{sit},\beta} = V_{\text{R}} M_{\text{d}} (M_{z,\text{cat}} M_{\text{s}} M_{\text{t}}) \qquad \textbf{(A3)}$$

And for the design wind pressure:

$$p = (0.5\rho_{\text{air}})[V_{\text{des},\theta}]^2 C_{\text{fig}} C_{\text{dyn}} \qquad \textbf{(A4)}$$

where

V_{R} = Regional gust wind speed in metres per second for annual probability of exceedance of 1/R (see **Table A4** and **Table A5** for values of V_R)
M_{d} = Wind direction multipliers for the cardinal directions (see **Section 3** of **AS/NZS 1170.2** or similar for further guidance, and also **Figure 3.1** therein for designated Wind Regions)
$M_{z,\text{cat}}$ = Terrain/height multiplier
M_{s} = Shielding multiplier
M_{t} = Topographic multiplier
ρ_{air} = Density of air, taken as 1.2kg/m3

$V_{des,\theta}$ = Building orthogonal design wind speeds (≥ 30m/s for *ULS*)
C_{fig} = Aerodynamic shape factor, refer to Section 5 **AS/NZS 1170.2** for calculation
C_{dyn} = Dynamic response factor, refer to Section 6 **AS/NZS 1170.2** for determination, value is generally 1.0 unless the structure is dynamically sensitive to wind

Table A4 — Regional wind speed for non-cyclonic regions (from **Table 3.1 AS/NZS 1170.2**)[4]

Regional Wind Speed (m/s)	Region		
	A	W	B
V_1	30	34	26
V_5	32	39	28
V_{10}	34	41	33
V_{20}	37	43	38
V_{25}	37	43	39
V_{50}	39	45	44
V_{100}	41	47	48
V_{200}	43	49	52
V_{250}	43	49	53
V_{500}	45	51	57
V_{1000}	46	53	60
V_{2000}	48	54	63
V_{2500}	48	55	64
V_{5000}	50	56	67
V_{10000}	51	58	69
V_R (R≥5 years)	$67-41R^{-0.1}$	$104-70R^{-0.045}$	$106-92R^{-0.1}$

Table A5 — Regional wind speed for cyclonic regions (from **Table 3.1 AS/NZS 1170.2**)[4]

Regional Wind Speed (m/s)	Region	
	C	D
V_1	$23 \times F_C$	$23 \times F_D$
V_5	$33 \times F_C$	$35 \times F_D$
V_{10}	$39 \times F_C$	$43 \times F_D$
V_{20}	$45 \times F_C$	$51 \times F_D$
V_{25}	$47 \times F_C$	$53 \times F_D$
V_{50}	$52 \times F_C$	$60 \times F_D$
V_{100}	$56 \times F_C$	$66 \times F_D$
V_{200}	$61 \times F_C$	$72 \times F_D$
V_{250}	$62 \times F_C$	$74 \times F_D$
V_{500}	$66 \times F_C$	$80 \times F_D$
V_{1000}	$70 \times F_C$	$85 \times F_D$
V_{2000}	$73 \times F_C$	$90 \times F_D$
V_{2500}	$74 \times F_C$	$91 \times F_D$
V_{5000}	$78 \times F_C$	$95 \times F_D$
V_{10000}	$81 \times F_C$	$99 \times F_D$
V_R (R≥5 years)	$F_C(122-104R^{-0.1})$	$F_D(156-142R^{-0.1})$

The force F on a surface or structural element is given by the vector sum of the forces due to the wind pressures p applicable on the relevant surface area A:

$$F = \sum p_z A_z \tag{A5}$$

where

p_z = Design wind pressure in Pascals (normal to the surface) at height z
A_z = A reference area at height z (in m²), upon which the pressure at that height (p_z) acts

This gives the *Designer* a basis for determining structural actions due to wind.

A1.1.1.2

The *Designer* should consider the lateral deflections, and any dynamic effects (where appropriate), generated by the action of wind upon the structure. **AS/NZS 1170.2 Section 6** provides advice on how dynamic wind effects may be accounted for in various scenarios, such as where structures have natural first-mode fundamental frequencies less than 1 Hz. There are some cases where wind tunnel testing may also be required, for more details see **AS/NZS 1170.2 Section 6.1**.

A1.1.1.3

The *Designer* should consider the effect of the cyclic nature of wind actions upon the fatigue of modular components and structures. Refer to **Section F3** of this document for further detail.

A1.1.1.4

The *Designer* should check the structure for lateral wind sensitivity and serviceability response limits. **AS/NZS 1170.2** Section 6 provides analysis guidance and **Appendix G** therein suggests an initial check of the building height and vertical mass distribution regarding acceptable crosswind acceleration levels.

A1.1.1.5

The design of a modular structure should consider the uplift effect of wind actions on the individual modular units' stability as well as considering any implications for the design of connections.

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A1.1.2 Seismic Actions

A1.1.2.1

Seismic design considers the structural effects of vibration transmitted through the ground. This should include an assessment for earthquake effects and a review of to what extent, if any, there may be local exposure of the project site to non-earthquake sources such as dynamic groundworks, mining or heavy vehicle transport.

A1.1.2.2

Where trams or trains run near to the project site, their associated vibrational effects should be considered. Trams frequently operate closer to buildings than trains and their track is often rigid and non-ballasted allowing for more efficient transmission of vibration. See **Figure A2**.

A1.1.2.3

For earthquake *risk* the *Designer* should refer to **AS 1170.4 – Earthquake actions in Australia**, which follows the procedure outlined in **Table A6**. In common with design for other actions it is required to determine the *Importance Level* (IL) for the structure. However, *Importance Level* 1 structures and complying domestic housing need not be considered. This is the same for modular structures.

Further detail is available in **AS 1170.4** concerning structural design in Australia based upon *seismic* loading.

Table A6 – Typical earthquake/seismic design procedure for Australia

Step	Description
1	Determine the probability factor (k_p) and hazard factor (Z)
2	Determine soil class (A-E), on the basis of a geotechnical investigation of the site
3	Determine the Earthquake Design Category (I-III) on the basis of k_p, Z, soil class and structure height using AS 1170.4 table 2.1
4	Use AS 1170.4 clause 5.2-5.5 plus static (AS 1170.4 Section 6) or dynamic (AS 1170.4 Section 7) analysis as appropriate
5	If structure design is seismic governed, use section 8 of AS 1170. to design parts and components

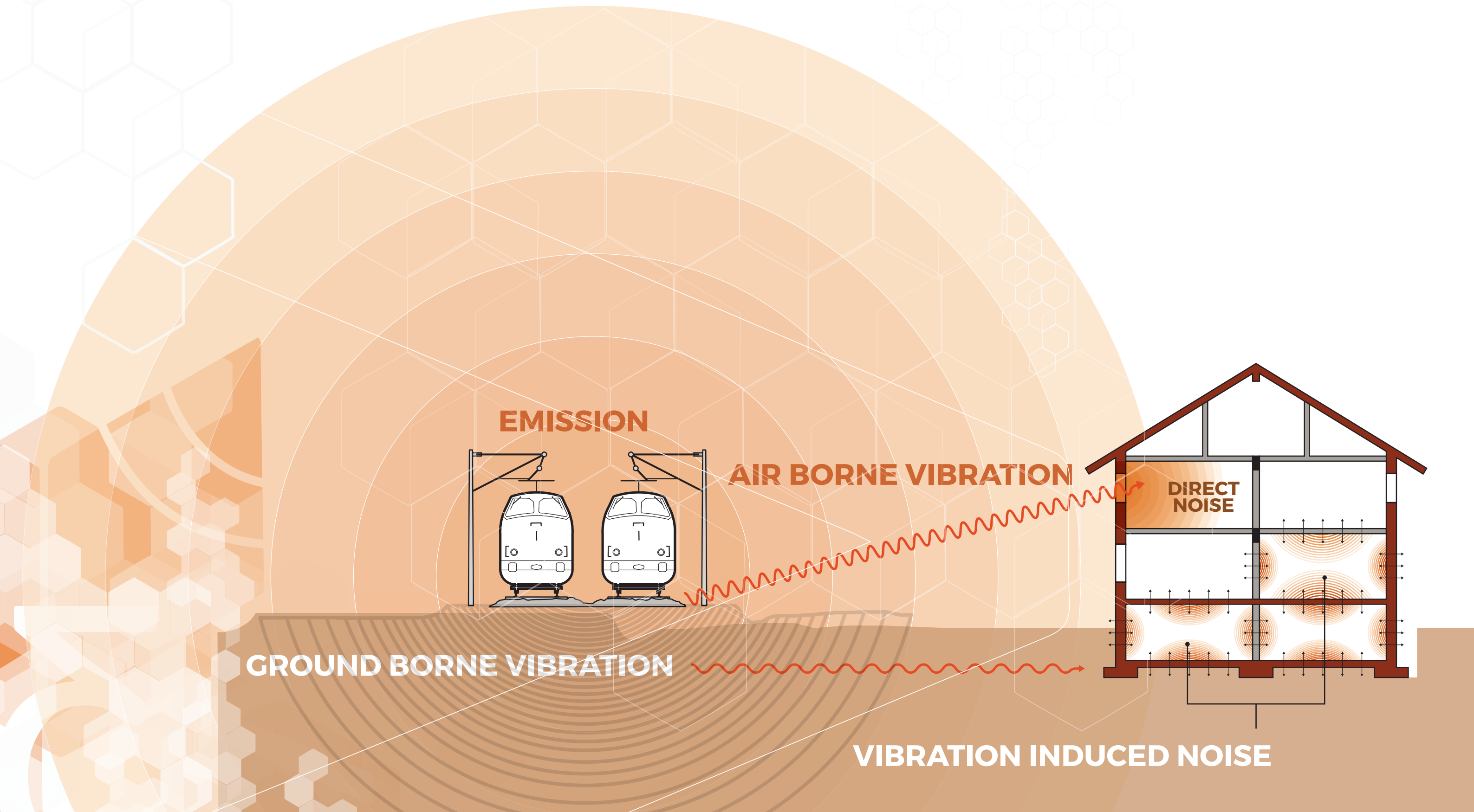

Figure A2 – Generation of vibration sourced via rail traffic

A1.1.2.4
Some locations will be subject to much greater earthquake loadings than those seen in Australia. In these cases, the *Designer* should ensure appropriate provision is made on the basis of local design Standards/Codes.

A1.1.2.5
In the case of a building where *Modular Construction* from a certain level is preceded by more substantial in-situ framing below, the *Designer* should account for the changes in building mass and stiffness as height varies.

The notional building height measured when designing for earthquake actions are related only to the base shear reaction at ground level where the building connects to the founding soil, which both applies *seismic* forces and provides footing support.

A1.1.2.6
A common issue with large scale *Modular Construction* is the change in stiffness between modular levels (often of light weight construction), and base or podium levels (often heavy weight construction including transfer spans and the like). When assessing the building under seismic actions it is important that the whole building is modelled to include all contributions to stiffness. Importantly it is not enough to consider the modular component of the structure separately from supporting structure below or alongside.

A1.1.2.7
Earthquake design for modular structures should also take into account the possibility of significant variations in earthquake-induced action effects due to:

i. The likely variation of structural period
ii. The P-Δ effect (due to out of verticality tolerances)
iii. Storey drift (due mainly to the use of discontinuous systems)

A1.1.2.8
Diaphragm action should be carefully considered in earthquake design as it plays a key role in the lateral behaviour of modular buildings. In particular, the uniform lateral movement of joints and structural elements in a storey, and the distribution of horizontal loads to vertical or lateral load resisting structural elements, are crucial. Modular Construction will often be associated with many discrete floor elements (unit diaphragms), whose integrity is provided by the diaphragm action. Further guidance in this area can be found in ASCE Standard 41-13 [6.35] and 7-10 [6.36].

A1.1.3 Precipitation Actions

A1.1.3.1
Precipitation of relevance here includes all forms of water from the atmosphere which can create loads onto a structure, not just snow or ice. Supporting the accumulation of rainwater via ponding may need to be considered where there is *risk* of blockage from hail in the roof drainage system. In this case the hail itself will be an additional loading.

A1.1.3.2
The *Designer* may refer to **AS/NZS 1170.3** for guidance concerning susceptibility and resistance to snow loads, whilst noting that its scope excludes the following:

i. Impact from snow or ice displacing from a higher structure
ii. Consequences from snow or ice blocking drainage systems
iii. Actions from snow or ice on bridges
iv. Additional wind loads which may be attracted from the accretion of snow or ice
v. Sites where snow is present all year (or above 1800 m altitude in New Zealand)
vi. Lateral loads from snow on the ground (e.g. drifts)
vii. Avalanche effects
viii. Increase in load from heavy rain onto snow
ix. Speculation about effects of future climate changes

A1.1.4 Other Actions

A1.1.4.1
The *Designer* is reminded that all reasonable and foreseeable actions and effects must be considered. One effect highlighted, under the *Performance Requirement* in reference to differential movement, is that of *axial shortening* in tall buildings. This is both foreseeable from known material behaviours and historically observable. Refer to **Section A3.6** for more details.

A1.1.4.2
The Designer should also consider the effects of constructional *tolerances*, which can create additional loads, affect the load-carrying capacity of elements and amplify the P-Δ effect. See **Section E2** for more details about *tolerances*.

A1.2 Temporary Loads on Modules

A1.2.1 Manufacturing

A1.2.1.1

All aspects of the manufacturing process should be accounted for by the *Designer* regarding effects on applied loads and material behaviour as the build progresses. This analysis is required at other times also prior to module erection on site. Aspects which should be considered at the manufacturing stage include:

i. **Temporary supports** — The module during manufacture should preferably retain the same vertical support arrangement throughout (e.g. not switch between a continuous bed and two or more trestles without the effects being checked). The support configuration will preferably account for the final conditions on the project site, which may typically be at the base corners, although this is dependent on the length of the module. The *Designer* should check and design for this temporary condition.

ii. **Stacked materials** — Pre-cambering of main beams might be considered. Loading conditions need to be controlled at the time when any structural connections are made (e.g. any stacked materials) and any residual stresses (e.g. from welding) should be managed.

iii. **Residual stresses** — Any induced material stresses or deformations from lifting or reorienting of modules or subassemblies during manufacture should be checked. This includes the effect of composite capacity creation within modules from the floor, wall or ceiling linings. This effect may be unintended and damaging. Similarly, consideration should also be given to any changes to support configurations or structural load paths.

A1.2.2 Lifting and Supports

A1.2.2.1

The support arrangements for a volumetric module during manufacture may be replicated or differ from that during lifting, transportation and once installed. The typical arrangement when erected on site is to support at four corners or at column locations. This potential for difference must be controlled by specifying what is required at each stage.

For example, consider a module that is based on standard shipping container dimensions and designed for support only under the four corners, perhaps even using conventional twist-lock castings. If it is transported on a common skeleton container trailer with multiple support arms for various container sizes and placements, then care must be exercised to ensure the module does not bear onto intermediate support arms. This would create reactions where there ought to be none and of a magnitude greater than for any of the corner supports normally. Note also that a trailer chassis is commonly cambered or arched upwards to offset net deflection when loaded. Where a steel container is supported at the corners during transportation, this camber may not be negated and would need consideration when loading the truck.

A1.2.2.2

For all stages of the structural life of a module, from partially complete during manufacture, through all lifting phases, to being complete and in-service on the project, the *Designer* should specify the intended support configuration. Other parties should not decide lifting, placement or storage techniques (e.g. relocation with a forklift or temporary placement directly on ground).

A1.2.2.3

For lifting of modules the *Designer* should make an assessment based on the cranes or lifting plant proposed. For a stationary crane (including overhead gantry crane or a tower crane) a dynamic factor of not less than 1.2 should be applied to the self-weight permanent actions. This allows for conventional winch speeds and brake dynamics. The dynamic factor when lifting using a crane can be as high as 2.2, so careful consideration is required. See **AS 3850.2** [5.12] and **AS 1418.1-2002** [5.27] for more details.

A1.2.2.4

The *Designer* and *Builder* should consider the *Centre of Gravity* (*CoG*) of the lifted module, which will be vertically under the hook when the module is freely suspended. This should be shown on all relevant staged construction drawings. Modules and any subassemblies should have their *CoG* calculated and shown on drawings. Lengths of multiple lifting *slings* (crane hook to module attachment point) may require prior adjustment to ensure control of the module orientation to the placement location. Multiple *slings* may also require use of load-equalisation devices. *Slings* inclined toward each other induce compression forces between them in

the suspended module. The *Designer* should check the module for such forces if applied.
Prior to lift-off, particular attention is required to ensure the crane hook is vertically above the module's *CoG* so that it will not start to swing when suspended (see **Figure A3**, overleaf).

The *Centre of Gravity* can be difficult to pinpoint by calculation given variability of finishes, joinery, etc. and even transport of other furniture, fixtures and equipment within a module. An 'approximate' centre of gravity should be required unless determined by factory testing to be precise. Lifting slings and beams should be designed to accommodate variability. For example, beams could have a range of lift points.

A1.2.2.5

The *Designer* should check the lifting stability of the module from the relationship of the *CoG* to the *Plane of Lift* and for any exposure to lateral loads such as from wind. Caution should be exercised where the *Plane of Lift* is below the *CoG*, since a tipping *hazard* may exist. Permissible wind loading during lifting may need to be specified, particularly if the module is underslung where a destabilising moment may be generated. It may be the case, however, that operational limits for wind load on the crane itself (including that transferred from the suspended load) govern before the overturning resistance of the suspended load to the wind forces are a concern.

A1.2.2.6

The *Designer* should clearly specify the lifting and connection arrangements where modules are to be temporarily stacked or otherwise interconnected. *Modular Construction* commonly involves the stacking of modules in a project building and may also entail temporary stacking in storage before, during or after transportation and with different detailing. These cases need to be considered (especially where modules are not intended for stacking) so as to avoid inappropriate loadings or where different connection arrangements are required for different stages.

A1.2.2.7

Any lifting assumptions made by the *Designer* should be clearly specified on all relevant documentation.

A1.2.3 Transportation

A1.2.3.1

During transportation modules and modular components are subjected to dynamic loading with variable intensity, frequency and duration *(IFD)*. These loads are typically described as multipliers (or acceleration coefficients) applied to the gravity-driven permanent actions, often as a worst-case value and additive to the vertical downwards effect of gravity itself.

A1.2.3.2

The *Designer* should assess the effects of dynamic forces in all applicable directions. Consideration needs to be given to peak instantaneous loads on strength resistance, cyclic effects on fatigue and structural response, variable positioning of modules within the transportation and means to increase or reduce dynamic effects.

Given the variability in transportation conditions (weather exposure, vehicle response, duration of stages) and that it usually coincides with a boundary between subcontracts, it is prudent to be conservative in design provisions for transport-induced actions.

A1.2.3.3

The *Designer* should assess the potential value of staged manufacture where transportation conditions may be arduous. Building materials which are more sensitive (e.g. glazing, brittle or moisture-sensitive linings, temperature-sensitive compounds) might better be installed nearer to the site of erection.

Note that sea containers, from the potential extremes of arctic wind chill to equatorial radiant sunshine, may typically be required to withstand a temperature range of -40˚C to +70˚C.

A1.2.3.4

The *Designer* should account for additional forces on any modules where they are positively restrained by tie-down action. Additional forces generated by tie-down and restraint against movement accelerations must also be resisted by the module's internal structure.

A1.2.3.5

Acceleration coefficients for transportation dynamics are cited in many sources, often in local Regulations. A single source has been referred to below as published by the International Maritime Organization – the Code of Practice for Packing of Cargo Transport Units (**CTU Code**) [6.5]. Given the primarily international nature of shipping and that

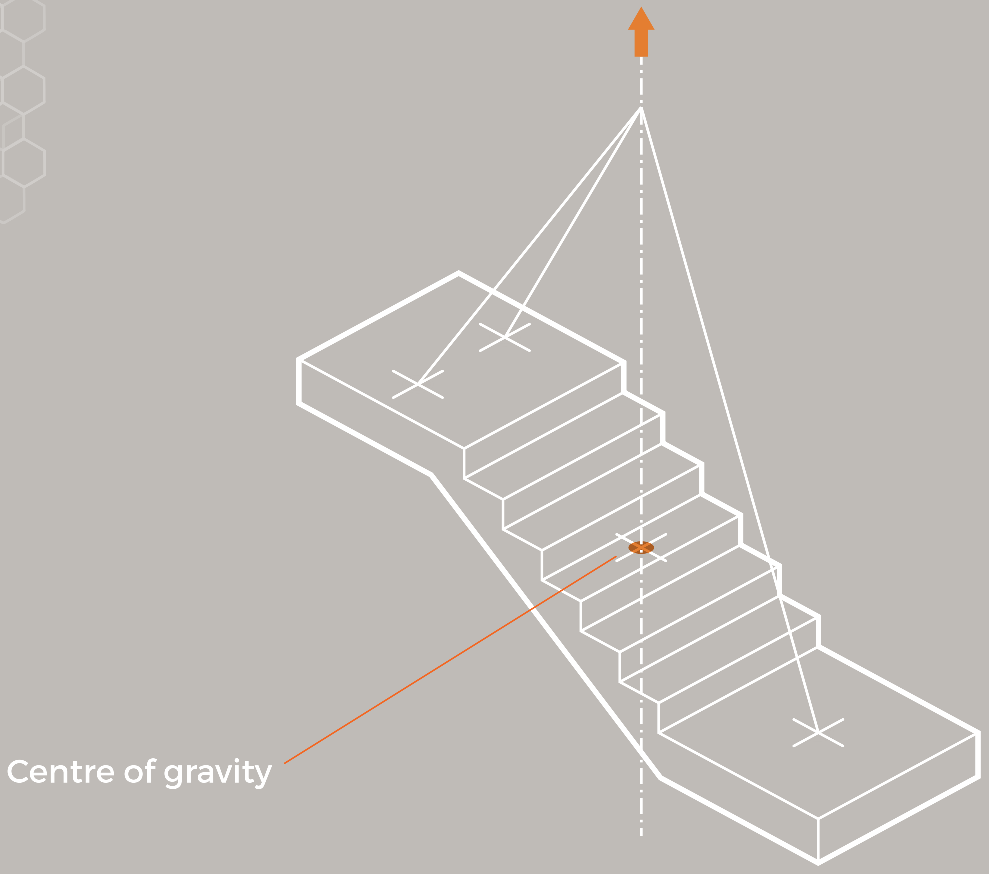

Figure A3 – Module CoG vertically below crane hook when suspended and unequal slings for control of orientation

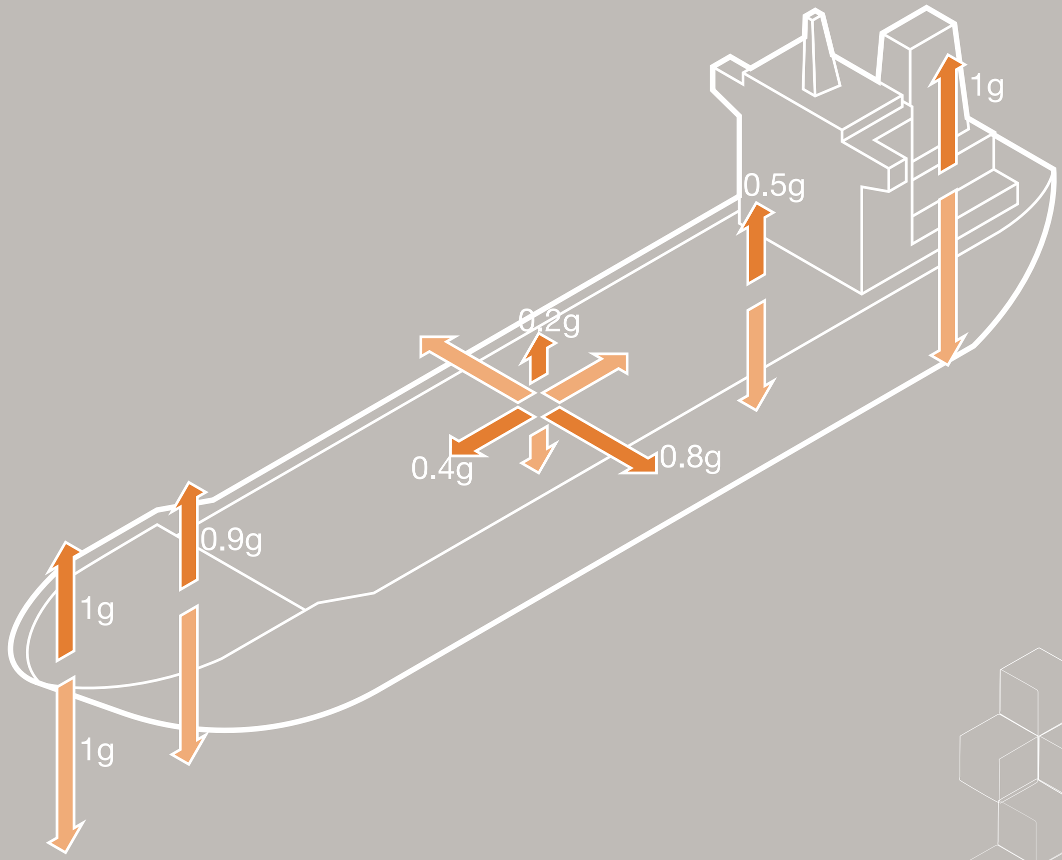

Figure A4 – Notional variation of vertical acceleration coefficients for shipping related to location along vessel.

the **CTU Code** also offers guidance for road and rail transport, it is beneficial generally. The *Designer* should assess and decide upon the appropriate transport loading information to be used based upon the origin and destination of the modules concerned and the intended transport route.

A1.2.3.6

The *Designer* should note that for all modes of transportation the vehicle dynamic loads are also additive to relative wind loads appropriate to the route of travel - although some shelter from packaging or internal stowage of modules may afford protection. Actual relative wind loads may be attributable solely to the vehicle travelling speed but in combination with rain and headwinds this may approximate cyclonic conditions. The component of air pressure applied to a module due to vehicle speed is a steady peak value unlike the measure for design wind which is averaged for a 0.2 second gust (refer **AS/NZS 1170.2** [5.2]). If the vehicle speed component is to be modelled as an equivalent additive wind then its value should be increased.

A1.2.4 Shipping

A1.2.4.1

Primary loads on conveyed goods at sea arise from the motion of the vessel through various weather conditions and is generally described by acceleration coefficients in the directions of three orthogonal axes, as shown descriptively in **Figure A4**.

For goods stowed above deck there is additional *risk* of forces from wave impacts.

Accelerations longitudinally (forwards, backwards) are applied uniformly throughout the vessel. However, accelerations vertically (up, down) and transversely (left, right) at different locations away from the axes centre can be further varied by the pitching rotation about the transverse axis and rolling rotation about the longitudinal axis.

Depending on the size of the vessel and other physical aspects the example in **Figure A4** suggests an additional 0.7g may act at the bow and stern plus the overall vessel centre vertical coefficient of 0.3g. The coefficients given in **Table A7** (from **CTU Code** [6.5]) are the minimum which apply at the intersection of these axes.

The vertical acceleration coefficients in **Table A5** are additive to that of gravity. The total coefficients applicable can be minimised by specifying the distance away from the axis of pitch for stowage.

Geographic sea areas around the world have been assessed and allocated appropriate H_s groupings. Refer again to Chapter 5 of the **CTU Code** [6.5].

Table A7 – Acceleration coefficients for sea transport (Hs = significant 20-year return wave height) [6.5]

Sea Transport

Hs	Direction secured in	Acceleration coefficient		
		Long	Trans	Vertical down (min)
<8m	Long	0.3	-	0.5
	Trans	-	0.5	1.0
>8m, <12m	Long	0.3	-	0.3
	Trans	-	0.7	1.0
>12m	Long	0.4	-	0.2
	Trans	-	0.8	1.0

In the context of sea containers (CTUs) and further to considerations of load restraint, tie-down and stacking forces the international Convention for Safe Containers [6.14] requires the following load resistance capacities in CTU construction:

i. End walls (each) 0.4 x rated Tare Capacity in racking
ii. Side walls (each) 0.6 x rated Tare Capacity in racking
iii. Base and floor fastenings (total) 2 x rated Gross Capacity in shear.

A1.2.5 Road

A1.2.5.1

Road transportation safety is regulated across Australia via the Heavy Vehicle National Law (HVNL). As with Building Regulation (in the *NCC*) it requires Performance Standards to be satisfied. The Load Restraint Guide [6.4] is an approved code of practice for compliance.

From Chapter 5 of the **CTU Code** [6.5] the appropriate road-based acceleration coefficients for road transport are shown in **Table A8**.

Table A8 – Acceleration coefficients for road transport [6.5]

Road Transport

Direction secured in	Acceleration coefficient			
	Long		Trans	Vertical down (min)
	Forward	Rearward		
Long	0.8	0.5	-	1.0
Trans	-	-	0.5	1.0

The relative air speed imparting pressure onto a road transported module in transit as a combination of vehicle speed and headwind may be as high as 180 km/hr (50 m/s), prior to adjustment for adding gust and non-gust components.

The airflow effects on the conveyed module may also include excitation/aeroelastic flutter.

A1.2.6 Rail

A1.2.6.1

Rail transportation safety in Australia is regulated via the Rail Safety National Law. It currently does not have an equivalent reference to the road-based Load Restraint Guide [6.4].

Appropriate rail-based acceleration coefficients from Chapter 5 of the **CTU Code** [6.5] are shown in **Table A9**.

Table A9 – Acceleration coefficients for rail transport [6.5]

Rail Transport

Direction secured in	Acceleration coefficient			
	Long		Trans	Vertical down (min)
	Forward	Rearward		
Long	0.5 (1.0)	0.5 (1.0)	-	1.0 (0.7)
Trans	-	-	0.5	1.0 (0.7)

The relative air speed imparting pressure onto a rail transported module in transit as a combination of vehicle speed and headwind may be as high as 215km/hr (60m/s), prior to adjustment for adding gust and non-gust components. Note this may also be affected by longitudinal/lateral pressure waves in tunnels from passing trains.

The airflow effects on the conveyed module may also include excitation/aeroelastic flutter.

A1.2.7 Erecting

A1.2.7.1

Prior to a module being finally positioned the *Builder* should ensure that the alignment of actual locations of the module connection points is within acceptable *tolerance* of the supports awaiting it. Where a module to be placed subsequently requires connection to following modules, then the support points it is to provide should also be checked for *tolerance* prior to placement.

A1.2.7.2

The *Designer* should make provision within the connection design to accommodate any misalignment of components within *tolerance*. Measures considered may include:

i. Shims/packers
ii. Racking correction/plumbing via active braces
iii. Localised flexural displacement around non-slip connections

A1.2.7.3

Further guidance for prefabricated concrete can be found in AS 3850 [5.12].

A1.2.8 Temporary structures

A1.2.8.1

Due to the relatively short service life of temporary structures even the permanent and imposed loads themselves are relatively temporary with regard to any time-dependent effects.

The Temporary Structures Standard [6.13] offers the following guidance shown in **Tables A10**, **A11**, **A12** for assessing wind and snow design loading in conjunction with **AS/NZS 1170** [5.2], accounting for the distinctive nature of temporary structures.

Table A10 – Importance Level for Temporary Structures [6.13][5]

Importance Level	Type of Temporary Structure
2	Designed to contain 300 people or less
3	Designed to contain > 300 people

Table A11 – Annual probability of exceedance for wind and snow actions for Temporary Structures [6.13][5]

Importance Level	Probability of Exceedance	
	Wind	Snow
2	1:500	1:50
3	1:1000	1:100

Table A12 – Reduction factors for regional wind speed on Temporary Structures[5]

Wind Region	Reference Duration		
	6month	1month	1week
	Reduction factor on regional wind speed		
A	0.95	0.85	0.75
B	0.95	0.75	0.55
C	0.95	0.75	0.55
D	0.95	0.70	0.50

A1.2.8.2

Temporary structures are frequently provided for events drawing short-term crowds. With this comes increased *risk* of unexpected and uncontrolled crowd overload.

The *Designer* should clearly document the maximum permissible distributed and concentrated load and the maximum occupancy capacity for which the temporary structure has been designed. This information should be provided to relevant *competent persons* with control of the temporary structure. Appropriate signage on the structure advising the occupancy capacity is recommended.

A2 Element design

A2.1 Material Reduction Factors

A2.1.0.1

The reliance of *Modular Construction* upon off-site manufacturing processes allows for greater *accuracy* and *precision* in finished products taken to site for assembly. The design rationale of *Reliability* accounts for these factors, and permits appropriate credit in the design process (for example, increase of capacity reduction factors). *Reliability* analysis is outlined in the *NCC* and mandated where a Deemed-to-Satisfy solution is not used. *Reliability* analysis is covered in detail in **Section A3.5 Reliability**.

A2.1.0.2

Where the *Reliability* approach is used to establish material capacity design values by testing, a methodology should be proposed by the *Designer* for obtaining and calibrating test data against proposed design output.

A2.1.0.3

Examples of capacity reduction factors for commonly used materials to Australian design standards are presented in the subsequent sections for reference.

It should be recognised that these capacity reduction factors are based on *Reliability* analysis. Alternate factors suitable to the client may be able to be utilised in some cases, depending on *risk*. This is discussed further in **Section A3.5 Reliability**.

A2.1.0.4

The use of capacity reduction factors in accordance with AS 4100 Steel Structures [5.15] is presented here. It should be noted that on the basis of **AS 4100** any steel member must satisfy the following for loading in axial compression and tension

$$N^* \leq \phi N_\mathrm{c} \qquad \textbf{(A6)}$$

$$N^* \leq \phi N_\mathrm{t} \qquad \textbf{(A7)}$$

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[5] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

where

N^* = Design axial compression or tension force
N_c = Nominal member compression capacity
N_t = Nominal member tension capacity
ϕ = capacity factor

For combined actions the in-plane constraint applies:

$$M_x^* \leq \phi M_{rx} \qquad \textbf{(A8)}$$

where

M_x^* = Design bending moment about major principle axis
M_{rx} = Nominal section moment capacity, reduced by axial force

$$= M_{sx}\left(1 - \frac{N^*}{N_s}\right)$$

N_s = Nominal section capacity
M_{sx} = Nominal section in-plane moment capacity

Also for combined actions, the out-of-plane constraint applies:

$$M_y^* \leq \phi M_{ry} \qquad \textbf{(A9)}$$

where

M_{ry} = Nominal section out-of-plane moment capacity, reduced by axial force

$$= M_{sy}\left(1 - \frac{N^*}{N_s}\right)$$

M_{sy} = Nominal section out-of-plane moment capacity

The following overall constraint must also be satisfied:

$$\frac{N^*}{\phi N_s} + \frac{M_x^*}{\phi M_{sx}} + \frac{M_y^*}{\phi M_{sy}} \leq 1 \qquad \textbf{(A10)}$$

For further guidance on determining nominal section and member capacities, refer to **AS 4100** Sections 5–8 or the appropriate Standard for the *Designer's* jurisdiction. Typical capacity *reduction factors* for Australian steel structures are given in **Table A13**.

A2.1.0.5

For cold-formed steel members additional specific design guidance to **AS 4100** [5.15] is provided in **AS 4600 Cold-formed steel structures** [5.17]. The *capacity reduction factors* (ϕ) typically used within Australia are repeated in **Table A14** for the *Designer's* convenience.

A2.1.0.6

For the design of concrete elements and structures, the Designer should refer to **AS 3600 Concrete Structures** [5.16] **Table A15** shows typical values of the *capacity reduction factor* (ϕ) used in Australia for concrete.

Table A13 – Capacity factors (ϕ) for strength limit states for steel structures as per Table 3.4 **AS 4100 (Steel)** [5.15][6]

Design Capacity for	Capacity Factor (ϕ)
Member subject to bending	
- Full lateral support	0.9
- Segment without full lateral support	0.9
- Web in shear	0.9
- Web in bearing	0.9
- Stiffener	0.9
Member subject to axial compression	
- section capacity	0.9
- member capacity	0.9
Member subject to axial tension	0.9
Member subject to combined actions	
- section capacity	0.9
- member capacity	0.9

A2.2 Design Considerations

A2.2.0.1

Table A16 provides a number of design considerations relating to various components in *Modular Construction*. Detailed design must be conducted using appropriate Standards or methods for the *Designer's* jurisdiction.

A2.2.0.2

In general, the *Designer* should consider ductility measures and structure overload response to permit load redistribution (refer to **Section A3.4** on the topic of *Robustness*) and also consider making provision for eventual safe dismantling.

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Table A 14 — Capacity factors (ϕ) for cold-formed steel structures as per **Table 1.6 AS/NZS 4600** [5.17][7]

Design Capacity for	Capacity Factor (ϕ)
(a) Members subject to axial tension (ϕ_t)	0.90
(b) Members subject to bending	
(i) Section moment capacity	
(A) For sections with stiffened or partially stiffened compression flanges (ϕ_b)	0.95
(B) For sections with unstiffened compression flanges (ϕ_b)	0.9
(ii) Member moment capacity	0.9
(A) Members subject to lateral buckling (ϕ_b)	
(B) Members subject to distortional buckling (ϕ_b)	0.9
(C) Beams having one flange through-fastened to sheeting (channels or Z-sections) (ϕ_b)	0.9
(iii) Web design	
(A) Shear	0.9
(iv) Bearing (ϕ_w)	
(A) For built-up sections	0.75-0.9
(B) For single web channel or channel-sections	0.75-0.9
(C) For single web Z-sections	0.75-0.9
(D) For single hat sections	0.75-0.9
(E) For multiple web deck sections	0.6-0.9
(c) Concentrically loaded compression members (ϕ_c)	0.85
(d) Combined axial load and bending	
(i) Compression (ϕ_c)	0.85
(ii) Bending (ϕ_b) c.f. AS 4600	
(A) Using clause 3.3.2	0.9 or 0.95
(B) Using clause 3.3.3.1	0.9
(f) Cylindrical tubular members	
(i) Bending (ϕ_c)	0.95
(ii) Compression (ϕ_c)	0.85

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Table A 15 — Typical capacity factor (ϕ) values for concrete as per **Table 2.2.2 AS 3600** (Concrete) [5.16][8]

Type of Action Effect	Capacity Reduction Factor (ϕ)
(a) Axial force without bending:	
(i) Tension members:	
- with Class N reinforcement and/or tendons	0.8
- with Class L reinforcement	0.64
(ii) Compression members	0.6
(b) Bending without axial tension or compression:	
(i) for members with Class N reinforcement and/or tendons	$0.6 \le \left(1.19 - \frac{13k_{uo}}{12}\right) \le 0.8$
(ii) for members with Class L reinforcement	$0.6 \le \left(1.19 - \frac{13k_{uo}}{12}\right) \le 0.64$
(c) Bending with axial tension:	
(i) for members with Class N reinforcement and/or tendons	$\phi + \left[(0.8 - \phi)\left(\frac{N_u}{N_{uot}}\right)\right]$ ϕ from item (b) (i)
(ii) for members with Class L reinforcement	$\phi + \left[(0.64 - \phi)\left(\frac{N_u}{N_{uot}}\right)\right]$ ϕ from item (b) (ii)
(d) Bending with axial compression where:	
(i) $N_u \ge N_{ub}$	0.6
(ii) $N_u \ge N_{ub}$	$0.6 + \left[(\phi - 0.6)\left(1 - \frac{N_u}{N_{ub}}\right)\right]$ ϕ from item (b)
(e) Shear	0.7
(f) Torsion	0.7
(g) Bearing	0.6
(h) Bending, shear and compression in plain concrete	0.6
(i) Bending, shear and tension in fixings	0.6

Table A 16 — Design considerations for structural elements in Modular Construction

Component	Potential Issues	Recommendations /Considerations
Columns	(i) Lack of continuity and efficient load transfer between floors and laterally	(i) Design of connections to allow for acceptable load/moment transfer and composite action, through use of stitching plates or similar
	(ii) Difficulty of erection on-site	(ii) The Designer should allow for accessibility and/or ease of making connections and sufficient tolerances
	(iii) P-Δ effect arising from small deviations between levels due to tolerances/slip	(iii) The Designer should design for low slip connections and/or the ability to use tolerances to correct deviations
	(iiii) Axial shortening in tall structures	(iiii) The Designer must account for the effects of any axial shortening that may occur on the vertical load-bearing members; differential axial shortening may result in a P-Δ effect (destabilising moment due to lateral displacement).
Beams Floors Ceilings Fixtures	(i) Reduced effective stiffness of frame	(i) The Designer should account for the reduced diaphragm action and overall stiffness of the frame compared to in-situ builds when designing for the fully assembled structure.
	(ii) Effect of transportation (i.e. cracking of claddings, racking)	(ii) The Designer should consider the effect of dynamic loading on any cladding attached to framing (i.e. plasterboard walls, ceilings), especially given their generally semi-rigid nature.
	(iii) Stiffness of floor slabs or elements	(iii) It is important to consider the possibility for composite action to result from design decisions and the effect of any racking upon glazed openings and hung doors. This will be particularly important for the comfort of occupants, as the lean nature of Modular Construction. Designers should ensure any flooring system is of sufficient stiffness to afford occupant comfort without the addition of unnecessary material.

Table A 16 (continued) — Design considerations for structural elements in Modular Construction

Component	Potential Issues	Recommendations /Considerations
Bracing	(i) Insufficient lateral stiffness of final structure	(i) Depending upon the ability of designed modules to resist lateral actions collectively (i.e. global stiffness of finished building), it may be necessary to design bracing elements such as a structural core, shear walls, or external frame to which the modules connect.
	(ii) Insufficient lateral resistance of single module	(ii) Lateral resistance of individual modules may be accomplished either through improved connection design or internal bracing. The Designer should exercise caution and testing may be necessary to ensure lateral resistance is sufficient for claddings and fittings to survive any transient conditions.
Connect-ions	(i) Insufficient load transfer and lack of continuity	(i) Load transfer (particularly between modules) will rely heavily upon connection design. The Designer should consider the use of stitching plates or similar to ensure composite action between modules and continuity in load transfer. Section 6.2.3 of **AS/NZS** 1170.0 [5.2] specifies that the connections shall be capable of transmitting 5% of the value of $(G+\psi_c Q)$ for the connection under consideration.
	(ii) Conduction of thermal loads and/or acoustics	(ii) As the majority of modular connections will be steel, there is the possibility for thermal loads and acoustics to be transferred. The Designer should consider how to design connections to nullify the conduction issues (i.e. through damping with a sandwiched material) including connection between any sacrificial temporary elements to permanent structures.
	(iii) Slip and low lateral resistance	(iii) Bolted connections in particular will have some slip and associated moment-rotation behaviour. The Designer should account for slip, either through correction on site or through design of slip-resistant connections, and should provide sufficient lateral resistance for transient and Serviceability loads.

A2.3 Connections

A2.3.0.1

For steel connections of hot-rolled sections, the Australian *Designer* should refer to **AS 4100** [5.15] for guidance.

A2.3.0.2

In jurisdictions adhering to the Eurocodes, the Desinger may refer to **EN 1993-1-8:2005 Eurocode 3: Design of steel structures – Part 1-8: Design of joints** [6.6]. As joint behaviour (i.e. semi-rigidity) is important in modular structures, two definitions from **Eurocode 3** [6.6] are repeated here for the benefit of the Designer when analysing and designing their structure. A joint is considered nominally pinned when[9]

$$S_{\mathrm{j,ini}} \leq 0.5 E I_{\mathrm{b}}/L_{\mathrm{b}} \qquad \textbf{(A11)}$$

where

$S_{\mathrm{j,ini}}$ = the initial rotational stiffness of a joint, found from the slope of the initial section of simplified bi-linear moment-rotation characteristic curve (see Figure A5)
I_{b} = the second moment of area of a beam
L_{b} = the span of a beam (centre-to-centre of columns)
E = modulus of elasticity

If $\frac{K_{\mathrm{b}}}{K_{\mathrm{c}}} \leq 0.1$ joints should be classified as semi rigid, where

K_{b} = the mean value of $I_{\mathrm{b}}/L_{\mathrm{b}}$ for all beams in the storey considered
K_{c} = the mean value of $I_{\mathrm{c}}/L_{\mathrm{c}}$ for all columns in the storey considered
I_{c} = the second moment of area of a column
L_{b} = the span of a beam (centre-to-centre of columns)
L_{c} = the column length

A connection is considered rigid if [9]

$$S_{\mathrm{j,ini}} \geq K_{\mathrm{b}} E I_{\mathrm{b}}/L_{\mathrm{b}} \qquad \textbf{(A12)}$$

A connection is considered semi-rigid if $S_{\mathrm{j.ini}}$ lies between the values described in Equation A11 and Equation A12.

A2.3.0.3

For steel connections of cold-formed steel members, Designers are referred to **AS/NZS 4600** [5.17] or similar.

A2.3.0.4

For connections and anchoring into concrete (both post-installed and cast-in), the *Designer* should make use of Technical Specifications such as **SA TS 101:2015 "Design of post-installed and cast-in fastenings for use in concrete"** [5.18] or European Technical Approval Guideline **ETAG 001 – Metal Anchors for Use in Concrete** [6.7]. Further guidance may also be found in **AS 3850** [5.12].

A2.3.0.5

Design of joints/connections involving timber should be referenced to Standards such as AS 1720 Timber structures [5.20]. In the case of pre-engineered timber like Cross Laminated Timber (CLT), Eurocode 5 (EN 1995-1-1:2004) [6.33] offers a more comprehensive design procedure for timber and connections than the Australian standards and should therefore be considered as part of the design process, particularly as many technical approvals for such materials, screws and proprietary connects directly reference the Eurocode.

A2.3.0.6

Connection detailing in building systems which contain a mix of wood-based components should take different movement into account, which can arise due to shrinkage and swelling in engineered timber panels as a result of seasonal changes and ambient environment.

A2.3.0.7

In the case of new or innovative connection detailing, the Designer is encouraged to employ multiple methods of proving the design. These include but are not limited to testing and finite element analysis (see Section A3.1).

A2.3.0.8

Good connection design can be a significant driver for costs and speed of assembly, and should be detailed thoroughly in the design process. The design of connections and how they affect the overall efficiency may have an influence on the selection of member sizes.

A2.3.0.9

The Designer should consider that connections strongly influence the overall structural stability and robustness of the assembly of modules. The connections are designed to transfer horizontal forces (e.g. due to wind loading), and the extreme forces due to loss of support in the event of accidental events. Adequate vertical shear transfer (for example as a result of wind-induced uplifts or differential movements) between units must be considered to maintain the integrity of the system in such occasions.

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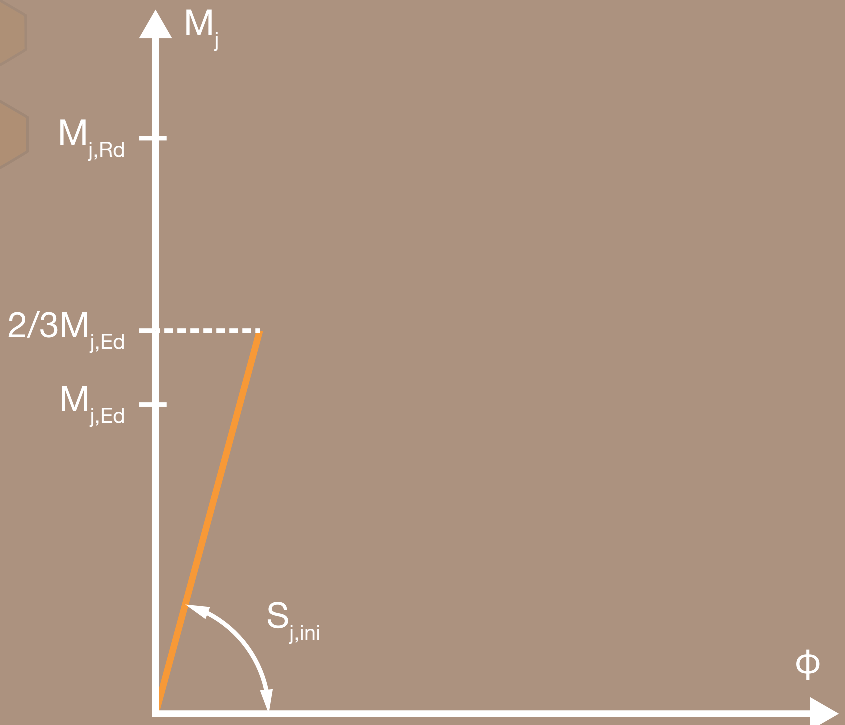
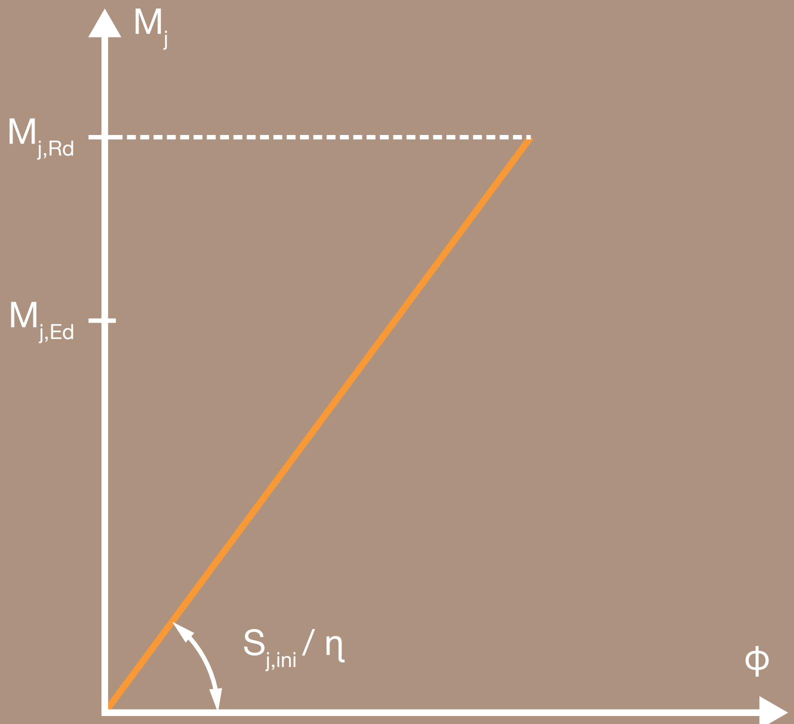


a) $M_{j,Ed} \leq 2/3\ M_{j,Rd}$



b) $M_{j,Ed} \leq M_{j,Rd}$

Figure A5 — Simplified bi-linear moment rotation curve for design, indicating how the initial joint stiffness is found as the slope of the moment M_j vs. rotation ϕ.[10]

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A2.4 Certification

A2.4.0.1

Design *certification* (as distinct from as-built *certification*) should entail independent checking of design assumptions, validity of loading and material capacity data, analysis of structural form and load paths, and assessment of *Reliability* and *Robustness*. The *Certifier* should account for any related regulatory *compliance* that is required regarding, in Australia, the *NCC* and *WHS*, or in other jurisdictions the appropriate local Codes and laws.

A2.4.0.2

Regarding building materials a *Certification* may be attesting to the absence of *non-conforming building products* or *non-compliant building products* or both.

A2.5 Performance criteria

A2.5.0.1

The *Designer* should clearly state the Performance Criteria the design is to satisfy, with the minimum level being that nominated in the *NCC* (for the completed building) and also regarding *WHS* during the construction phase. In addition, from *WHS* requirements, the handling & transportation phases may require further criteria to be considered including cyclic/vibration loading and cyclonic loading.

A2.5.0.2

Durability is also particularly important to consider when provisioning performance criteria. This includes provision of anti-corrosion coatings/treatments (as necessary), maintenance scheduling and minimum lifetime of components. See **Chapter F** of this document for further details.

A2.6 Testing-Based Design (TBD)

A2.6.0.1

Testing-Based Design refers to the use of experimental or observational data to establish design values for the strength/resistance or response of members, materials or assemblies. Unless a *Proof testing* process is employed (testing 100% of samples) a statistical process is required, using the coefficients of variation and statistical analysis to establish minimum values for use in design with the studied member or assembly.

A2.6.0.2

Guidance on this subject is provided by **AS 1170.0 Appendix B** [5.2]. Typically tests for *Modular Construction* will be performed to establish the resistance or serviceability properties of the modular system or components (or parts thereof). As such the *Designer* or *Tester* performing the test should establish a clear test plan incorporating:

i. Objectives and scope: What is to be measured? What varied parameter(s) is the *tester* interested in? What are the limitations on the test and are there any required conversions (e.g. scaling effects)?
ii. Prediction of test results: The *tester* should account for geometrical parameters and their variability, any geometrical imperfections, the material properties (and their variation), parameters which are influenced by fabrication and testing procedures, and any scale effects of environmental parameters (and accounting for any relevant sequencing). Expected modes of failure and any calculations or finite element analysis should be clearly described, along with any variables which affect these.

A2.6.0.3

Designers in Europe may refer to **EN 1990 Basis of structural design Annex D** [6.8] for guidance on testing

A2.6.0.4

The *tester* should consider that any structural member may have multiple failure modes, and if there is significant doubt about which failure mode is expected, testing should be developed on the basis of pilot tests.

A2.6.0.5

The *tester* should clearly specify all specimens to represent the conditions of the real structure. Any dimensions and *tolerances* should be accounted for, in addition to material and fabrication of samples, number of specimens tested, sampling procedures and any restraints. Sampling procedures should be done with a view to obtain a statistically representative sample, drawing attention to any difference between test specimens and the product in the field.

A2.6.0.6

The loading and environmental conditions should be specified clearly including: Loading point(s), loading history, restraints on samples, temperatures, relative humidity and loading method (by deformation or force control etc.). Some parameters may not be relevant, but it should be clearly stated why these are not considered.

A2.6.0.7

The *tester* should also ensure the load sequence represents the anticipated use of the structural member/assembly, under both normal and severe conditions of use. Any interactions between structural response and test apparatus should be taken into account where relevant.

A2.6.0.8

Should structural behaviour depend upon the effects of one or more actions that are not varied systematically, then those effects should be specified by their representative values.

A2.6.0.9

Testing equipment used should be relevant for the testing required and the expected range of measurement. The *tester* should also consider any requirements there may be for obtaining sufficient strength and stiffness of loading and supporting rigs, any allowance for deflection etc.

A2.6.0.10

Before any testing is conducted, relevant properties which are to be measured during the test should be listed. Additionally, a list should be made that:

i. Defines measurement locations
ii. Defines procedures for recording relevant results

A2.6.11

Any determination of properties from test results should account for the spread of data, statistical uncertainties related to the number of tests, any prior statistical knowledge, and if the response of a structure or member is dependent upon influences not sufficiently covered by tests. **AS 1170.0 Appendix B** [5.2] (or **EN 1990 Annex D** [6.8] for *Designers* in Europe) gives guidance on the determination of design values based on test data.

A2.6.0.12

The *Designer* or *tester* should determine the design value of a property (such as strength or stiffness) on **no less** than 3 tests. Sufficient tests should be done such that all possible variation is accounted for when determining a design value.

A2.6.0.13

The method of analysis on the basis of **AS 1170.0** states that the design capacity X_d should not exceed

$$X_\mathrm{d} = \frac{X_\mathrm{min}}{k_t} \tag{A13}$$

where X_{min} is the minimum value of the test results, and k_t is taken from **Table A17**.

Table A17 – Table of k_t values to allow for variability of structural units (as per **AS 1170.0** Table B1)
Note: n represents the number of tests conducted[11]

n	Coefficient of variation of structural characteristics (V_{SC})						
	0.05	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.40**
1	1.20	1.46	1.79	2.21	2.75	3.45	5.2
2	1.17	1.38	1.64	1.96	2.36	2.86	3.9
3	1.15	1.33	1.56	1.83	2.16	2.56	3.3
4	1.15	1.30	1.50	1.74	2.03	2.37	2.9
5	1.13	1.28	1.46	1.67	1.93	2.23	2.7
10	1.10	1.21	1.34	1.49	1.66	1.85	2.1

For any values of V_{sc} where n lies between those listed in **Table A17** the *Designer* may use linear interpolation, however extrapolation is not allowed for.

A2.6.0.14

An industry-derived example using **Table A17** to determine design values is that given in the National Association of Steel-frame Housing's (NASH) **Technical Note 4** [6.1] which gives further guidance on minimum coefficients of variation as in **Table A18**.

Table A18 – Minimum Coefficients of Variation (as per NASH Technical Note 4 Table 1)[12]

Measured Property	Minimum Coefficient of Variation
Member or connector strength	0.1
Connection strength	0.2
Assembly strength	0.2
Member stiffness	0.05
Assembly stiffness	0.2

The values in this table may be significantly higher than those derived from test results. *Prototype testing* tends to take material or components from a single batch and thus does not necessarily capture all variability that may occur in practice.

A2.6.0.15

While the process outlined by **AS1170 Appendix B** provides a tool for the Designer to determine design values from test data, the process outlined

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[12] © NASH 2005. Sourced from NASH Technical Note 4.

by **EN 1990 Annex D** is more robust. It provides the following equation for determining the design value X_d of a property based upon the characteristic value:

$$X_{\mathrm{d}} = \frac{\eta_{\mathrm{d}}}{\gamma_m} m_X (1 - k_n V_X) \tag{A14}$$

where

V_X = coefficient of variation
η_{d} = the design value of the conversion factor
γ_m = partial factor for resistances, selected according to the field of application for test results
m_X = mean value of X based on test results
k_n = correction factor to account for variation

A2.6.0.16

EN 1990 Annex D provides two methods for determining k_n; where the coefficient of variation is known from prior knowledge (i.e. previous testing) and where the coefficient of variation is unknown. The value of k_n may be taken from **Table A19**.

Table A19 – Values of k_n for the 5% characteristic value taken from EN 1990 Annex D Table D1[13]

n	1	2	3	4	5	6
V_x known	2.31	2.01	1.89	1.83	1.80	1.77
V_x unknown	-	-	3.37	2.63	2.33	2.18
n	8	10	20	30	∞	-
V_x known	1.74	1.72	1.68	1.67	1.64	-
V_x unknown	2.00	1.92	1.76	1.73	1.64	-

A2.6.0.17

If the coefficient of variation V_x is unknown, then it may be estimated from test data using the following equations:

$$s_X^2 = \frac{1}{n-1} \sum_i (x_i - m_X)^2 \tag{A15}$$

$$V_X = s_X / m_X \tag{A16}$$

For this analysis the sample Standard Deviation (s_x) is proposed, using the (n-1) divisor.

A2.6.0.18

For directly assessing the design value for ULS verifications, the following equation is provided.

$$X_{\mathrm{d}} = \eta_{\mathrm{d}} m_X (1 - k_{\mathrm{d},n} V_X) \tag{A17}$$

Here η_d should cover all uncertainties not covered by tests, and $k_{(d,n)}$ values are taken from **Table A20**.

Table A20 – Values of $k_{d,n}$ for the ULS design value. Taken from EN 1990 Annex D Table D2[13]

n	1	2	3	4	5	6
V_x known	4.36	3.77	3.56	3.44	3.37	3.33
V_x unknown	-	-	-	11.4	7.85	6.36
n	8	10	20	30	∞	-
V_x known	3.27	3.23	3.16	3.13	3.04	-
V_x unknown	5.07	4.51	3.64	3.44	3.04	-

A2.6.0.19

It should be noted that these expressions assume that test data follows a normal distribution or log-normal distribution. If the test data follows a log-normal distribution, equation (A17) becomes

$$X_{\mathrm{d}} = \frac{\eta_{\mathrm{d}}}{\gamma_m} \exp(m_y - k_n s_y) \tag{A18}$$

where if V_x is known, then s_y is given by (A19) or if V_x is unknown, s_y is given by (A20)

$$s_y = \sqrt{\ln(V_X^2 + 1)} \tag{A19}$$

$$s_y = \sqrt{\frac{1}{n-1} \sum_i (\ln x_i - m_y)^2} \tag{A20}$$

While equation (A18) becomes

$$X_{\mathrm{d}} = \eta_{\mathrm{d}} \exp(m_y - k_{\mathrm{d},n} s_y) \tag{A21}$$

This gives the Designer multiple methods for determining design values on the basis of testing.

A2.7 Testing during Manufacturing

A2.7.0.1

Generally, testing of anything may be warranted to check the actual properties of a physical item. The property concerned might be unknown or has been claimed by others. Physical performance and/or *compliance* liability might rely upon the property tested. It is preferable to verify by a testing process the property in question as close as possible to the point of supply. Further to this any subsequent value-adding/manufacturing steps should not commence until preceding tests are acceptable. For example:

i. Strength and ductility of steel coil should be tested/verified (by the coil Supplier) before being accepted for cold-rolling into structural sections
ii. Connections and dimensions of cold-formed steel framing should be tested/verified (by the framing Manufacturer)

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before addition of services

iii. Where the manufacturing process varies any material or section properties, relied upon for performance or not, this should be tested/verified (by the Manufacturer)
iv. *Certification* of materials for services should be tested/verified (by the respective material Suppliers) before installation into the module framing
v. *Certification* of in-frame services should be tested/verified (by the services Installer) before completion and closing up of cladding
vi. Re-testing/verification of preceding works may need to be confirmed prior to any new temporary load case or handling by a further contracted party, especially regarding lifting and transportation.

A2.7.0.2
The requirement to test for *compliance* purposes is dealt with in **Chapters J** and **K**. It is emphasised again the need for testing processes to be independent of the party whose materials/work is being tested. Where recognised appropriate test methods do not exist already they should be developed in conjunction with a testing organisation with independent approval (e.g. from NATA). Such an organisation should carry out the tests to produce an appropriate *Test Report*.

A2.7.0.3
The rigour of testing processes decided upon should be appropriate to the degree of uncertainty and scale of potential consequences from irregularities in a given property.

A2.7.0.4
The *Designer* should consider inclusion of independent process auditing from time to time.

A2.7.0.5
Specifically in relation to Manufacturing the *Designer* and *Builder* should consult to agree to a testing and verification process appropriate for manufacturing to provide the required level of assurance and verifiability.

A2.7.0.6
Where timber is being utilised as a structural element, it is important to test the moisture content prior to use. Further guidance can be found in:

i. AS 2796 “Timber - Hardwood - Sawn and milled products” [5.32]
ii. AS 2082 “Timber - Hardwood - Visually stress-graded for structural purposes” [5.33]
iii. AS 4785 “Timber - Softwood - Sawn and milled products” [5.34]
iv. AS 1810 “Timber – Seasoned cypress pine - Milled products” [5.35]

A3 Structural Analysis

A3.0.0.1
The *Designer* should generally refer to **AS/NZS 1170** [5.2] for structural design guidance. **AS/NZS 1170.0 Section 5** briefly advises on methods of analysis, but the *Designer* should refer to other standards specific to the particular design problem under consideration, including those standards which relate to specific materials. These include:

i. **AS 4100 Steel Structures** [5.15]
ii. **AS/NZS 4600 Cold-formed Steel Structures** [5.17]
iii. **AS 3600 Concrete Structures** [5.16]
iv. **AS 1720 Timber Structures** [5.20]
v. **AS 2327 Composite Structures** [5.30]

Further references are made therein to standards covering aspects of these materials.

A3.0.0.2
The *Designer* should consider what method of structural analysis is appropriate for the given problem; these may include (but are not limited to):

i. First order elastic analysis, otherwise known as linear analysis (LA);
ii. Second order elastic analysis, otherwise known as geometric nonlinear analysis (GNA);
iii. Advanced analysis, otherwise known as geometric and material nonlinear analysis with imperfections (GMNAI).

The *Designer* should take care to consult the appropriate standards to determine the conditions under which these methods, or others, are allowed or required.

A3.0.0.3
The analysis methods above can be employed using a variety of computational tools; the *Designer* should make use of tools which provide a level of analysis appropriate to the jurisdiction, materials, structure and intent under consideration.

A3.1 Finite Element Analysis

A3.1.0.1
The *Designer* should consider whether any given structural design problem requires, or would be better served by, the use of advanced

computational techniques for structural analysis such as finite element analysis (FEA).

Finite element analysis (FEA) is a computer-based numerical technique to find approximated solutions to differential equations for solving structural problems. In FEA, the complex structure model (containing information e.g. geometry, material properties, loads, boundary conditions) is meshed into finite number of small elements and the overall structural behaviour is obtained based on the analysis of each individual elements. (Pavlou 2015 [8.15]).

While traditional design approaches (e.g. manual calculations, use of handbook data and small-scale testing) are mainly suitable for routine design of low-rise regular buildings, FEA is used when it is impractical to predict structure behaviours through conventional approaches, particularly when one or more of the following aspects are expected in a structural analysis:

i. large-scale or irregular structures
ii. detailed features of structural component (locations, geometry, fixity, etc.)
iii. complex loading scenarios
iv. advanced material properties e.g. non-linear, time-dependent, temperature-dependent properties
v. advanced connection behaviours (semi-rigidity and nonlinearity, etc.)
vi. other effects e.g. geometric nonlinearity
vii. demand of detailed and accurate results
viii. more efficient use of material

A3.1.0.2

The *Designer* of a modular structure may wish to consider the use of FEA in the following contexts:

i. Simulation of transportation and craning process of a single module (through dynamic or equivalent static analysis)
ii. Detailed analysis of modular components (e.g. inter-module connections)

A3.1.0.3

The *Designer* should select the appropriate FEA software and modelling technique depending on the purpose of analysis and the required level of accuracy.

A3.1.0.4

Where the *Designer* uses FEA there should be a process allowed for with some scale of validation testing so as to calibrate the numerical model for projected behaviours.

A3.1.0.5

A number of important considerations must be made when analysing a modular structure or components as in **Table A21**.

Table A21 – Considerations for Finite Element Modelling of modular structures

Component	Potential Issues
Continuity of concrete slabs / rigid diaphragm action	In the case of buildings formed using volumetric modules, or modular elements, floor elements may not be continuous, as compared to an in-situ build.
Effect of connections	Unlike an in-situ build, where a continuous slab or deck provides a stiff diaphragm, the primary conduit for energy/loads in a modular structure will be the connections. This leads to a large number of discontinuities which, while favourable for robustness (as it leads to higher redundancies/alternative load paths), may have a negative effect upon the response of the structure to lateral loads
Connection fixity/stiffness	It has been shown recently through Finite Element Analysis that connection stiffness can affect the response of modular structures (Styles et al. 2016 [8.11]). This may have implications for the overall design and analysis of the structure.
Floor Layout	Non-symmetrical floor layout with non-uniform lateral stability stiffness distribution may lead to the extreme external connection element being subject to higher fatigue loads.

In essence, the assumptions made during the finite element analysis of a modular structure or component play a key role in the results and final design, especially given the multiplicity of connections.

A3.1.0.6

The *Designer* should clearly state any assumptions made during the construction and analysis of a finite element model. The reasoning, and any supporting documentation/references, should be stated and clearly documented.

A3.1.0.7

The *Designer* should test the sensitivity of the model to changes in key assumptions and variables. A key example of this is connection fixity/stiffness.

A3.1.0.8

The role of FEA is mainly a computational tool in structural design and analysis. The results obtained from FEA should be validated by engineering judgement and simple manual calculations, etc.

A3.1.0.9

The use of FEA for modular structures should also consider wind-induced uplifts, differential movements, catenary action for accidental loading, and the effects of construction tolerances on the overall stability.

A3.2 Serviceability

A3.2.0.1

The *Designer* should account for static and dynamic displacements as with conventional structures. *Modular Construction* introduces no novel considerations except for the influence of possibly a more dense distribution of connections throughout the structure compared to typical in-situ construction, and connection performance is significant.

A3.2.1 Sway

A3.2.1.1

It should be noted there are acceptance levels for sway behaviour (frequency & amplitude) for various structure uses and heights. Dynamic displacement susceptibility can be dominated by wind or *seismic* forces depending on building height and other factors.

A3.2.1.2

The *Designer* should consider the comfort of users and their perception of any horizontal motion or sway under the lateral loads. A number of simple checks exist including the building lateral displacement or sway, which can be calculated as

$$\frac{\Delta}{H} \qquad \textbf{(A22)}$$

and the interstorey drift, which is calculated as

$$\frac{\delta_n - \delta_{n-1}}{h} \qquad \textbf{(A23)}$$

where:

Δ = Total building lateral displacement
H = Total building height
δ_n = Lateral deflection of the n-th floor
δ_{n-1} = Lateral deflection of (n-1)th floor
h = Storey height

AS1170.0 [5.2] suggests typical limits of H/500 for both total building drift and for interstorey drift due to wind. See Table C1 therein for more details.

A3.2.2 Acceleration due to Wind

A3.2.2.1

A more robust check of occupant comfort due to wind movement in a structure is by determining the peak acceleration due to wind actions. Typical limits on this acceleration are taken from **Figure A6** on the basis of a building's natural frequency based on **ISO 10137** [6.9].

Acceleration due to wind actions may be determined by numerous methods including finite element analysis, wind tunnel testing, and calculation in accordance with **AS/NZS 1170.2-2011** [5.2].

A3.2.3 Vibration

A3.2.3.1

Vibration is considered similarly to the previous aspects as a part of serviceability. Note a suggested simple check is to limit any static deflection for a 1 kN point load to 1 mm as per **AS/NZS 1170.0 Table C1** [5.2].

A3.2.3.2

Further guidance is offered in **AS 2670.1 Evaluation of human exposure to whole-body vibration** [5.19] where it states the frequency ranges for certain human responses to vibration. See **Table A22** for details.

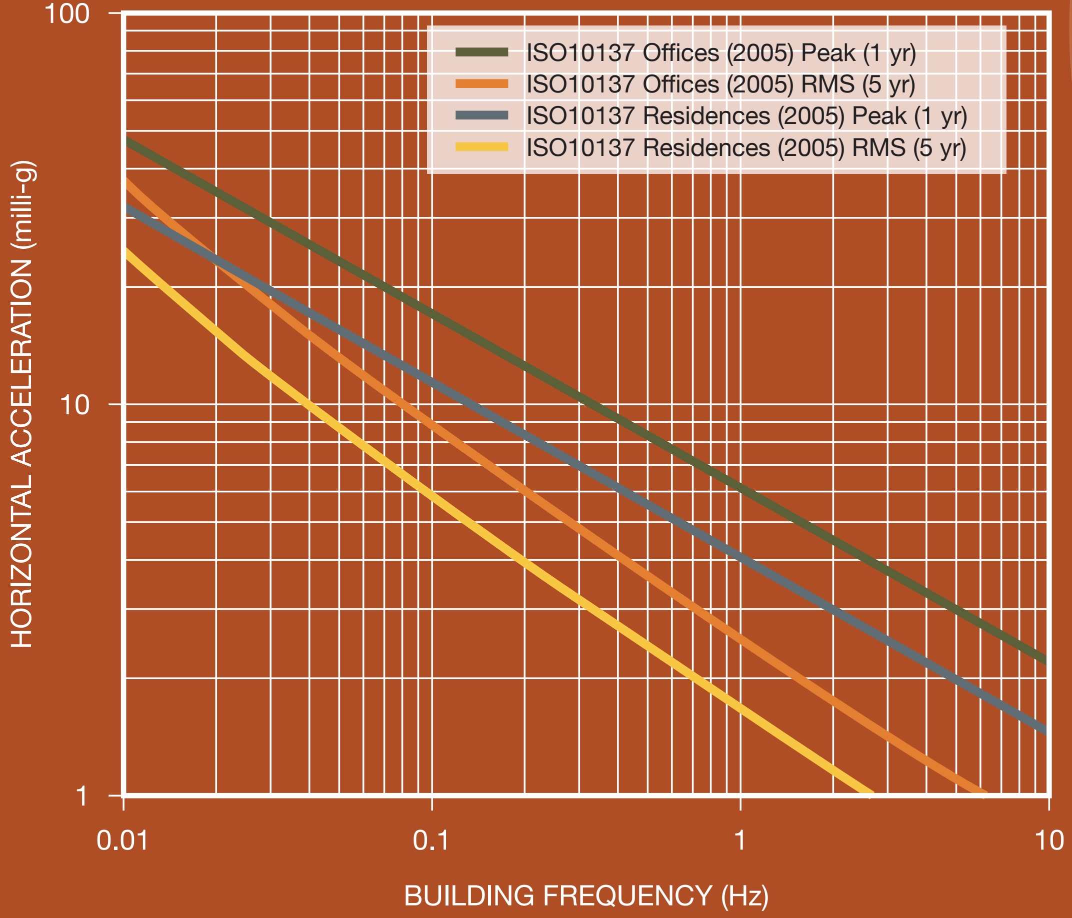

Figure A6 – Typical limits of horizontal acceleration due to wind action from ISO 10137 [6.9]

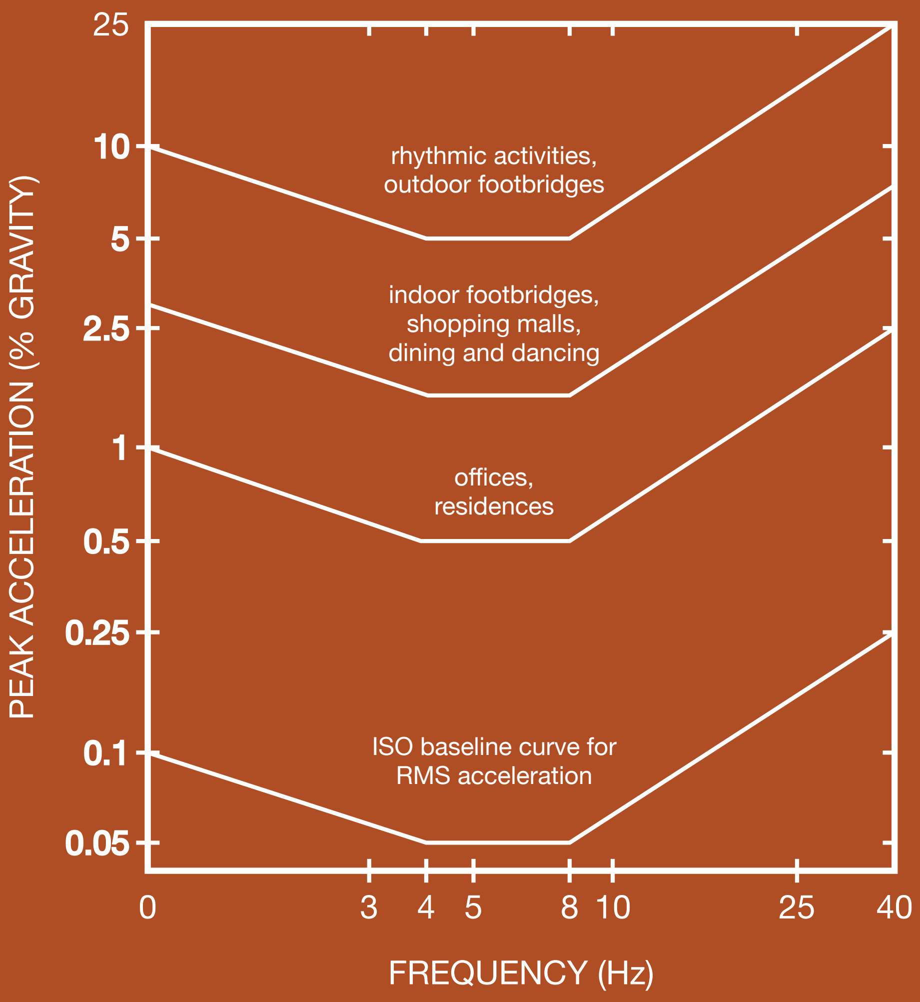

Figure A7 – Suggested limits of peak accelerations due to human activity for human comfort (Murray et al. 2016 [8.2])

Table A22 – Human responses to whole body vibration as per AS 2670.1 [5.19].[14]

Frequency	Response Considered
0.5-80 Hz	Human health, comfort and perception
0.1-0.5 Hz	Motion sickness

While this gives some guidance for general vibration, there is a more specific source of vibration worth considering; that caused by human activity. **Figure A7** has been developed to provide suggested peak accelerations from these activities (i.e. footfall) based on Murray et al., 2016 [8.2].

A3.2.3.3

Where a structure is intended to support vibration sensitive equipment, the *Designer* should ensure that vibration induced by external sources (such as human footfall, mechanical services, vehicles etc.) does not adversely affect the equipment. Further guidance on design for this can be found in Design Guide 11 published by the American Institute of Steel Construction (Murray et al. 2016, [8.2]) .

A3.2.3.4

The *Designer* should consider occupant comfort when designing floor systems for modular structures. Determination of floor vibration frequency/peak acceleration may be performed in a number of fashions including, but not limited to, finite element analysis or the method outlined in Design Guide 11 published by the American Institute of Steel Construction (Murray et al. 2016 [8.2]).

A3.2.3.5

Human sensitivity to vibration is likely to be important in the design of modular structures, as the floor systems may be much leaner than a typical in-situ build, combined with their discontinuous nature.

A3.3 Ductility

A3.3.0.1

The general principle of ensuring a safe & controlled structural response at overload and after onset of permanent material damage is applicable in *Modular Construction* at all stages of construction as well as for the completed structure. The *Designer* should consider the aggregated adequacy of available alternate load paths (i.e. load redistribution), structural redundancy, specific material ductility in elements and connections.

A3.3.0.2

The *Designer* should not confuse ductility with over-design by mere addition of material. The possible failure mode of any element or system should be identified correctly and then its ductility ensured.

As an example concerning steel connections using heat-treated bolts refer to **Figures A8**, **A9** and **A10**. The *Designer* should consider the reduced ductility and higher energies present at fracture of these connectors. Where the progress of distortion to the bearing surface plates under the bolt or screw head can initiate prying action the consequent damage may result in instantaneous fracture. Where plates can bend and incline relative to the axis of connectors fixed to them, there is *risk* of this failure mode and potentially severe consequences. The *Designer* should consider a system of relatively stiff end plates and stiffener plates when specifying heat-treated connectors. Similar factors can impact on the behaviour of heat-treated screws as are common in light-gauge steel connections.

Testing was conducted upon a particular joint for the connection of a beam to a column (both structural steel members); the joint included gusset plates in order to improve *rotational stiffness*. However, as the steel yielded in the end and gusset plates, it began to pry the bolt head in a fashion which ultimately lead to the fracture of the bolt as pictured.

Figure A8 – Joint specimen with bolt fracture

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This failure mode resulted from the ductile behaviour of the steel plates as they yielded, and the inability of the heat treated bolt to yield in a ductile manner, resulting in the instantaneous (and dangerous) failure observed. This is a clear example of connection design inducing failure which may not typically be expected.

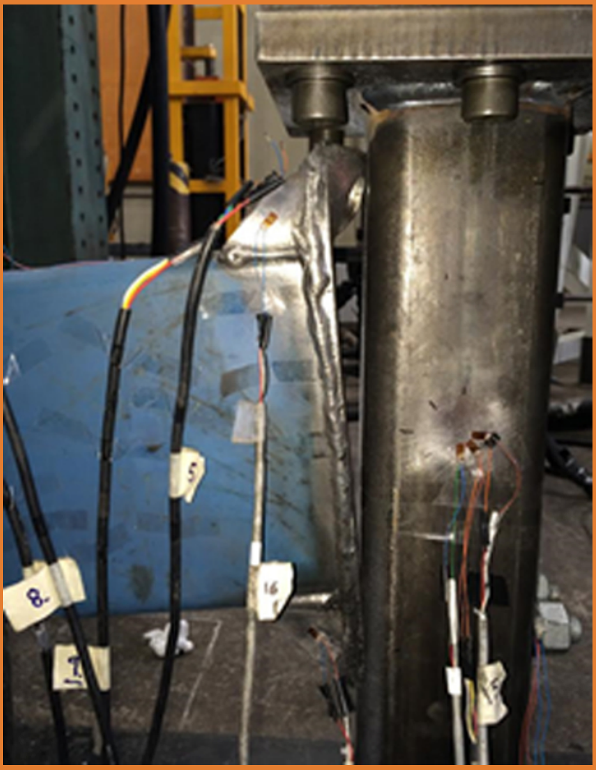

Figure A9 – Side view showing plate yielding and bolt fracture

Figure A10 – Bolt fracture resulting from prying action of yielding end and gusset plates

A3.4 Robustness

A3.4.1 General

A3.4.1.1

The concepts considered with ductility (i.e. sustained performance at overload and controlled progression of material failure) are extended under the *NCC* requirement for *Robustness*, which intends to safeguard the safety of persons and prevent excessive property damage arising from *Accidental actions*. The *Designer* should be familiar with the physical processes required for disproportionate and uncontained damage, which includes the mechanism known as "*progressive collapse*". The *Designer* should also be aware that management of *robustness* in buildings is mandated by Regulation.

A3.4.1.2

From 2016 the *NCC* sets a *Performance Requirement* regarding *Robustness* that buildings are to:

> "…be designed to sustain local damage, with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage"[15] (Vol1, BP1.1 a) iii)).

There follows a Verification Method (applicable where a "Deemed to Satisfy" solution is not used) wherein the *Designer* must ensure the building remains stable and sustains only local damage (not extending beyond immediately adjacent storeys) if any one *load-bearing* member (supporting more than just self-weight) is removed AND the *Designer* must conduct a *risk* assessment if any component is relied upon for support of >25% of total structure (Vol1, BV2).

A3.4.1.3

It follows that it is critical to identify the most sensitive *load-bearing* members with respect to the consequence of their removal. Via the *NCC*, *robustness* analysis does not account for likelihood of the element removal nor its cause (e.g. vehicle impact or gas explosion), or any realistic secondary effects which may follow such scenarios (e.g. dispersal of shock loads or ballistic debris) where a supporting structural element carries no more than 25% of the total structure. The element is simply considered to be absent and the remaining structure assessed for static response. In this case, *Robustness* assessment is qualitatively different to *Reliability* assessment (via the *NCC*) which considers probabilities throughout.

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[15] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

A3.4.1.4

Following the guidance of the *NCC* (BV2), the requirement that a building remains stable after the removal of any one element means that a building must not be supported by only one element.

A3.4.1.5

When designing for *Robustness*, the *Designer* should consider the loss of any structural *load-bearing* members. The remaining structural members should be able to support the resulting load without loss of stability or disproportionate collapse of the structure (either progressive or instantaneous).

A3.4.1.6

Typically, structures will be designed for *Robustness* on the basis of their consequence for failure, by controlling the probability of a hazard occurring through e.g. the provision of alternative load paths. Consequence Classes in Australia are shown in **Table A1**.

A3.4.1.7

In considering accidental actions in European jurisdictions, **EN 1990 Appendix B** [6.8] gives definitions for Consequence Classes which are repeated in **Table A23** for the Designer's convenience.

These consequence classes are comparable to the *Importance Levels* defined in **AS/NZS 1170.0** [5.2]. It should be noted that the **Eurocodes** treat the design requirements for *Robustness* differently depending upon Consequence Class as summarised in **Table A24**.

Table A24 – Robustness measures as per Table 7.3 in Canisius 2011 [6.22].

Consequence Class	Robustness Measure
CC1	No special considerations
CC2, lower group Frames	Horizontal ties in floor
CC2, lower group Wall structures	Full cellular structures. Anchoring floors to walls
CC2, upper group	Provisioning of horizontal ties and effective vertical ties or limited damage on notional removal of critical elements or special design of key elements
CC3	Risk analysis based upon consequences and risk frequency and/or advanced structural analysis is recommended

Table A23 — Consequence classes as per **Table B1 EN 1990 Appendix B** [6.8][16].

Consequence Class	Description	Examples
CC3	**High** consequence for loss of human life or economic, social or environmental consequences **great**	Grandstands, high rise buildings etc.
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	**Lower group** – Most buildings up to 4 storeys **Upper group** – Most buildings up to 15 storeys
CC1	**Low** consequence for loss of human life and economic, social or environmental consequences **small or negligible**	Low rise building with few people present

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A3.4.1.8

Alternative load paths in a structure form for a number of reasons including:

i. Catenary action (Load transfer moves from flexural to tensile)
ii. Hogging or sagging above failing column inverts flexural load transfer
iii. One-way slabs turning into two-way slabs as a result of a failure i.e. transition from plane to spatial load transfer

A3.4.1.9

An alternative is advanced structural analysis involving the removal of one or more key structural elements (including dynamic and non-linear analysis), and this may be conducted in conjunction with a detailed risk analysis.

A3.4.1.10

A typical way in which *Designers* might improve *Robustness* of modular structures is to design connections which are able to offer alternative load paths in the event of a local failure.

Care should be taken when analysing a structure for *Robustness* in a *Modular Construction* project, due to the fact that connecting many volumetric modular units together may result in pairs or clusters of redundant structural elements, particularly columns tied side-by-side. In this case, the removal of a single *load-bearing* member in the cluster may not lead to *progressive collapse*, but the removal of the entire cluster could initiate such a failure. The *Designer* should look for all such cases which could yield an adverse effect to the overall structure.

A3.4.1.11

A typical way in which *designers* might improve *Robustness* of modular structures is to design connections which are able to offer alternative load paths in the event of a local failure.

A3.4.2
Low-to-Medium Risk Structures

3.4.2.1

EN 1991 Part 1-7 General Actions – Accidental actions [6.10] provides definitions concerning the minimum force which each tie must be capable of sustaining. For **CC2, lower group** framed structures the horizontal ties must be capable of sustaining a force of the larger of 75 kN or

$$T_\mathrm{i} = 0.8(g_k + \Psi q_k)sL \qquad \textbf{(A24)}$$

for internal ties and

$$T_\mathrm{p} = 0.4(g_k + \Psi q_k)sL \qquad \textbf{(A25)}$$

for perimeter ties, where

T_i, T_p = the tie forces in each case
g_k = *characteristic value* of self-weight in kN/m^2
q_k = *characteristic value* of imposed load in kN/m^2
Ψ = combination factor
s = tie spacing in metres
L = span in metres

3.4.2.2

Horizontal ties should be provided around the perimeter of each floor/roof and internally at right angle directions to tie the columns to the structure. Edge columns should be *anchored* with vertical ties which are capable of sustaining a tensile load equal to 1% of the vertical design load on the column at that level.

3.4.2.3

For **CC2, upper group** structures constructed with *load-bearing* walls, the requirements for horizontal ties are similar to framed structures but become

$$T_\mathrm{i} = \frac{F_t(g_k + \Psi q_k)}{7.5}\frac{z}{5} \qquad \textbf{(A26)}$$

$$T_\mathrm{p} = F_t = (20 + 4n) \qquad \textbf{(A27)}$$

where all symbols have the same meaning as before, n is the number of storeys, z is the lesser of 5h (h being storey height) and the greatest distance in the direction of the tie, between centres of columns or other vertical *load-bearing* elements.

3.4.2.4

For vertical ties, the following expression applies instead:

$$T_\mathrm{v} = \frac{34A}{8000}\left(\frac{h}{t}\right)^2 \qquad \textbf{(A28)}$$

But T_v must not be less than 100 kN/m times the length of the wall. A is the *load-bearing* area of the wall in mm^2, and t is the wall thickness.

A3.4.2.5

More generally **EN1991 Part 1-7** allows, for **CC2** equivalent structures, that the *Designer* may use a simplified analysis by a static equivalent action for a given *accidental action*.

A3.4.2.6

In the case of impacts from road traffic to superstructures (i.e. buildings), the equivalent static actions are given in **Table A25**.

Table A25 – Indicative equivalent static design forces due to road traffic impact on superstructures as per **Table 4.2 EN 1991 Part 1-7**[17]
Note – x = directional of normal travel

Category of traffic	Equivalent static design force F_{dx} *[kN]*
Motorways and country national and main roads	500
Country roads in rural areas	375
Roads in urban area	250
Courtyards and parking garages	75

A3.4.2.7

For further detail on *accidental actions* resulting from impact events (such as river traffic or helicopters), the *Designer* should refer to **EN 1991 Part 1-7 Section 4**.

A3.4.2.8

Accidental actions may also occur due to internal explosions within a structure. The determination of a representative explosion pressure on the structural members should account for any reactions which may be transmitted to the structural element by non-structural elements.

A3.4.3 High Risk Structures

A3.4.3.1

EN 1991 Part 1-7 [6.10] allows the *Designer* to mitigate the consequence of any foreseeable *accidental action* (and thus satisfy *Robustness* requirements) by:

i. Design of key elements, upon which structural stability depends, to sustain the effects of an *accidental action*
ii. Design the structure such that in the event of a localised failure (i.e. notional removal of a single structural member), the stability of the whole structure, or a significant part of it, is not compromised
iii. Application of prescriptive design/detailing rules that provide acceptable *Robustness* [e.g. such as equations (A24-A28), sufficient ductility of elements]

A3.4.3.2

For **CC3** structures, a detailed *risk* analysis (similar in process to that outlined for *Reliability* below) should be conducted to determine the probability of failure. If the probability of failure (the total *risk* R) is below the maximum acceptable *risk* (R_a), then the design may be considered adequate from a *Robustness* point of view (i.e. $R<R_a$). Potential consequence classifications (taken from Figure B.2a **EN 1991 Part 1-7**) are shown in **Table A26**.

Table A26 – Consequence classifications as per Figure B.2a **EN 1991 Part 1-7** [6.8][17].

Consequence classifications	Definition
Severe	Sudden collapse of structure with high potential for loss of life and injury.
High	Failure of part(s) of the structure with high potential for partial collapse and some potential for injury and disruption to users and public.
Medium	Failure of part of the structure with total or partial collapse of structure unlikely. Small potential for injury and disruption of users and public.
Low	Local damage.
Very Low	Local damage of small importance.

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A3.4.3.3

When considering the *risk* acceptance levels, the *Designer* should consider both of the following when formulating *risk* acceptance levels:

i. **Individual acceptable level of *risk:*** Individual *risks* are usually expressed as fatal accident rates, expressed either as an annual fatality probability or as the probability per unit time of a single fatality during a specific activity
ii. **Societal acceptable level of *risk:*** Often presented as an F-N curve, which indicates a maximum yearly probability F of having an accident with more than N fatalities. Typical F-N curves for various European guidelines appear in **Figure A11**.

A3.4.3.4

Once the acceptable level of *risk* is identified, the *Designer* should[18]:

i. Identify all possible *hazards* and *hazard* scenarios for the structure
ii. Describe the consequences of the *hazard* occurring (e.g. loss of life, injury, local damage, partial or total collapse)
iii. Determine the probability of *hazards* occurring with their intensities – $P(H_i)$
iv. Assess the probability of different states of damage $P(D_j|H_i)$ (i.e. local damage, partial or total collapse) and corresponding consequences for a given *hazard*
v. Assess the probability for the damaged structure to perform inadequately $P(S_k|D_j)$ together with the corresponding consequences $C(S_k)$

The total *risk* for a structure may then be assessed with equation (A29) from **EN 1991 Part 1-7**[18]:

$$R = \sum_{i=1}^{N_H} P(H_i) \sum_{j=1}^{N_D} \sum_{k=1}^{N_S} P(D_j|H_i)P(S_k|D_j)C(S_k) \quad \textbf{(A29)}$$

A3.4.3.5

For equation (A29), the structure is assumed to be subjected to a number N_H different *hazards*, which may damage (D_j) the structure in N_D different ways (can depend upon the considered *hazards*), and that the performance of the damaged structure can be discretised into N_S adverse states (S_k) with associated consequences $C(S_k)$. The probabilities are:

$P(H_i)$ = corresponding probability of the ith hazard occurring (within a reference time interval)
$P(D_j|H_i)$ = Probability for the jth damage state to occur given the ith *hazard* has occurred
$P(S_k|D_j)$ = Probability for the kth adverse state to occur given the jth damage state

A3.4.3.6

These probabilities and associated consequences may be obtained based upon observed data, information taken from literature, analysis and/or expert opinion.

These probabilities (and thus the total *risk*) may be reduced by design (or practice) decisions, thus reducing the total *risk*. For example:

i. The probability of a *hazard* occurring $P(H_i)$ might be reduced in the case of an explosion by removing explosive materials from the site.
ii. The probability for significant damage to follow a *hazard* $P(D_j|H_i)$ might be reduced in the case of a fire by control systems such as sprinklers or the protection of structural steel. In the case of a failure of a column, this may be reduced by designing floor slabs to be able to provide adequate catenary action.
iii. The probability of adverse structural performance (i.e. *progressive collapse*) may be reduced by designing the structure to have adequate redundancies and thus alternative load paths are available.

A3.4.3.7

However, a simplified method for consideration may be the following equation as given in (Canisius, 2011) [6.22]:

$$R = P(F|LE)P(L|E)P(E)C(F) \qquad \textbf{(A30)}$$

where:

R = *Risk* of global failure related structural collapse
$P(E)$ = Probability for *hazard* (accidental action) E to occur
$P(L|E)$ = Probability for local damage, L, given hazard E
$P(F|LE)$ = Probability of collapse given that a *hazard* and local damage have occurred
$C(F)$ = Expected consequence of a global failure or partial failure

It should be noted that a global failure does not necessarily mean total or partial collapse of the structure as a whole, and may refer to limits such as that in **EN 1991 Part 1-7** i.e. 100 m^2 or 15% of floor area.

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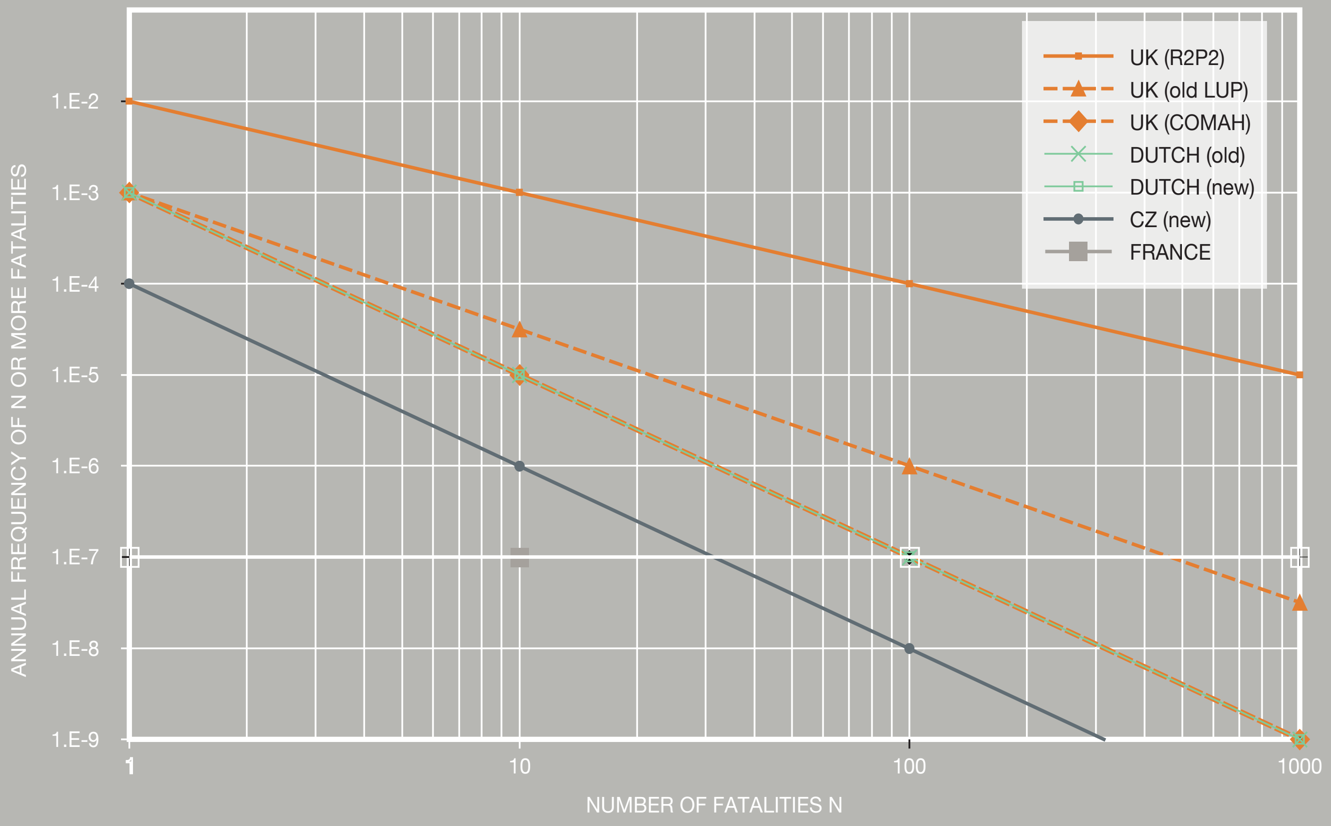

Figure A11– F-N curves for accidents with N or more fatalities from Trbojevic, 2005 [8.19].

A3.4.4 Strategies for Design for Robustness

A3.4.4.1

There are numerous tools available to the *Designer* to ensure a structure fulfils the requirements of *Robustness*, such as the following:

i. Provision of additional strength or resistance to impact
ii. Provision of multiple load paths or redundancy
iii. Selection of materials/material properties to enhance robustness of the structure
iv. Design of sacrificial elements
v. Introduction of a "structural fuse"
vi. Specifying operation practices for the structure

A3.4.4.1(i) refers to the design of elements to resist additional actions which may be applied as the result of a failure/collapse of an element. It may also refer to the ability for an element (e.g. a column) to resist the action applied to it by an impact from a vehicle or explosion. This may also be used to design a structure to limit the extent of a collapse by strengthening particular elements to resist loads which may occur as the result of a *hazard* (i.e. every fifth column is strengthened to take the loads resulting from local damage due to a *hazard*). This is to ensure damage is minimised and the structure may be rehabilitated.

A3.4.4.1(ii) may be addressed by a number of methods. For instance, the *Designer* may design connections (or ties) to be able to support additional forces transferred through them as the result of a failure of an element. Equally, the *Designer* may design floor elements to provide catenary action in the event of a column failure, providing a path through which the previous vertical loading may be transferred. This may be supplemented by the provision of redundant load paths in the event that a horizontal transfer path fails.

A3.4.4.1(iii) is for the *Designer* to consider the expected failure modes of materials, and the effect of material behaviour upon structural *Robustness*. For instance, consider the steel reinforcement within, and steel beams supporting, a reinforced concrete floor slab under which a column has failed. The ductile behaviour of the steel is key in allowing the slab to support catenary action by switching to tensile load transfer. The strain hardening of materials may also present an opportunity for the *Designer* to use the material properties to their advantage to improve resistance to *Progressive Collapse*.

Further, the *Designer* should consider the effects of any local weakening (such as openings, bolt holes, corrosion damage) and how it affects the *Robustness* of a structure. For instance, consider a bolted connection which connects a steel beam to a column. If a nearby column has failed, the tensile load on the connection is now higher, which may lead to the sudden failure near the bolt holes or the fracture of weld material on end-plates. This may then cause further failures of elements as the load on these increases, leading to a *Progressive Collapse* scenario.

A3.4.4.1(iii) may be related to **A3.4.4.1(ii)** by the ductile failure of elements. These failures will occur typically with the deformation of a structure with a number of plastic hinges. This therefore increases the resistance of the structure to further collapse through the creation of an alternate pathway. However the *Designer* should ensure that the locations at which plastic hinges may form are sufficiently far away from bolted connections (see commentary on **Section A3.3** of this document for further detail of the consequences that may arise due to this).

However, the *Designer* should remain cognisant of the effects of cyclic loading (i.e. fatigue) upon material behaviour, as this may reduce the ductility of materials over time, and thus reduce the structure's *Robustness*. This is one disadvantage of the strain hardening of materials.

A3.4.4.1(iv) & (v) are arguably interrelated. The design of sacrificial elements may be related to the provision of external elements to protect against impact (from vehicles or other objects) or the design of "knock-out" elements. Where it is not possible or economically feasible to design a given member with sufficient strength, it may be necessary to design the element which may be subject to an impact (such as a wall or column) or an explosion (i.e. a wall) to be knocked-out in the event of a *hazard*. The knock-out of a column in the event of an impact will ensure that its deadweight does not "weigh down" the rest of the structure, and thus reduces the overall load requirements for the members. While in the case of an explosion, the knock-out of a wall element serves much the same purpose as a pressure-relief valve in a tank. This will work to reduce the pressure applied to the remaining elements, thus increasing the likelihood of their survival of the *hazard*. However, care should be taken to ensure the knock-out element does not become a projectile and thus impact upon the remaining elements. This could be achieved through the addition of hinges (either real or plastic) which remain intact following the knock-out of the element to relieve pressure.

A “structural fuse” fulfils a similar role, whereby the fuse limits the force which may be transferred through a given load path (usually through ductility). In the event of the fuse element being deformed, the entire system should maintain its resistance.

A3.4.4.1(vi) covers the use of the structure in-service, and the *Designer* should consider the following points

i. Proper maintenance and inspection of key elements
ii. Remediation of a structure following a *hazard* event
iii. Reduction of probability of a *hazard* occurring (i.e. removal of explosive materials)
iv. Appropriate quality control of structural elements

A3.4.4.2
Design for *Robustness* in structures may be broadly broken down into three key questions:

i. What are my *hazards* and how can I reduce their probabilities?
ii. What damage may occur as a result of my *hazards* and how likely is this?
iii. What (global) damage is likely to occur to the structure as a result of local damage and how can I limit its probability and consequence (i.e. risk)?

A3.4.4.3
The *Designer* should consider the effect that any failure may have upon the deformation/deflection of the structure, as this may initiate a *Progressive Collapse* as a result of a P-Δ type effect.

A3.4.4.4
The *Designer* should consider the effect of durability factors upon the *Robustness* of a structure. For instance, the degradation of steels through corrosion may result in the brittle failure of elements versus ductile failure, which may be sufficient to initiate the progressive failure of the structure.

A3.4.5 Accidental Impacts and Malicious Acts

A3.4.5.1
Unlike conventional structures, where the threat of accidental impact and malicious damage is considered only during the on-site construction phases, damage during off-site fabrication should be considered in the design of modular structures. For example, damage to the modular fabrication facility could result in a significant impact not only to life safety but also to the construction programme. Nevertheless, it is normally the operational and occupancy on-site phases that pose the greatest risk in terms of potential financial losses and casualties.

A3.4.5.2
Although such events are highly unpredictable, the *Designer* and other responsible parties should undertake a thorough *risk* assessment to ascertain the potential *hazards* posed for a given project and their given likelihood and impact compared with the cost of providing improved resilience and/or preventative measures.

A3.4.5.3
The range of incidents that should be considered may have both accidental and malicious origins, and include the following:

i. Vehicle impacts
ii. Aircraft impacts
iii. Bomb explosions
iv. Gas explosions

Catastrophic nuclear explosions would typically be outside the scope of a risk assessment, in contrast with car or truck bombs which are far more likely to occur. However, the considerations may be different for nuclear facilities, which are outside the scope of normal building design. For such facilities, a nuclear incident could have catastrophic consequences, and would require a site-specific *hazard* assessment based on their location.

Furthermore, nuclear power stations are usually designed for more onerous extreme events than normal buildings. Typically, they are designed for 1-in-2,000 year earthquakes (or greater) whereas normal building are usually designed for 1-in-500 year events. For example, buildings in the UK are not normally designed to resist earthquake whereas nuclear facilities are.

A3.4.5.4

In the case of car or truck bombs being detonated close to the structure, the *Designer* should make an estimate of the size of the maximum credible bomb to be considered, and calculate the magnitude of the expected blast pressure according to the ”stand-off” distance between the detonated device and the structural element or component being considered. Due to the rapid nature of explosions, nonlinear time-history analysis and a knowledge of material properties at high strain rates and high temperatures will be required to accurately estimate the damage that can be expected.

A3.4.5.5

A design which includes a flexible, ductile and redundant structural response, with robust connections (such as those recommended in earthquake engineering principles) will be more likely to withstand the effects of a blast. Nevertheless, increasing the ”stand-off” distance by the provision of bollards or other security measures is likely to prove more cost-effective than designing the structure to resist blast pressures, because peak blast pressures reduce exponentially with increased ”stand-off” distance.

A3.4.5.6

In the case of vehicle or aircraft impacts, similar principles apply to those for blasts. However, typically the speed of the event is slower. The size of projectiles (e.g., the turbine shaft of a jet engine) can be readily estimated but it should be noted that technological advances may lead to larger and/or faster projectiles than currently in use. Keeping the source of the projectile distant from the structure, by locating the structure away from roads, railways and/or airports, can be helpful in reducing the *hazard*.

If the structure fails when subjected to an accidental impact or malicious damage, the result can be catastrophic, as observed for the 9/11 aircraft impacts on the World Trade Center in New York. This event highlighted the importance of progressive collapse and the effects of consequential fire, which needs to be addressed. Nevertheless, in many cases it is not the structure but the façade which poses the most risk. Falling or flying façade elements can be lethal. For such elements, the use of laminated multi-layered glass panels, with robust anchorage of glass panes, and larger elements should be considered.

A3.4.5.7

Design guidance is quite limited in this field. In many cases, specialist expert advice should be obtained. However, the *Designer* may consider the following to achieve a rigorous design method:

i. General principles discussed in the FEMA reports for 9/11 [8.17]
ii. Blast loads estimation and design methods such as those in TM 5-1300 [8.18]
iii. Detailed knowledge of projectiles
iv. General earthquake and robustness principles
v. Specialist materials knowledge
vi. Expert security risk assessments
vii. The application of first principles analysis

A3.5 Reliability

A3.5.0.1

The concept of *Reliability* covers the inter-related factors of structural actions, response and resistance, workmanship and quality control. Generally, *Reliability* (as it relates to building regulations in Australia) is used as a verification method for the strength of structures subjected to foreseeable actions including, but not limited to, permanent, imposed, wind, snow and earthquake actions. Thus, it involves mainly structural actions and resistance, where workmanship and quality control are assumed to be maintained in accordance with appropriate current standards and practice, and are accounted for within the model of structural resistance.

A3.5.0.2

The premise underlying *Reliability* analysis is that the properties of a system, which determine whether or not it performs adequately, are generally not determined exactly, but rather follow a probability distribution which describes the likelihood that the property takes on a particular value. As a result, the performance of the system also follows some probability distribution, i.e. it is more sensible to talk in terms of how likely a system is to fail, rather than simply whether it will or will not fail.

A3.5.0.3

This approach can be contrasted with the usual approach, which is to take nominal values for the resistance and action, and apply prescribed *capacity reduction factors* and *load factors*. In the latter approach, there is no explicit consideration of probabilities. Using reliability analysis gives the *Designer* the advantage of being able to include more detailed knowledge of the relevant loads and resistance, e.g. through testing of structural elements.

A3.5.0.4

Modular Construction may present opportunities and motivation for *reliability* analysis to be utilised for leaner design, due to the potential for more rigorous testing to be integrated into the design process as a result of repetitive manufacture of modular components under controlled conditions. See **Section A2.6** for more guidance on testing-based design.

A3.5.1 The performance function

A3.5.1.1

The performance function, denoted for example by G, quantifies how the interplay between the various properties of a system can lead to sufficient performance or otherwise failure. In structural engineering one would typically consider the resistance, R, of a structural element and the load, Q, to which it is subjected as the relevant variables. In this case the performance function might be defined simply as G=R-Q. When this performance function G is positive, we have R>Q (resistance greater than imposed action), and the structure is not likely to fail. On the other hand, when the performance function G is negative, we have R<Q (resistance less than imposed action), and the structure is likely to fail. *Reliability* analysis is about quantifying the probability of failure, that is, the probability that G<0.

A3.5.2 Reliability index, β

A3.5.2.1

From a technical standpoint, the *Reliability* of a structure or structural element is quantified by the probability of failure (p_f) or equivalently the *reliability* index (β) which are related by $p_f=\phi(-\beta)$, where ϕ is the cumulative distribution function of the standardised normal distribution. **Table A27** shows the relationship between β and p_f.

Table A27 – Relationship between the reliability index β and the probability of failure p_f.

β	p_f	
1.00	1.59E-01	15.9%
1.28	1.00E-01	10.0%
1.50	6.68E-02	6.7%
2.33	1.00E-02	1.0%
3.09	1.00E-03	0.1%
3.50	2.33E-04	0.023%
3.72	1.00E-04	0.010%
3.80	7.23E-05	0.0072%
4.26	1.00E-05	0.0010%
4.75	1.00E-06	0.0001%

The probabilities of failure presented in **Table A27** are exact if the performance function is defined as G=R-Q and if R and Q are normally distributed and independent but they are approximate for other distributions. Nevertheless, they may be used to estimate the failure probabilities for these cases. For the exact case, the resulting performance function G will also follow a normal distribution, which is depicted in **Figure A12**.

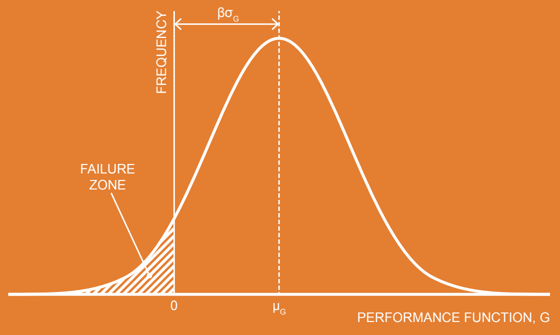

Figure A12 – A schematic explanation of the reliability index β

The mean value μ_G of the performance function, G, is given by

$$\mu_G = \mu_R - \mu_Q$$

and the standard deviation σ_G is given by

$$\sigma_G = \sqrt{\sigma_R^2 + \sigma_Q^2}$$

where σ_R and σ_Q are the standard deviations of the resistance and load respectively.

The *reliability* index, β, is defined as:

$$\beta = \mu_G/\sigma_G$$

It is evident from **Figure A13** that the *reliability* index, β, is the number of standard deviations that the mean value, μ_G, of the performance function, G, is above zero, i.e., the number of standard deviations that it is above the failure zone.

It should be noted that if the *reliability* index reduces from 3.80 to 3.50, then from **Table A27** we can see that there is a resulting three-fold increase in the probability of failure. In terms of the figure above this would be apparent as a three-fold increase in the area of the indicated failure zone.

A3.5.3 Regulatory requirements

A3.5.3.1

In some jurisdictions, the local construction code may permit the *Designer* to utilise *reliability* analysis to optimise the design, by reducing the load factors or increasing capacity reduction factors. Any design must still comply with the relevant *Performance Requirements* laid out in the construction code, but the designer can do a better job based on specific knowledge of their design and materials.

The *Designer* may instead choose to use tabulated values of capacity reduction and load factors, which themselves are likely to have been determined using *reliability* analysis. However, this approach can lead to an inefficient use of resources as the reduction and load factors do not take into account the specific information the designer may have access to.

Most engineering design involves either materials with variable physical properties and/or variable parameters. However, the design approach used in codes of practice standards is deterministic. That is, single values are input into the design equations and the result is a single value, although modification factors (safety factors) are introduced to provide safe solutions that are intended to minimise the risk of failure. Nonetheless, without being able to quantify the variability of the input parameters when using a deterministic approach, it is impossible to determine if the risk of failure is acceptable.

Fundamentally, *reliability* analysis is relatively straight forward. The same basic equations are used to model the processes but instead of the input data for the various parameters being deterministic (i.e., single values) they are expressed as distributions that represent the range of values that may occur.

In structural engineering, *reliability* analysis is often applied to strength calculations for the *Ultimate Limit State* (ULS), where the load applied to a member or building is compared with the strength of the system. **Figure A13** illustrates this approach, where the load (or action) variable, Q, is a normal (Gaussian) distribution shown in white and the resistance variable, R, is a normal distribution shown in blue. Failure occurs in the overlapping zone between the load and resistance variables.

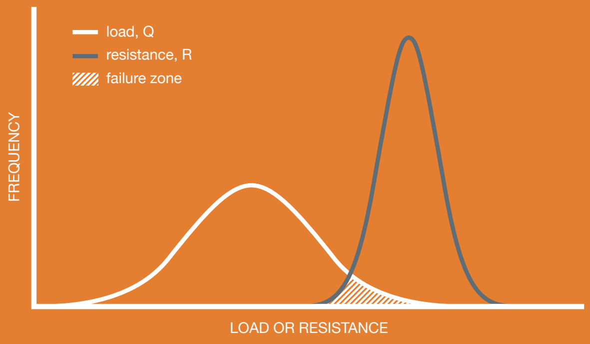

Figure A13 – Example of Load and Resistance Variable Distributions showing Failure Zone

Nevertheless, it can be applied to other limit states, such as deflection, fatigue, cracking of concrete, etc. For example, a simple representation of *reliability* analysis is shown in **Figure A14** applied to the risk of cracking of a concrete element.

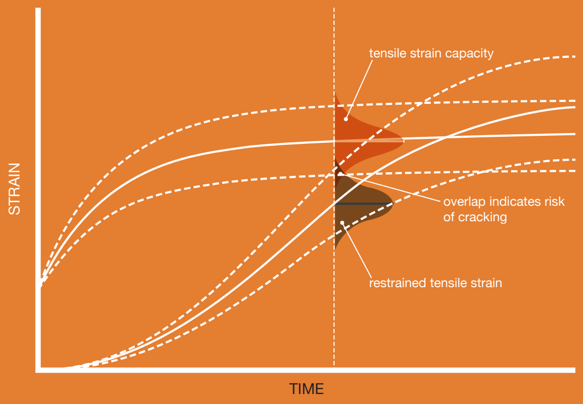

Figure A14 – Representation of Reliability Analysis for Early-age Cracking of Concrete (CIRIA C660, 2007 [6.27])

In **Figure A14**, both the estimated restrained-strain and the assumed tensile strain capacity are represented by a distribution of values. In the example shown, the distributions begin to overlap and the degree of overlap is an indication of the risk of cracking. In this case, probabilistic analysis would consider the risk of cracking by determination of the likelihood that the ratio of restrained strain to tensile strain capacity exceeds 1.

It should be noted that CIRIA C660 [6.27] states that the reliability analysis shows that the risk of cracking is < 1% when compared with the deterministic calculations in Eurocode 2. However, replication of the analysis shows that a saving of more than 15% can be achieved in the critical steel ratio. This reduction in the steel ratio conforms to previous practice for anti-crack reinforcement. Moreover, the CIRIA C660 analysis is an excellent example of the usefulness of carrying out a reliability analysis to achieve economies, whilst remaining within the codified probabilities of failure.

Furthermore, *reliability* analysis may be applied to other engineering disciplines, e.g., hydrological engineering, in which the load could be the flow of water into a system and the resistance would be the capacity of the system. In cases such as this, it is useful to think of the load and resistance variables in the following terms:

Load:	A variable is a load variable (or action variable) if failure is more likely when it takes values higher than the mean.
Resistance:	A variable is a resistance variable if failure is more likely when it takes values less than the mean.

There are exact mathematical solutions for *reliability* analysis for combinations of normal (Gaussian) distributions or combinations lognormal distributions but for other distributions approximate methods are usually used, such as the First Order Reliability Method (FORM). However, in many cases it is simpler to use the Monte Carlo method to run a simulation of the range of possible outcomes, especially when the input parameters comprise several different types of probability distributions. Commercial software can be used to run the Monte Carlo simulation but it is relatively straightforward to perform the simulation by using the random generator in a spreadsheet.

A3.5.3.2

In Australia, building construction is regulated by the *National Construction Code* (*NCC*; [6.2]). The completed structure must comply with prescribed *Performance Requirements*. For structural *reliability*, from 2015, the *NCC* mandates a Performance Verification Method where "Deemed to Satisfy" solutions are not used or are unavailable. This may be found in BV1 (Volume 1) and V2.1.1 (Volume 2). The Performance Verification involves prescribed lower bounds on the calculated Annual Structural *Reliability* (ASR) Index limits[19].

The *NCC* sets target *reliability* indices for structural components and connections. If the component or connection being designed has no corresponding *NCC* Deemed-to-Satisfy Provisions or referenced documents, then the *Designer* may choose to meet the target *reliability* indices as a method to demonstrate *compliance* and satisfy the relevant *Performance Requirement(s)* for strength.

A3.5.3.3

The *Reliability* Verification Methods distinguish between **primary** and **secondary** structural components and connections. **Primary** components or connections are defined as those whose failure may result in the collapse of the building, structure or other property. All other components or connections in the structure that do not affect the building, structure or other property are considered **secondary**. **Primary** components or connections must meet unadjusted Reliability Indices, while secondary components or connections may have their target Indices reduced by a factor of 0.3 (see caption of *NCC* BV1 Table BV1.1). It should also be noted that where *Robustness* conditions have been satisfied (as per *NCC* 2016) then no one **primary** structural component (and connection) could fail and cause building collapse and so the prescribed ASR indices may be reduced by 0.3 (see caption of *NCC* BV1 Table BV1.1)[19].

A3.5.3.4

Additional guidance concerning structural *reliability* management may be found in **EN 1990 Section 2.2** and **Annex B** concerning Construction Works. This is a rationale for acceptable combinations of Consequences Class and *Reliability* Class.

A3.5.4 Probabilistic models

A3.5.4.1

When assessing the *Reliability* of a structural component or connection, the *Designer* should develop two *probabilistic models*: the action model and the resistance model.

A3.5.4.2

The action model accounts for the variation in the action applied to the structural component or connection, which may be quantified by the mean value of action (denoted Q_m), the coefficient of variation of the action (V_Q) and the nominal design value of the action (Q_n). The determination of these values will depend on the type of action being considered; for example, for permanent actions, the *Designer* will have to consider the probability distribution for the weight of the building imposed upon the structural element in question.

A3.5.4.3

The resistance model accounts for the variability of the resistance of the structural component or connection, which may be quantified by the mean

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[19] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

value of resistance (denoted R_m), the coefficient of variation of the resistance (V_R) and the nominal design value of the resistance (R_n).

A3.5.4.4

The *Designer* should clearly state the assumed distribution used to determine the mean value and coefficient of variation of the action and resistance. Typically, the actions and resistances are modelled as the product of a number of statistically independent parameters.

A3.5.4.5

The *Designer* must choose an appropriate probability distribution to describe the resistance and action. There are many options for this, including normal, lognormal, Weibull, Gumbel, etc. The best choice will depend on the material (for resistance) or the nature of the action (for actions). For example, wind actions may skew towards lower actions, slowly tailing off for higher actions, the latter being more extreme events such as cyclones. It is often the case that a normal distribution suffices.

A3.5.4.6

The choice of distribution will affect the way in which the *Reliability* index is calculated. There is a limited set of distributions (normal, lognormal among others) for which the index can be calculated simply using a formula. For other distributions, it may be necessary to instead use a Monte Carlo calculation, which involves a more intensive computation.

A3.5.5 Reliability with lognormal variables

A3.5.5.1

The *NCC* [6.2] includes only a single formula for the *Reliability* index, under the assumption that the resistance and action both follow a lognormal distribution.

The rationale behind utilising a lognormal distribution is two-fold:

i. The *reliability* index can be easily calculated via a closed form when both the load and resistance are assumed to follow the lognormal distribution;
ii. The lognormal distribution is bounded below by zero (unlike the normal distribution, which also satisfies the above condition), which is a sensible behaviour for variables that should not take on negative values.

The formula in this case is[20]

$$\beta = \ln\left[\left(\frac{R_m}{Q_m}\right)\sqrt{\frac{C_Q}{C_R}}\right] / \sqrt{\ln(C_R \cdot C_Q)} \qquad \textbf{(A31)}$$

where

$$C_R = 1 + V_R^2 \qquad \textbf{(A32)}$$

$$C_Q = 1 + V_Q^2 \qquad \textbf{(A33)}$$

and where V_Q and V_R are the coefficient of variation of the action and resistance respectively. The coefficient of variation of a random variable X is given by

$$V_X = \frac{\sigma_X}{\overline{X}}$$

where σ_X is the standard deviation of the random variable X.

A3.5.5.2

In relation to Equation (A31) the *Designer* should note that in general the calculated *Reliability* Index (β) is increased where:

i. Mean Resistance is increased
ii. Mean Action is decreased
iii. Coefficient of variation for Resistance is decreased
iv. Coefficient of variation for Action is decreased

The converse applies also.

The *Reliability* Index is more sensitive to proportionate changes in mean values than in the coefficients of variation.

A3.5.5.3

The traditional approach to structural design uses deterministic rather than probabilistic methods. In this approach, the basic design requirement for a component or connection is

$$\gamma Q_n \leq \phi R_n \qquad \textbf{(A34)}$$

where γ is the load factor and ϕ is the capacity factor.

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[20] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

A3.5.5.4

To bridge the gap between the traditional approach and the *reliability* approach, the ratio $\frac{R_m}{Q_m}$ is re-expressed as[21]

$$\left(\frac{R_m}{Q_m}\right) = \left(\frac{\gamma}{\phi}\right)\left(\frac{R_m}{R_n}\right) / \left(\frac{Q_m}{Q_n}\right) \qquad \textbf{(A35)}$$

In what follows the ratios $\frac{Q_m}{Q_n}$ will be prescribed with some generality for different types of actions.

A3.5.5.5

Typical values for the target *reliability* indices appear in **Table A28**.

Table A28 – Target reliability indices for primary components under various actions as per **Table BV1.1 NCC 2016.**[21]
Note: Secondary structural components and connections may have their target reliability indices reduced by 0.3

Importance Level	Permanent/ Imposed	Wind, seismic, snow
1	3.8	3.2
2		3.4
3		3.6
4		3.8

A3.5.6 Specific action models

A3.5.6.1

The analysis of *reliability* for any given structural element is performed individually for each type of applicable action. In Australia, the *NCC* specifies the following actions: permanent, imposed, wind, seismic and snow. For each action, a model is constructed which accounts for relevant factors. These models are then related back to nominal values.

For each type of action (permanent, imposed, wind, snow and earthquake), an *action model* is proposed, which relates the action to various dependent variables, and additionally a *nominal design action model* is proposed, which differs only in that the dependent variables are treated as fixed nominal values rather than random variables. The purpose of constructing two models in this way is because it is possible to provide general guidance on how the random variables are distributed (i.e. mean and variation) with respect to their corresponding nominal values.

A3.5.6.2

When evaluating the ratio $\frac{Q_m}{Q_n}$, which is necessary for calculation of the *reliability* index via Equation (A31), it will be necessary to consider the mean value of a function of random variables. The rules for doing this will depend on the distribution assumed for the random variables. In the present study, all random variables are assumed to follow a lognormal distribution. Since a product of lognormally distributed random variables is itself lognormally distributed, it will be the case that all action random variables will be lognormal.

A3.5.6.3

If X_1 and X_2 are lognormally distributed random variables, and we construct a new random variable

$$X = X_1 \cdot X_2$$

then the mean and coefficient of variation are given by

$$\overline{X} = \overline{X_1} \cdot \overline{X_2}$$

and

$$V_X^2 = (1 + V_{X_1}^2)(1 + V_{X_2}^2) - 1$$

This rule can be applied repeatedly to handle the case of products of several random variables, which includes the case where one or more variables are raised to a whole number power, e.g. $X = X_1 \cdot X_2^2$.

A3.5.6.4

The action models outlined below incorporate the concept of an "action effect". Where the action is modelled as some expression incorporating various relevant factors, an extra "conversion" factor is included in order to find the overall "effective" action. These factors provide some flexibility in accounting for any implicit sources of action dependence.

A3.5.6.5

For the Permanent Action on a structural component or connection, the model used for the Permanent Action effect is to be

$$G = H_G \cdot g$$

where

G = permanent action effect
H_G = factor to convert action to action effect
g = permanent action

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[21] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

The nominal design action effect corresponding to this is

$$G_n = H_{Gn} \cdot g_n$$

It follows that

$$\frac{G}{G_n} = \frac{H_G}{H_{Gn}} \cdot \frac{g}{g_n}$$

The mean and coefficient of variation values for the parameters have been assessed by the *NCC* and are provided as follows

$$\overline{\left(\frac{H_G}{H_{Gn}}\right)} = 0.95 \qquad V_X\left(\frac{H_G}{H_{Gn}}\right) = 0.07$$

$$\overline{\left(\frac{g}{g_n}\right)} = 1.05 \qquad V_X\left(\frac{g}{g_n}\right) = 0.07$$

$$\overline{\left(\frac{G}{G_n}\right)} = 1.0 \qquad V_X\left(\frac{G}{G_n}\right) = 0.10$$

A3.5.6.6

For the Imposed Action on a structural component or connection, the model used for the Imposed Action effect is to be

$$Q = H_Q \cdot q$$

where

Q = imposed action effect
H_Q = factor to convert action to action effect
q = imposed action

The corresponding nominal design action given is by

$$Q_n = H_{Qn} \cdot q_n$$

Thus

$$\frac{Q}{Q_n} = \frac{H_Q}{H_{Qn}} \cdot \frac{q}{q_n}$$

With the mean and coefficient of variation values for the parameters being assessed by the *NCC* as follows

$$\overline{\left(\frac{H_Q}{H_{qn}}\right)} = 0.95 \qquad V_X\left(\frac{H_Q}{H_{Qn}}\right) = 0.07$$

$$\overline{\left(\frac{q}{q_n}\right)} = 0.52 \qquad V_X\left(\frac{q}{q_n}\right) = 0.43$$

Therefore

$$\overline{\left(\frac{Q}{Q_n}\right)} = 0.5 \qquad V_X\left(\frac{Q}{Q_n}\right) = 0.43$$

A3.5.6.7

For the Wind Action on a structural component or connection, the model used for the Wind Action effect is to be

$$W = H_W \cdot C \cdot (M \cdot V)^2$$

where

V = the basic wind speed whose statistics are available and given in **AS/NZS 1170.2** [5.2] in terms of annual probability of exceedance
M = factor to cover all multipliers for the wind speed: direction, exposure, shielding and topographic
C = the aerodynamic shape factor to convert wind speed to wind pressure
H_W = factor to convert wind pressure to wind action effect

The corresponding nominal design wind action is given by

$$W_n = H_{Wn} \cdot C_n \cdot (M_n \cdot V_n)^2$$

Therefore

$$\frac{W}{W_n} = \frac{H_W}{H_{Wn}} \cdot \frac{C}{C_n} \cdot \left(\frac{M}{M_n}\right)^2 \cdot \left(\frac{V}{V_n}\right)^2$$

With the mean and coefficient of variation values for the parameters assessed by the NCC as follows

$$\overline{\left(\frac{H_W}{H_{Wn}}\right)} = 0.08 \qquad V_X\left(\frac{H_W}{H_{Wn}}\right) = 0.1$$

$$\overline{\left(\frac{C}{C_n}\right)} = 1.0 \qquad V_X\left(\frac{C}{C_n}\right) = 0.2$$

$$\overline{\left(\frac{M}{M_n}\right)} = 1.0 \qquad V_X\left(\frac{M}{M_n}\right) = 0.15$$

Table A29 shows values for the purpose of calculating *Reliability* Indices.

Full details concerning the probability distribution of values of $\left(\frac{V}{V_n}\right)$ for all regions of Australia may be found in **Appendix B4 ABCB Structural Reliability Handbook** [6.28].

Table A29 – Mean and Coefficient of Variation values for peak annual wind actions for non-cyclonic and cyclonic regions of Australia as per **Table 4.3.1 ABCB Structural Reliability Handbook** [6.28].[22]
IL – denotes Importance Level

IL	Non- cyclonic $\overline{\left(\frac{W}{W_n}\right)}$	Non- cyclonic $V_X\left(\frac{W}{W_n}\right)$	Cyclonic $\overline{\left(\frac{W}{W_n}\right)}$	Cyclonic $V_X\left(\frac{W}{W_n}\right)$
1	0.41	0.49	0.21	0.72
2	0.34	0.49	0.18	0.72
3	0.32	0.49	0.16	0.72
4	0.30	0.49	0.14	0.72

A3.5.6.8

For the Snow Action on a structural component or connection, the model used for the Snow Action Effect is given by:

$$S = H_S \cdot C_E \cdot C_F \cdot s_G$$

Where:

s_G = the ground snow load whose statistics are available and given in **AS/NZS 1170.3** in terms of Annual Probability of Exceedance
C_E = factor to cover the effects of exposure
C_F = factor to cover the geometrical effects such as the roof slope
H_S = factor to convert snow action to snow action effect

With a corresponding nominal design snow action effect of

$$S_n = H_{Sn} \cdot C_{En} \cdot C_{Fn} \cdot s_{Gn}$$

Therefore it follows that

$$\frac{S}{S_n} = \frac{H_S}{H_{Sn}} \cdot \frac{C_E}{C_{En}} \cdot \frac{C_F}{C_{Fn}} \cdot \frac{s_G}{s_{Gn}}$$

With the mean and coefficient of variation values of the parameters assessed by the *NCC* as follows

$$\overline{\left(\frac{H_S}{H_{Sn}}\right)} = 0.9 \qquad V_X\left(\frac{H_S}{H_{Sn}}\right) = 0.10$$

$$\overline{\left(\frac{C_E}{C_{En}}\right)} = 1.0 \qquad V_X\left(\frac{C_E}{C_{En}}\right) = 0.15$$

$$\overline{\left(\frac{C_F}{C_{Fn}}\right)} = 1.0 \qquad V_X\left(\frac{C_F}{C_{Fn}}\right) = 0.10$$

Table A30 shows values allowed for the determination of *Reliability* Indices with respect to snow action.

Table A30 – Mean and coefficient of variation values for peak annual actions for snow as per **Table 4.4.1 ABCB Structural Reliability Handbook** [6.28][22]
IL – denotes Importance Level

IL	$\overline{\left(\frac{S}{S_n}\right)}$	$V_X\left(\frac{S}{S_n}\right)$
1	0.32	0.57
2	0.30	0.57
3	0.28	0.57
4	0.27	0.57

Full details of the values for $\left(\frac{s_G}{s_{Gn}}\right)$ may be found in **Appendix B5 ABCB Structural Reliability Handbook**.

A3.5.6.9

For the Earthquake Action on a structural component or connection, the model used for the Earthquake Action Effect is given by

$$E = H_E \cdot C_R \cdot C_S \cdot C_W \cdot a$$

where

a = the ground acceleration coefficient whose statistics are available and given in **AS 1170.4** in terms of annual probability of exceedance
C_W = factor to cover the effects of mass distribution of the building
C_S = factor to cover the effects of the ground condition
C_R = factor to cover the dynamic response of the building
H_E = factor to convert earthquake action to earthquake action effect

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[22] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

With a corresponding nominal design earthquake action effect given by

$$E_n = H_{En} \cdot C_{Rn} \cdot C_{Sn} \cdot C_{Wn} \cdot a_n$$

It follows that

$$\frac{E}{E_n} = \frac{H_E}{H_{En}} \cdot \frac{C_R}{C_{Rn}} \cdot \frac{C_S}{C_{Sn}} \cdot \frac{C_W}{C_{Wn}} \cdot \frac{a}{a_n}$$

The mean and coefficient of variation values for the parameters have been assessed by the *NCC* as follows

$$\overline{\left(\frac{H_E}{H_{En}}\right)} = 0.9 \qquad V_X\left(\frac{H_E}{H_{En}}\right) = 0.1$$

$$\overline{\left(\frac{C_R}{C_{Rn}}\right)} = 1.0 \qquad V_X\left(\frac{C_R}{C_{Rn}}\right) = 0.1$$

$$\overline{\left(\frac{C_S}{C_{Sn}}\right)} = 1.0 \qquad V_X\left(\frac{C_S}{C_{Sn}}\right) = 0.1$$

$$\overline{\left(\frac{C_W}{C_{Wn}}\right)} = 1.0 \qquad V_X\left(\frac{C_W}{C_{Wn}}\right) = 0.1$$

For the determination of *Reliability* Indices, **Table A31** is provided.

Table A31 – Mean and coefficient of variation values for peak annual earthquake actions as per **Table 4.5.1 ABCB Structural Reliability Handbook** [6.28][23]
IL – denotes Importance Level

IL	$\overline{\left(\frac{E}{E_n}\right)}$	$V_X\left(\frac{E}{E_n}\right)$
1	0.072	1.97
2	0.054	1.97
3	0.042	1.97
4	0.036	1.97

Full details of the values for $\left(\frac{a}{a_n}\right)$ may be found in **Appendix B6 ABCB Structural Reliability Handbook**.

A3.5.7 Resistance models

A3.5.7.1

When developing the model of resistance, the *Designer* should account for all sources of uncertainty in the determination of a resistance for the structural component or connection under study. Thus a model relating the resistance R (a random variable) to the standard specified resistance R_n is[23]

$$R = K_m \cdot K_f \cdot K_s \cdots R_n$$

Where uncertainties in the resistance arise from sources including (but not limited to):

i. Variability in the mechanical properties of the materials
ii. Variation in dimensions resulting from fabrication or construction processes
iii. Uncertainties in the structural modelling of the component

And all factors are assumed to be statistically independent and given as

K_m = value to account for variability of relevant mechanical properties, usually obtained from test data used for quality control of material manufacturing processes
K_f = value to account for variability of fabrication/construction processes, obtained from the allowable *tolerance* and measurement of the dimensions of the component
K_s = value to account for variability in structural modelling, obtained from the test data used in construction of the structural model

A3.5.7.2

The *Designer* may assess all of the variability through testing an adequate number of full size samples of the component. This is *Design by Testing* and results in the direct assessment of the resistance design value as a five percentile value of resistance. Refer to **Sections A2.6** and **J3** of this document for further details on this process. The *Designer* should allow for an adequate number of tests to gain confidence in the outcomes.

A3.5.7.3

Once the Resistance and Action Models have been evaluated, the *Designer* may calculate the *Reliability* Index (β) using equation (A31).

A3.5.8 Reliability, testing and safety factors

A3.5.8.1

Typically design requirements will take the form of equation (A1) where

$$R_d = \phi R_n \geq E_d = \gamma_E E_n$$

where:
R_d = design resistance,

---

[23] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

ϕ = capacity reduction factor
R_n = nominal resistance
E_d = design load
γ_E = load factor
E_n = nominal load

The *capacity reduction factor* ϕ is generally taken from the appropriate Standard for the *Designer's* jurisdiction (such as those presented in **Section A2**), and the *load factor* (γ_E) is taken from a Standard such as **AS1170.0** [5.2]. The nominal values R_n and E_n are often taken from appropriate Standards or Codes.

A3.5.8.2

Alternatively, on the basis of testing values, the *Designer* may determine the nominal and mean values of resistance for their particular component or assembly, in addition to the standard deviation and thus coefficient of variation.

This gives a *probabilistic model* for the resistance, and the *Designer* may then develop *probabilistic models* for actions which are to be applied to their component or assembly, and thus determine the *reliability* index (β) on the basis of equation (A31). It is then of interest to note that the *Designer* may determine the resistance factor (ϕ) with the following relationships

$$\phi = \frac{1}{\gamma_R}$$

$$\gamma_R = \frac{R_n}{R_m(1 - \alpha_R \overline{\beta} V_R)}$$

where:

$\overline{\beta}$ = target *reliability* index
α_R = a value often fixed dependent upon the design situation being considered. For example, α_R =0.8 is often chosen for the most important resistance variable in a design situation, while all other resistance variables use α_R =0 (Schneider 1997).

This provides a process by which a *Designer* may reduce the *capacity reduction factor* for use with a particular component/assembly on the basis of test data and *reliability* analysis.

Similarly, it is possible to write the following for the load factor (γ_E)

$$\gamma_E = \frac{Q_m}{Q_n}(1 - \alpha_E \overline{\beta} V_Q)$$

Where similarly to the key resistance variables, α_E =0.7 may be taken for the key load variable, while for other load variables very small α_E values may be taken (Schneider 1997).

It should be noted that the following should be true to ensure the design is safe:

$$\sum_i \alpha_i^2 > 1$$

i.e. the sum of all α^2 values for each design case should be greater than 1.

A3.6 Axial shortening

A3.6.1 Description

A3.6.1.1

This section represents a summary of a larger paper on the topic of *axial shortening* prepared by Davey & McFarlane (2016) [8.13].

Axial shortening of columns is the shortening of a column along its length, due to a combination of loading and material changes with time. The effect of this needs to be considered at all stages of design and construction.

A3.6.1.2

Vertical *axial shortening* of building elements is generally not difficult to accommodate provided that it is uniform across all elements. To ensure correct floor levels are obtained, pre-set values can be calculated, and the building level can initially be constructed slightly higher to compensate for the shortening. This is called 'superelevation'. The superelevation values may be either lumped together every few levels or applied on a floor-by-floor basis.

Axial shortening comprises three main elements:

i. **Elastic shortening:** Elastic shortening is the component of shortening due to the elastic deformation of a column being placed under load. The term 'elastic' indicates that, should the column be unloaded, the shortening would be fully recovered. Elastic shortening will occur regardless of the material used (concrete, steel, timber, fibre-reinforced plastic etc.), and is dependent on the loading, dimensional and material properties. Elastic shortening can be calculated using a form of Hooke's law:

$$\delta_{ES} = \frac{P \cdot L}{A \cdot E}$$

Where: δ_{ES} = elastic shortening
P = applied load
A = cross-sectional area
E = elastic modulus
L = length of component

ii. **Shrinkage:** Shrinkage results from the evaporation of moisture from a material, such as concrete or timber. In the case of concrete, the commentary to **AS 3600-2009** [5.16] describes three components of shrinkage. Drying shrinkage is primarily caused by evaporation of water as concrete dries. Chemical or autogenous shrinkage is a chemical reaction that occurs in the cement in the early stages of the concrete setting and developing strength. Thermal shrinkage occurs shortly after setting as the heat of hydration disperses.

iii. **Creep:** Creep shortening is an increase in shortening over time occurring in materials such as timber and concrete when under load. It is dependent upon loading and material properties, and occurs in time-dependent materials such as concrete and timber.

A3.6.1.3

Differential shortening can arise when certain vertical load bearing elements shorten differently to adjacent vertical load bearing elements. This can cause significant problems in terms of floor design, as the floor structure is required to deform with the vertical supports. This imposes stresses and strains for which the floor system needs to be designed. Non-structural elements also need to be designed to take into account this difference in shortening. An example of this is shown in **Figure A15**, where potential cracking of internal walls and damage to services pipes are highlighted.

A3.6.1.4

Differential *axial shortening* can also cause building lateral movement that needs to be assessed and, in some cases, compensated for. This is generally the result of a large difference between the centre of loading and centre of stiffness of a building. This can arise in situations where stiffer, lightly stressed elements are concentrated to one side of the floor plan (see example in **Figure A16**), or in situations where heavy loading is applied only to one side of a building.

There are generally three main methods of dealing with lateral movement due to differential shortening:

i. **Tangential:** Building every level vertically from the level below, and will result in the final position of the building being a result of gravity (i.e. no compensation). This may be acceptable where in cases where minor lateral movement is expected.

ii. **Re-centring:** Re-centring every level to the nominal position at the time of casting. This strategy tends to work well for buildings with minimal stiffness and mass eccentricities.

iii. **Over-compensation:** Constructing the building in the opposite direction to the predicted displacement trajectory such that the building will correct during construction. This is most suitable for buildings with highly eccentric loading or eccentric stiffness relative to the centre of mass.

Consideration needs to be given to these movements in design and construction to ensure there are no issues with building alignment.

A3.6.2 Designer and Builder inputs

A3.6.2.1

In the design stage, preliminary analysis should be undertaken utilising preliminary material properties based on experience, information from local material suppliers and previous data. This stage is within remit of the *Designer.* Initial construction staging and timings can be assumed and estimated, and refined at a later date once a *Builder* has been appointed and construction-level documentation is required. Provision for this revision and reanalysis should be shown clearly on the documentation.

Construction sequence analysis should be undertaken during the design stage, initially utilising assumptions based on experience. Attempts should be made to minimise any potential differential shortening in design. Potential means of minimising this include ensuring vertical load bearing elements are similarly stressed, developing appropriate connections and planning suitable construction staging with the *Builder.*

A3.6.2.2

It is critical that shortening of vertical elements is considered during construction such that floors can be built at correct levels. This stage is normally within the remit of the *Builder,* but is occasionally carried out by the *Designer.* In the event that differential shortening cannot be sufficiently mitigated using a design based solution, a construction-stage solution may be required. In this case, the designer should still identify this issue clearly and propose some form of construction-stage solution on the drawings.

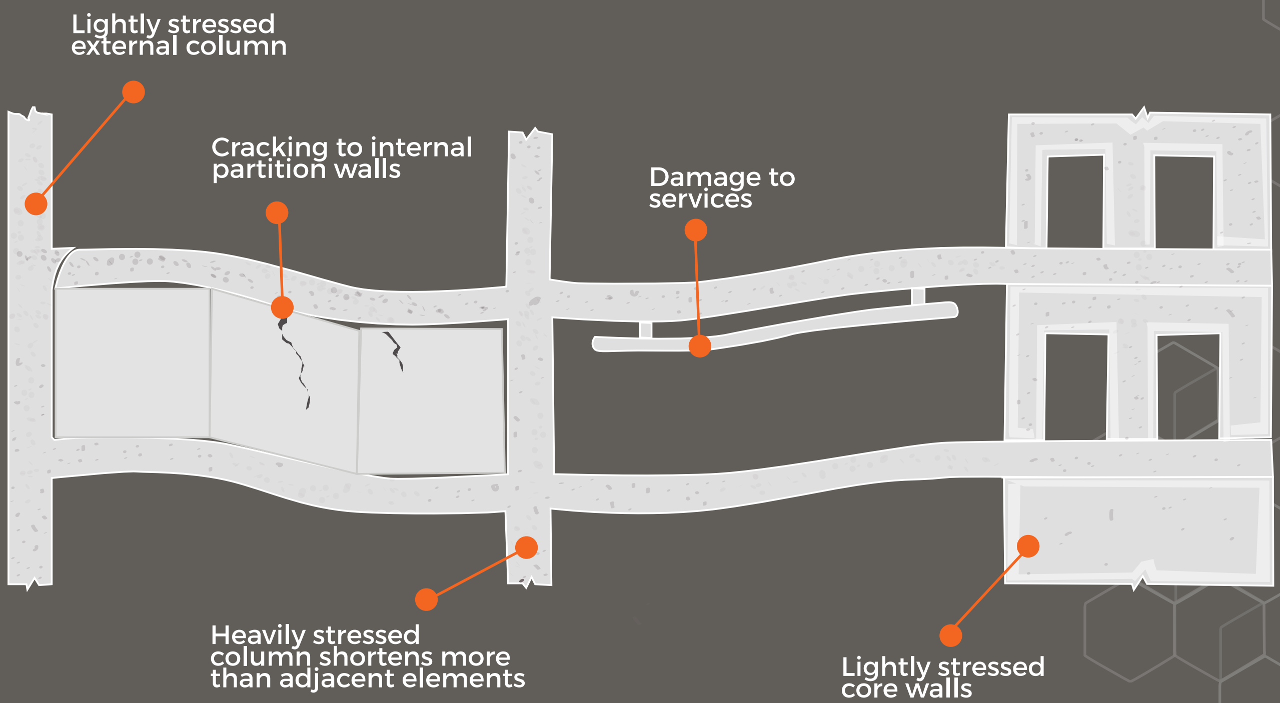

Figure A15 – Potential problems as a result of differential shortening

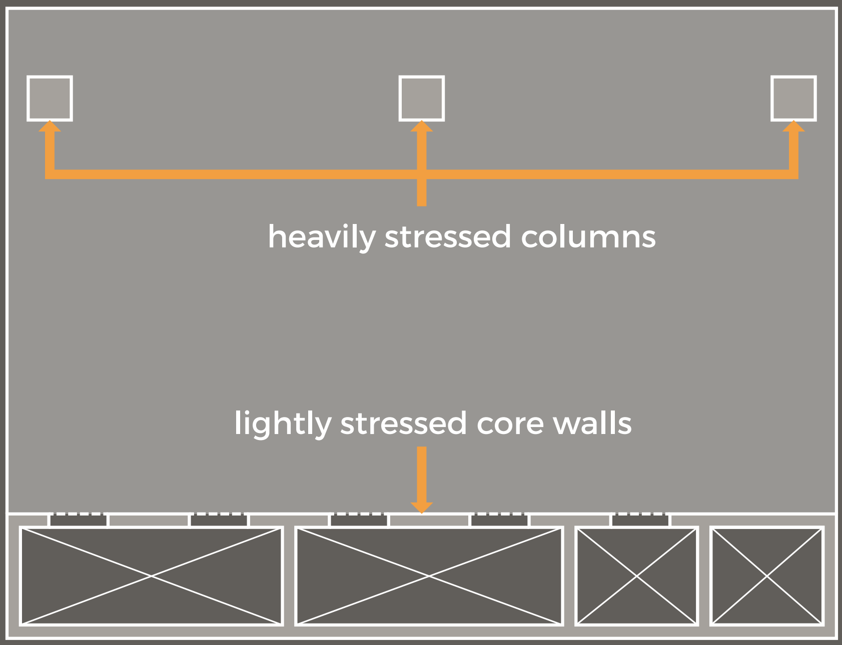

Figure A16 – Illustrative floor plan with eccentric stiffness, prone to lateral movement

A3.6.3 Material behaviour

A3.6.3.1

Material properties can be estimated using prediction models in various relevant design codes, however these methods are noted as only being approximate. Therefore, these prediction methods should be used for preliminary design only, and should be supplemented with local material supplier recommendations and design experience whenever possible.

In terms of concrete, approximate methods of predicting both elastic modulus, shrinkage and creep exist in various design standards (e.g. **AS 3600-2009** [5.16], **fib Model Code 2010** [6.23], **ACI-209** [6.24]). Where *axial shortening* is suspected to cause design issues, final design calculations should be undertaken using material data gathered from testing of actual concrete used on the project. Concrete specimens of critical load bearing elements should be taken throughout the height of the building. The code prediction methods do not generally consider the restraining effects provided by steel reinforcement, which can be significant. A suggested method of incorporating this effect is discussed in Fintel, Ghosh and Iyengar, 1987 [8.16].

A3.6.3.2

Axial shortening may also be an important consideration where structural timber is utilised. The *Designer* should ensure that the bearing strength (that is, the compressive strength perpendicular to grain) is well characterised and sufficient. Appropriate countermeasures for *axial shortening* should be put in place, which may include slip flashings over windows sills and flexible services connections (see **Chapter B** for more details about services in this regard).

A3.6.4 Non-structural components

A3.6.4.1

Designers of non-structural components (such as architects and services engineers) need to ensure there is sufficient *tolerance* in their connections to accommodate any differential shortening. This should be considered in addition to any floor deflections. The specifications should be discussed between all relevant *Designers* to ensure *compliance*.

A3.6.5 Design Codes

A3.6.5.1

Codified limits on acceptable amounts of differential *axial shortening* or associated lateral movement generally take the form of construction tolerances. For concrete structures, **ACI 117-10** [6.25], Clause 17.5 of **AS3600-2009** [5.16] and **EN 13670** [6.26] provide some construction *tolerances* for various elements in reinforced concrete structures. Other material standards (such as **AS4100** [5.15] for steel) refer to appropriate *tolerances* for other material construction.

The commentary to **AS3600-2009** [5.16] notes that these limits mainly serve to ensure that the structural design assumptions are not compromised; however, more stringent requirements for serviceability, aesthetics and constructability often apply. Therefore, it is important to give due consideration to other potential requirements at both design and construction stages.

B Chapter

Building Services, Fire, Acoustics & Sustainable Thermal Regulation

B Building Services, Fire, Acoustics and Sustainable Thermal Regulation

B0.0.0.1

The term "building services" generally refers to those aspects of the built environment which actively create amenity (i.e. safe functionality) for human use; this covers both intended and reasonably foreseeable human use. The range of specialised building service disciplines includes:

i. Mechanical (e.g. heating, ventilation and air conditioning, i.e. HVAC)
ii. Electrical (power, communications)
iii. Hydraulic (water, gas, sewer, stormwater)
iv. Fire protection service
v. Fire engineering including fire resistance
vi. Lifts/escalators
vii. Civil (stormwater)
viii. Environmentally sustainable design (e.g. thermal efficiency)
ix. Acoustic/vibration

Of these, only fire engineering and resistance is purely preventative in nature for safety reasons and solely concerned with the acceptable *risk* of adverse outcomes. There are significant regulatory provisions beyond the services envelope for fire performance, primarily concerning structural design and building materials.

B0.0.0.2

Modular Construction in itself does not require qualitatively different levels of specification or performance from the architectural demands required of the completed building. That is, a completed, assembled modular building has the same minimum requirements for regulated performance as would the same building had it been constructed traditionally in-situ.

However, the sizing of elements and interconnection of modules may require additional continuity or isolation measures for these architectural performance aspects at connections and junctions as well as special details to enable or optimise inspection requirements.

B0.0.0.3

The additional requirements for services design on account of *Modular Construction* arise from the multiplicity of module connections and desired minimisation of on-site construction work. Some of the implications include:

i. Modules manufactured with installed services may be required to resist handling and transport effects.
ii. Modules with regulated services (e.g. plumbing, electrical wiring) may require *Compliance* certification prior to occupancy but with minimal work on site (see **B0.0.0.4** below).
iii. Module services should allow for connection tolerances.
iv. Some module connections should provide continuity (e.g. wiring, hydraulic, waterproofing) whilst others should provide discontinuity (e.g. thermal breaks, acoustic separation).
v. Services pre-installed within modules may require a certain minimum level of exposure to allow access for connection and enclosure on site.

B0.0.0.4

It is reasonable that compliance certification be performed on complete modules in the manufacturing facility prior to transport to site, in keeping with the lean construction philosophy. However, transport, storage, lifting and assembly of the completed modules may result in damage to pre-installed services, so it may be desirable to perform final checks following assembly on-site.

Appropriate design measures may also mitigate these effects, by considering early in the design phase how in-built services will respond to the loads to which they are subjected between manufacture and assembly.

B0.0.0.5

The *Designer* of any building services should consider how any penetrations made to accommodate services may affect the fire rating of modules. Provisions should be considered that any penetrations are fire and smoke stopped via methods that are approved by the local regulatory building controls.

It is typical for volumetric modular construction that floors and ceilings are fire rated via the use of fire-rated plasterboard, which should be accounted for in the design of services when considering penetrations.

B0.0.0.6

The *Designer* and *Manufacturer* should consider local OH&S and WHS guidelines during all stages of design and construction, to ensure that the installation and connection of all services can be performed without causing unreasonable *risks* and *hazards*. See **Chapter G** for further discussions on safety and OH&S.

B0.0.7

Documentation of any *compliance* verification of building services in Australia should make reference to the latest applicable revision of the *National Construction Code* (NCC) [6.2] as determined by the responsible party. For further discussion on *compliance*, see **Chapter J**. For further details about Documentation, see **Chapter M**.

B0.0.8

The *Designer* should provide in their documentation of building services a clear scope of responsibility with respect to works that are to be completed off-site (i.e. the modular component) and on-site. Furthermore, the *Designer* should indicate the extent of the *complexing works* that are required to facilitate the final installation of services. The party responsible for the *complexing works* should be clearly stated. There should be a clear, documented demarcation for the roles and responsibilities of the off-site work and the on-site works by contractors.

B0.0.9

The *Designer* and *Manufacturer* should ensure that testing and approvals of any services installations are performed to the appropriate local requirements. Fixing should comply to local requirements whilst taking into account the additional vibrational loadings that may occur during transport.

B0.0.10

The design of building modules should consider transport and erection effects on services (pipes, cabling, etc.). This may include the combination of material distortion under vibration (affecting services and supports) as well as any shearing or abrasion effects at these supports, for example where cabling or pipework penetrates wall studs. Options to be considered may include flexible or damper mounted rigid services or armoured electrical cabling.

B0.0.11

Overall the *Designer* must identify where all continuity or discontinuity of materials, systems and services is required, and account for the modular assembly process on site as well as the transport and handling effects beforehand, which may tend to disrupt the intended connection or isolation or material integrity of components. This has implications for:

i. Fire isolation and resistance design (composite elements at module junctions);
ii. Weatherproofing;
iii. Vibrational and acoustical isolation;
iv. Thermal insulation.

The *NCC* [6.2] makes direct provision for all these aspects and the *Designer* should consider the effects of these upon the comfort of users. Due to the comparatively lean nature of *Modular Construction*, these issues may become more likely. For further guidance on suggested limits to vibrations in particular, the *Designer* should refer to **Section A3.2**.

B0.0.12

In order to ensure that continuity issues are not present in the final erected structure, it may be necessary for the *Designer* or *Manufacturer* to conduct testing upon the partition and floor elements of the structure to measure thermal, acoustic and fire performance. If no testing is done prior to erection of the final structure (i.e. by an appropriate tester), it is suggested that 10% of all final partitions be tested in-situ to verify performance is adequate. While predictive methods are available, verification is key to ensuring *compliance* with required limits.

B1 Hydraulics

B1.0.0.1

For hydraulic services within Australia and New Zealand, all design and installation should comply to **AS/NZS 3500 Plumbing and drainage** [5.9] and the Plumbing Code of Australia [6.30]. The international *Designer* and/or *Manufacturer* should comply to Standards and Codes relevant to their jurisdiction.

B1.0.0.2

For gas installations and piping, the Australian/New Zealand *Designer* and/or *Manufacturer* should ensure design and installation of these services complies to the relevant version of **AS/NZS 5601 Gas installations** [5.10]. The international *Designer* and/or *Manufacturer* should comply with Standards and Codes relevant to their jurisdiction.

B1.0.0.3

As part of the compliance with the Plumbing Code of Australia it is recommended that modules undergo *certification* under the WaterMark™ scheme. This system confirms that a product complies with the Plumbing Code of Australia and relevant Australian Standards. Modules should have the WaterMark™ applied as a whole product, with *certification* done by a Certification Accredited Body external to the *Manufacturer*.

The WaterMark™ system provides a methodology by which a module may be installed and deemed to comply with the NCC for Australia as they arrive on-site with no further *certification* required on the part of the on-site contractor (for works relating to services installed off-site).

B1.0.0.4
In general the *Designer* and *Manufacturer* should consider a *compliance* pathway that will be suitable for the locality of the final installation, which may include appropriate plumbing *compliance* certificates. The *Designer* should furthermore familiarise themselves with any additional requirements set-out by the insurance industry at the place of the final installation, as well as those requirements of local council and other authorities such as plumbing and gas inspectors.

B1.0.0.5
The module *Manufacturer* should consider local commissioning practices and ensure that their requirements are followed for any off-site installations. The module *Manufacturer* should furthermore consider sub-contracting qualified plumbers that are registered in the relevant jurisdiction for the supervision of manufacturing and/or commissioning of the hydraulic systems.

B1.0.0.6
The *Designer* of hydraulics services should give consideration to the following areas:

i. Cold water;
ii. Hot & warm water;
iii. Recycled water;
iv. Sanitary drainage;
v. Stormwater drainage;
vi. Gases.

B1.0.0.7
The *Designer* should consider provisions in their design for on-site complexing works to facilitate the interconnection of modular hydraulic services. These services connections can be provided in a manner that is either horizontal, vertical, or a combination of both horizontal and vertical.

Modular project experience has shown that tolerances between module services pipework can vary in the order of 30mm in horizontal and vertical planes. Exact tolerances should be confirmed with the module supplier. In addition to the hydraulic work *tolerances* the *Designer* should confirm any relevant structural tolerances.

B1.0.0.8
Consideration should be given to the type of connection provisions and design implications with respect to site complexities and impacts of these connection methods to the performance of the hydraulic system (including velocities and pressure losses through fittings).

B1.0.0.9
Construction tolerances should be allowed for between modules and module connections should be designed to allow for these tolerances. The *Designer* should consider *tolerances* in all planes as well as the angular *tolerances*. See **Section E2** for further discussion of *tolerances*.

B1.0.0.10
In instances where tolerances are significant and cannot be overcome via the provision of pipe fitting/coupling tolerances, the *Designer* should consider means of specialist fittings and/or the inclusion of pipe routing and on-site works that enable the interconnection of modules.

B1.0.0.11
Given the modular nature of the construction, the *Designer* should consider provisions for the thermal expansion and shrinkage of hydraulic services. This will typically affect drainage, hot water and gas services.

B1.0.0.12
The *Designer* should consider services provisions to meet *seismic* conditions of the area that the module is to be installed in.

B1.0.0.13
The *Designer* should also consider potential ceiling space impacts of the modular nature of the drainage design and the connection restriction requirements at the base of sewer stacks and for any above-ground stack offsets.

B1.0.0.14
The *Designer* should ensure that pipework connections are flexible enough to account for differential movement which may occur during normal use, maintenance or as a result of installation on-site. This may include allowing for *tolerances* of approximately 10 mm or more in horizontal and vertical planes

B1.0.0.15
Consideration should be given to adequate protection of completed modules during transportation. The module manufacturer shall consider utilising UV-resistant materials as well

as materials that would minimise any possible corrosion during sea transport. Additional corrosion treatment of metal materials should be considered. See **Section F2** for more details about this topic. Particular attention should be paid to temperature and vibration loadings associated with proposed modes of transport. See **Section A1.2.3** for more details about this topic.

B1.0.0.16
Consideration should be given to quarantine issues which may arise during transport of modules between jurisdictions. The responsible party should determine whether it is necessary to liaise with local ports to validate requirements for physical water testing. Any water pipework should be capped and sealed during transportation to ensure that there is no risk of contaminated water entering the local jurisdiction along with the module. Disinfection measures should be considered. Following any water testing at of the hydraulic services off-site the Manufacturer should completely drain all services and ensure the pipework is dry prior to sealing to minimise any potential fungal growth.

B1.0.0.17
Consideration should be given by designers for water proofing and drainage to the base of the modular structure in the event of plumbing failure in concealed spaces and vertical risers.

B1.0.0.18
Where pipework will be installed in modules in another jurisdiction, the *Designer* and *Manufacturer* should carefully consider whether there are any local supply chain issues such that the materials used might not meet local materials standards requirements.

B2 Electrical

B2.0.0.1
For the Australian or New Zealander *Designer* and/or *Manufacturer*, all wiring and electrical installations should comply to and be done in accordance with the guidance in **AS/NZS 3000 Electrical installations** [5.7]. This will ensure that any wiring and electrical installations will comply within the jurisdiction in which it is applied. For the international *Designer* or *Manufacturer*, **AS/NZS 3000** may be substituted for an equivalent Standard or Code for their jurisdiction.

B2.0.0.2
While the general design and installation of wiring and electrical components is covered in **AS/NZS 3000** [5.7] or equivalent, it is particularly pertinent that all systems and wiring installed within modular structures or components be verified at the source of manufacture/installation to ensure quality is maintained and faults are minimised. A module/modular component may be treated much like an appliance. These tests include, but are not limited to:

i. The visual inspection of wiring for faults (both prior to and following transportation of components);
ii. Earth continuity test;
iii. Relevant tests as elected by the Designer or Manufacturer which may be taken from sources such as **AS/NZS 3760 In-service safety inspection and testing of electrical equipment** [5.21].

B2.0.0.3
The majority of testing for wiring and electrical components should occur at the source of manufacture, with clear documentation outlining:

i. All components which have undergone testing;
ii. Which tests must be performed on each component;
iii. Tests performed on each of these components, and the methodology followed – noting especially any deviations from standard procedure;
iv. To which Standard or Code do these components comply.

B2.0.0.4
A detailed plan for Inspection and *Compliance* procedures should be developed early in the design phase and form a part of the tender. Relevant details include inspection visit schedules, testing methods and frequencies and failure contingencies. See **Chapters J** and **K** for guidance on *Compliance* and Inspection respectively.

B2.0.0.5
At a minimum, wiring and electrical installations within modular structures or components, and any verification and tests done on these, within Australia and New Zealand must comply to:

i. **AS/NZS 3000 Electrical installations** [5.7] for design and installation of wiring and electrical components;
ii. **AS/NZS 3017 Electrical installations – Verification guidelines** [5.22] for the verification of any wiring or installations;
iii. **AS/NZS 3760 In-service safety inspection and testing of electrical equipment** [5.21]

for any safety inspection and testing;
iv. **AS/NZS 1768 Lightning protection** [5.5] for the protection of circuitry and installations against lightning.
v. **AS/CA S009 Installation requirements for customer cabling** [5.1] for safety and integrity of cabling installation.

B2.0.0.6

Generally the *Manufacturer* should bear the *risk* associated with any electrical installation which occurs during the manufacture of modules, being the one who should ensure *compliance* with appropriate Standards and Codes, in contrast with the on-site contractor who is responsible for the connection between modules to create the building circuit.

B2.0.0.7

The *Designer* should engage with the electrical engineering contractor at an early stage to ensure that the configuration of modules, and positioning of risers, does not unduly complicate the wiring schemes and circuit design.

As a specific example, in the case of stacked three dimensional modules, electrical wiring can run either through vertical risers built into each stack of modules or up through a single riser and then horizontally around each floor. This choice should be made earlier as it may impact heavily on other design considerations.

B2.0.0.8

The following issues should be considered:

i. Three-phase power balancing; this may be more straightforward with a single vertical riser carrying all three phases to each floor, so that modules can be phased alternately to achieve better balancing.
ii. Fire protection zones; wiring circuits connecting together volumes comprising a single fire protection zone will be optimally achieved where a single vertical riser carries all electricals.

B2.0.0.9

Consideration should be made of how metered circuits will be run between modules, for example in the case of an apartment building where multiple modules may comprise a single apartment. It may be unavoidable to have wiring run from each module into a central corridor and back into adjoining modules, in which case metered and unmetered circuitry may intermingle. Extra care and diligence is required in such a situation.

B2.0.0.10

Certain electrical components in central corridors such as smoke detectors, emergency lighting and emergency speakers may occur at different spacing, so that if these components are to be pre-installed in modules at a factory, there will be a variety of module types. Care will need to be taken when placing these modules in the correct order. If homogeneous modules are preferred, some of these services will have to be installed in-situ.

B2.0.0.11

Other issues and considerations particular to *Modular Construction* include:

i. The *Designer* and *Manufacturer* should provision at a minimum 500–1000 mm of extra cable length to allow connections to be made between modules;
ii. The weight and support of this extra cable length should be accounted for;
iii. A reasonable connection methodology between modules should require a power tool to remove the connection (in the case of electricity);
iv. Attention should be paid to the location of risers within modules and the overall structure. Their location should reasonably allow for future access;
v. The *Designer* and *Manufacturer* should allow for clearances (of approximately 100–150 mm) and separation between low and extra low voltage cabling;
vi. Separation may also be required between the termination points of cabling with voltage discrepancies;
vii. The *Designer* and *Manufacturer* should consider the location and clearances of any distribution boards, allowing for reasonable ease of access;
viii. Where cable trays are preinstalled in corridor segments of modules, consideration needs to be made for continuity of the trays.

B2.0.0.12

When considering data connectivity (where applicable) for modular structures, the following considerations should be made in addition to those for general electrical wiring/installation:

i. The *Designer* should consider the number of connection points which may be required between the data rack and end service point;
ii. The *Designer* and *Manufacturer* should consider the effect of signal attenuation and loss due to:
    a. Distance from data rack/source; this may require the provisioning of repeater units;

   b. Disconnection or degradation of signal due to differential movement within the structure;
iii. For wireless connectivity, the *Designer* should consider the capabilities and specifications of the Wireless Access Points elected for use, particularly taking into account signal blocking from module walls;
iv. As in the case of electrical wiring, the *Designer* should allow for ease of access to risers following installation.

B2.0.0.13

Where consideration is given to specifying on-site electricity generation (e.g. photovoltaic) and also on-site electricity storage or battery systems the *Designer* should account for any consequent actions in the structure (e.g. additional self-weight and wind effects).

B2.1 Modular Wiring Solutions

B2.1.0.1

The electrical *Designer* should consider the use of modular wiring solutions where appropriate. Such solutions may be suitable particularly in *Modular Construction* where significant gains are often made by prefitting services in such a way that on-site assembly works are minimal. In the case of modular wiring solutions, entire volumetric modules could be prefitted with electric services that can simply be plugged together on-site.

In the construction sector, Modular or pre-fabricated cabling systems for lighting and small power distribution in modern buildings, are often regarded as a relatively new technology. In actuality it has already been present for over 50 years, particularly in Europe and the United States.

Modular wiring is a pre-fabricated wiring system that is simply plug and play, it is a quick and easy install alternative to the traditional hard wired electrical installation methods. Solutions compliment and/or replace traditional wiring of electrical sub-circuits, with systems that are rapidly and easily installed ranges of prefabricated connectors and cable assemblies.

The system is comprised of modular lengths of cable with a push fit connector at each end. By connecting standard components together, a complete installation from the distribution board to the pre-wired accessories at the furthest point of the circuit can be achieved.

Pre-fabrication of modular offsite builds raises a whole new series of challenges and opportunities. Where new ideas and methods are being designed and introduced; whilst benchmarks and comparisons are still being measured by onsite metrics and performance.

B2.1.0.2

The following benefits should be considered when making a decision on whether or not to employ a modular wiring system:

i. The wiring system can be delivered already tested to and complying with **AS/NZS 61535** [5.36].
ii. All cabling and connectors, are pre-tested by the manufacturer before delivery to site, making commissioning easier by minimising the possibility of faults (note that this does not eliminate the need to test to **AS/NZS 3000** [5.7]).
iii. Connections can be made to standard accessories and fittings.
iv. Simplified installation technique and reduced installation labour.
v. Reduced wastage on site – all cables and accessories are engineered to suit.
vi. Highly flexible system allowing for future alterations.

B2.1.0.3

Modular wiring needs to adhere to **AS/NZS 61535:2011 Installation couplers intended for permanent connection in fixed installations** [5.36]. This standard details various requirements, including:

i. Constraints on installation couplers, including that they are intended for permanent connection, with exceptions for reconfiguration or maintenance of the wiring system in which the couplers have been installed.
ii. Constraints on the cross-sectional area of the conductors to be connected
iii. Constraints on when earth and current-carrying connections are made and separated.

B2.1.0.4

Early engagement with the design team is critical and it is essential that sufficient information is provided to ensure that the manufacturer fully understands the client requirements. Workshops and design development sessions are encouraged as they may have an impact on how the project reticulation is to be laid out. It is essential that the philosophy for the secondary cable installation is understood to ensure the installed cables meet with the design team and industry standard requirements. Installation methods and routes may differ between ceiling, wall and underfloor situations. General items to be determined during the design stage are as follows:

i. Establish the conductor size required for each circuit.
ii. Establish whether there are any connector size constraints due to fire stopping or routed/conduit pathways.
iii. Establish the overall emergency philosophy: locally generated and switched via key switches; or locally generated and delivered to the light.
iv. Establish which circuits are hard switched and which are dimmable, and what type of dimming is required.
v. Establish which circuits require standard switching modules, which require bespoke switch modules and which require standard dimming modules.
vi. Establish the methodology for connecting groups of lights together: whether the lights will be daisy chained or connected in a spider formation.
vii. Establish the philosophy for connection to the lights themselves and whether connection leads are to be supplied to light manufacturers for factory fitting (including mating connectors for test leads to allow factory testing).
viii. Establish the requirements for mechanical protection in the wall drops.

B2.1.0.5
To ensure installation efficiencies, training either on-site or in a factory training facility should be arranged as and when required, prior to commencement of an installation.

B2.1.0.6
When installing any modular Wiring System, the installation team must follow manufacturers guidelines at all times and refer to any project specific documentation that may have been issued during training.

B2.1.0.7
A multi-circuit cable designated as a Home Run Cable (HRC) can be utilised and would run from the Electrical Distribution Board (EDB) to the Home Run Box (HRB).

B2.1.0.8
When installing final sub-circuits, it is essential to start by working away from the HRB or EDB, securing cabling to containment using nylon or steel cable ties or the building fabric using approved proprietary fixings to final positions as shown on layout drawings.

B2.1.0.9
Ensure cables are installed going in the right direction. Female connectors should head away from the EDB and male connectors back toward the EDB.

B2.1.0.10
All secondary cabling is mechanically coded and clearly labelled to aid component identification and to prevent mis-mating on site. Connectors are designed so that only male and female connectors mate. An audible ‘click’ should be heard when the connectors are fully mated.

B2.1.0.11
It is essential that there is minimal strain placed upon the connections in any plane. Best practice would be to fix the assembly within 100 mm from the connector if practical ensuring no bends occur on cabling within 150 mm of the connector. Conduct a hand pull test to establish that the connection is satisfactory.

B2.1.0.12
Modular components may be fixed to soffits, walls, containment, floor slabs or suspended within pre-set zones within suspended ceilings. These components and their associated wiring are to be installed in line with the System Schematic and with fixing centres not exceeding the regulatory guidelines. All outgoing circuits should be labelled both on the EDB and the corresponding outgoing cable with the circuit reference.

B2.1.0.13
It is recommended that the installation of power and lighting circuit cables begin at the EDB/HRBs to prevent the incorrect installation of circuit cabling. HRBs are supplied with female connectors so that if disconnection of circuit cables inadvertently takes place under load, then live contacts are not exposed. It is recommended that mated connectors never be separated under load conditions.

B2.1.0.14
Manufacturers should carry out visual and electrical tests to ensure the modular components comply to the requirements of the Low Voltage Directive and are controlled within the guidelines of the relevant

standards. It should be noted that the installation needs to be fully tested and inspected to **AS/NZS 3000** on site and the provision of pretested leads does not take away from the installer the need to follow the required testing.

B3 Mechanical (HVAC)

B3.0.0.1

For the Australian or New Zealander *Designer* and/or *Manufacturer*, the mechanical (HVAC) installation should comply to and be done in accordance with the relevant Australian standards. Key standards include (but are not limited to):

i. The *National Construction Code* (NCC) [6.2]
ii. **AS/NZS 1668 The use of ventilation and air conditioning in buildings** [5.37] (particularly **Parts 1–2**)
iii. **AS/NZS 3000 Electrical installations** [5.7] (also known as the Australian/New Zealand Wiring Rules)
iv. **AS/NZS 3013 Electrical installations – Classification of the fire and mechanical performance of wiring system elements** [5.38]
v. **AS 3666 Air-handling and water systems of buildings** [5.39]
vi. **AS 4254 Ductwork for air-handling systems in buildings** [5.40]

Consultation of the relevant standards will ensure that the HVAC installations comply within the jurisdiction in which it is applied. For international projects substitute for the equivalent Standard or Code for the relevant jurisdiction.

B3.0.0.2

While the general design and installation of HVAC systems and components is covered in the relevant standards, it is particularly pertinent that all systems installed within modular structures or components be verified at the source of manufacture/installation to ensure quality is maintained and faults are minimised. A module/modular component may be treated much like an appliance. These tests include, but are not limited to:

i. Pressure testing of all pipework and ductwork
ii. Operational checks of all fans, HVAC equipment and controls systems
iii. Performance testing of all air and water flow rates as far as practical
iv. The visual inspection of wiring for faults (both prior to and following transportation of components)
v. Relevant tests as required by the equipment manufacturer

Consideration should also be given to the qualifications of the personnel carrying out testing and commissioning of equipment in the manufacturing factory. This may include, for example, NEBB certification. Where qualifications of factory commissioning staff cannot be verified then the site contractor will need to assume full responsibility for all testing and commissioning.

B3.0.0.3

The majority of testing of the HVAC systems, wiring and control components should occur at the source of manufacture, with clear documentation outlining:

i. All components which have undergone testing;
ii. Which tests must be performed on each component;
iii. Tests performed on each of these components, and the methodology followed – noting especially any deviations from standard procedure;
iv. To which Standard or Code do these components comply.

B3.0.0.4

Generally the *Manufacturer* should bear the *risk* associated with any HVAC installation which occurs during the manufacture of modules, being the one who should ensure *compliance* with appropriate Standards and Codes, in contrast with the on-site contractor who is responsible for the connection between modules to create the integrated HVAC system. Final certification of the completed system will need to be provided at completion of the project. Responsibility for this should be clearly defined within the contract and specification.

B3.0.0.5

The *Designer* should engage with the mechanical engineering contractor at an early stage to ensure that that the configuration of modules, and positioning of plant, equipment, ductwork and risers, does not unduly complicate the final installation and connections on site. In the case of stacked three dimensional modules, pipe, duct and cabling can run either through vertical risers built into each stack of modules or up through a single riser and then horizontally around each floor.

B3.0.0.6

Issues and considerations particular to procurement of plant and equipment for *Modular Construction* include:

i. Where air conditioning and HVAC equipment is being procured overseas specific attention needs to be given to ensuring all equipment is compliant with all Australian Standards and requirements, including MEPS compliance for energy efficiency.

ii. Warranty on equipment procured overseas; consideration needs to be given to distribution regions as even though the same product may be available on the Australian market the warranty may not be valid unless equipment is procured through local distributors or appropriate agreements are in place.
iii. Where ductwork and insulation are procured overseas, compliance should be ensured with **AS 4254** [5.34] both in regards to construction and to materials choice. Where materials other than sheet metal are used, attention should be paid in particular to smoke development and flammability indices.
iv. Where power and controls cabling is procured overseas, full compliance should be ensured with Australian standards; compliance is also necessary with the HVAC equipment manufacturers requirements. Refer to **Section B2** of this document for further guidance on electrical considerations, which arise for mechanical services.

B3.0.0.7

Issues and considerations particular to the installation of plant and equipment for *Modular Construction* include:

i. Fire rating of duct and pipework where crossing fire rated elements; in modular construction these fire rated elements will differ from conventional construction. Where fire dampers are used ensure that these are compliant with and are installed in accordance with Australian Standards, and ensure adequate access is provided for inspection and maintenance.
ii. Where central plant is provided such as chilled water/heated hot water or central exhaust or ventilation systems, ensure adequate provision is made for balancing and commissioning.
iii. When designing systems ensure there is adequate provision for connections in duct and pipework between modules and to connect to site infrastructure. Ensure sufficient access is available to make connections and where relevant permanent access is provided for maintenance.
iv. Ensure all electrical work is carried out in accordance with relevant Australian Standards; refer to **Section B2** of this document for further guidance on electrical for mechanical services.

B4 Fire Protection

B4.0.0.1

All fire protection systems should be designed to and be *compliant* with the Standards and Codes relevant to the jurisdiction in which the modules/modular components will be used. This includes the *compliance* with an appropriate fire engineering report to ensure fire protection systems and structural elements achieve the performance required by the Standards and Codes within the jurisdiction.

Any building products for use as part of a regulated system in Australia should be listed within an Accredited Scheme or have documented evidence of suitability as outlined in the *NCC*. If the product is not listed but is claimed to be *compliant* with the appropriate Standards, then written certification must be provided from an appropriate authority or testing body holding relevant accreditations.

B4.0.0.2

Any fire protection system/equipment, emergency planning and lighting should be routinely tested and these tests should comply with the appropriate Standards/Codes for the completed structure's jurisdiction. In Australia, the following standards are relevant:

i. **AS 1851 Routine service of fire protection systems and equipment** [5.23] provides guidance on tests, and frequency of these, for fire protection systems/equipment, in addition to emergency planning.
ii. The routine testing and maintenance of emergency and exit lighting should comply with **AS 2293 Emergency escape lighting and exit signs** [5.24].

The *Designer* should account for the requirements outlined in the above (or similar in other jurisdictions) standards as part of their design including fire protection system drainage provisions.

B4.0.0.3

The *Designer* should account for the effect of transportation upon any fire protection services installed, such as the effect of vibrations. Where necessary, measures to eliminate damage should be provided which may include mounting of services with vibration resistant or damping connections. Other aspects to be considered include:

i. The fire engineering report should account for the transportation and handling phases when nominating appropriate systems.
ii. Fire protection systems may require inspection on installation and confirmation

once the modules are erected. In this case, it is advised that written instructions on inspection and verification accompany the fire protection systems throughout the construction process.

iii. The *Designer* shall consider transportation temperatures and the potential impacts on temperature sensitive fire protection equipment (i.e. sprinklers, etc.).

B4.0.0.4

When considering protection and warning systems for fires, the *Designer* should be cognizant of the following:

i. All smoke detectors should be configured such as to permit a looped installation.
ii. For Emergency Warning Systems, emphasis should be placed on the designation of end of line devices. E.g. the location of the last alarm speaker should be well-defined in the design documentation.
iii. Connection between smoke detectors and warning systems should follow a similar methodology to that adopted for general electrical wiring/installation, see **Section B2** for further detail on this matter.

B4.0.0.5

The *Designer* should consider the construction *tolerances* and their impact on the fire protection system design. Any pressure losses associated with the use of flexible fittings should be accounted for as part of the original design. Refer to **B1.0.0.9** for guidance relating to tolerances.

B5 Fire Engineering

B5.0.0.1

Fire performance of structures centres on prevention of injury or loss of life, prevention of damage to other property and management of the risk of the spread of the fire. In the case of completed buildings the design will typically have to comply with regulations in the relevant jurisdiction. In Australia, the design must comply with the *NCC* in all respects pertaining to materials, separation, warning, and fire-fighting and management systems.

B5.0.0.2

The *Designer* should consider the final use of the structure when determining the required fire rating of the modular structure and components. The *Designer* should consult the appropriate Codes and Standards for their jurisdiction for specific guidance.

B5.0.0.3

The *NCC* details a number of *Performance Requirements* for fire resistance that must be complied with. These *Performance Requirements* can be found in *NCC* Vol. 1, Sections CP1–CP9 [6.2] and cover the following aspects of fire resistance[1]:

i. Appropriate structural stability during a fire event;
ii. Limiting the spread of fire;
iii. Permitting orderly evacuation;
iv. Avoiding outward collapse of complete (e.g. precast) concrete panels;
v. Avoiding spread of fire to service equipment with high fire hazard or potential for explosion;
vi. Keeping emergency equipment working;
vii. Adequate access for fire brigade intervention.

B5.0.0.4

Many of the above *Performance Requirements* relate to the finished structure. However, the *Designer* and *Manufacturer* should consider how the nature of *Modular Construction* affects the fire protection of the completed structure. This may involve, for example, access to concealed spaces between modules.

It should be noted that whilst some systems will be considered "Deemed-to-Satisfy" in accordance with the *NCC* (for example, in the case of external façade elements this relies on the use of non-combustible materials in accordance with **AS 1530.1** [5.3]), an alternate route exists for ensuring compliance. This relates to the "performance-based" design, where a proposed system is tested to appropriate standards (generally **AS 1530** or equivalent) and by an accredited body.

The assessment of the applicability of the proposed system should form part of a detailed fire engineering report, where the system is shown to be compliant with the *Performance Requirements* set out in the *NCC*. Using the external façade as an example once more, many composite façade panels would not be "Deemed-to-Satisfy" as the plastic cores would be considered combustible when tested as per **AS 1530.1**.

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[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

B5.0.0.5

The following guidance is offered for the *Designer* and *Manufacturer*:

- i. It should be ensured that performance and continuity of any fire rating materials is maintained where structural connection between modules/modular components occurs.
- ii. Fire rating of walls should be tested and certified, with any fire rated walls being installed by a certified contractor.
- iii. Should fire rating of floors be required this may need further investigation depending upon the nature of the flooring system (including testing).
- iv. The required fire rating should be clearly stated, and may be taken from the Deemed-to-Satisfy provisions in Part C1 of the *NCC* or similar.
- v. Testing of the fire rating of structural elements should comply with **AS 1530** [5.3] or similar as required by the jurisdiction, covering the following:
  - a. Verification of the performance of the system should be provided by the Supplier or an accredited body at the point of manufacture.
  - b. Where appropriate, a qualified fire engineer may provide guidance on the equivalency or applicability of Codes and/or Standards (especially regarding testing methodologies) from other jurisdictions.
- vi. The *Builder* should ensure that all materials used in façade construction comply with *NCC* provisions for fire resistance.
- vii. Final checks of the product should be done on-site by the building *certifier* to ensure the finished product meets required standards.
- viii. An appropriate maintenance and inspection regime should be considered to ensure that fire compartmentation is appropriately maintained throughout the life of the building.
- ix. The *Designer* should consider that the stacking of modules may create a network of concealed voids. Care needs to be taken to ensure either pre-installed fire stops or adequate access for post-installation, so that the voids can be broken up through the vertical extent of the building.

B5.0.0.6

Modular Construction generally relies on lightweight construction elements. Therefore, the method used to achieve the required fire resistance needs to be considered, in particular for floor separation between levels and resistance to impact damage. As the wall systems used in some forms of *Modular Construction* are rarely tested in accordance with the relevant fire standards, a Performance Solution may be needed to demonstrate that the proposed design meets the *Performance Requirements*.

> For low-rise buildings, a significant degree of redundancy would generally be expected within the structure already to account for transportation loads.

B5.0.0.7

Where a lightweight construction method has been utilised, the increased likelihood of a structural element being impacted by fire should be considered; the structural redundancy of the building should therefore be carefully examined.

B5.0.0.8

An additional consideration of lightweight modular construction relates to fire brigade intervention. Where lightweight fire-isolated stairs are considered for fire brigade intervention, this should be discussed with the brigade as early as possible so that the design can account for potential damage caused to the walls by fire brigade personnel during intervention.

B5.0.0.9

Further to the above consideration, early discussions with authorities is essential as the fire brigade and approving authorities may not be familiar with the proposed construction method. Early consultation should be considered to identify any concerns from the relevant authorities and address those as required.

B5.0.0.10

Where wall systems have not been thoroughly tested, consideration should be given to temperature profiles within wall cavities to ensure that fire spread between compartments is sufficiently prevented.

B5.0.0.11

Consideration should be given to structural deflections which may be allowed for in the *Modular Construction* design; these deflections may not be appropriate for fire-rated plasterboard, leading to the possibility of creating openings between different compartments.

B5.0.0.12

Transportation of modules may affect the fire-rated elements due to damage, movement or penetrations during transportation. An inspection regime of the fire-rated elements should be implemented to ensure that the required fire separation is maintained as required from installation and delivery of the building. Contractual agreement may need to be implemented to appropriately define the chain of responsibility for construction, inspection and rectification of fire-rated materials throughout the off-site construction, transportation, on-site erection and maintenance phases.

B5.0.0.13
Where penetrations within a fire separation are necessary, for example to run services, it is recommended, and may be necessary, to implement a register to ensure that each penetration is appropriately identified, recorded and sealed.

B5.0.0.14
To ensure fire spread within a building is prevented (in non-sprinkler protected buildings), a 900 mm high fire rated wall is required above any openings, to prevent flames extending out of openings in a lower level reaching an opening in an upper level. In *Modular Construction*, if there is a gap between levels where there is no fire protection, flame could extend out of the window and cause fire spread to the cavity between levels. It is recommended that sprinkler protection always be considered in modular buildings; in the event that it is not provided, other measures should be taken.

B5.0.0.15
As of 2016, the *NCC* [6.2] permits the use of timber construction systems as a Deemed-To-Satisfy solution for Class 2, 3 and 5 buildings up to 25 m in effective height. Necessary fire engineering measures in this case include:

i. Compliant sprinkler systems
ii. Encapsulation
iii. Non-combustible insulation in cavities
iv. Use of cavity barriers

For further details, see NCC Volume 1 Part C1.13 and Specification C1.1 3.1(d)(iii).

B6 Acoustics

B6.0.0.1
Acoustic privacy is a significant issue that should be considered in *Modular Construction*. Along with thermal insulation, acoustics play a significant role in how partitions are designed in a building, and factor into what construction elements constitute an acceptable solution.

B6.0.0.2
Sound can be described as any propagation, that can be heard or felt, of vibrations through a medium, e.g. air. Generally, one can define a sound by two of its main characteristics: frequency (pitch) and amplitude. Frequency is measured in Hertz and in building acoustics most of the standards define the 100Hz – 3150Hz as the range of interest. Due to the physiological nature of the human ear, the amplitude of a sound is measured using the logarithmic decibels (dB) scale. The reduction of dB of sound going through a partition (wall or floor) is defined as sound insulation, and it is the primary characteristic of a construction element with respect to acoustics. There are two types of sound insulation: Airborne sound insulation and Impact sound insulation.

B6.0.0.3
Airborne sound insulation is the capacity of a material separating two spaces to minimise the transmission of noise originating in air, e.g. voices, music, traffic, etc. through a partition. Impact sound insulation noise makes reference to the acoustic energy transmitted through solid structures e.g. footsteps, jumping, and dropped objects. Impact sound transmission arises because the impact causes the building elements to vibrate, which in its turn generates sound waves.

B6.0.0.4
The acoustic performance of a partition is commonly described by a single number. For Airborne Sound Insulation, the weighted sound reduction index R_w is utilised as described in **AS/NZS ISO 717.1** [5.41]. This standard fits a standard reference curve to the measured sound reduction index curve.

Similarly, the single descriptor $L_{n,w}$ describes how easily impact sound travels through a wall or floor. Unlike R_w values, where the greater the value, the better the performance, the $L_{n,w}$ are maximums, therefore the lower the number the better acoustic performance a partition will achieve.

There is furthermore the Spectrum Adaptation Term C_{tr} which takes outside traffic noise into consideration.

B6.0.0.5
The ABCB Handbook “Sound Transmission and Insulation in Buildings” [6.34] provides the following guidance on acoustical performance. The sound insulation performance of building elements can be improved by[2]:

i. Increasing the mass of the material;

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[2] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

ii. The use of additional skins of material, typically with a cavity;
iii. Increasing the depth of cavities;
iv. The use of limp materials or materials with low stiffness; and
v. The addition of damping, especially to thin stiff elements in a partition system.

The amount of structure-borne noise can be reduced by increasing the vibration isolation in a system. This can be done by:

vi. Using a suitably soft connecting material such as rubber, neoprene or isolation springs between the elements within a building element;
vii. Designing and installing a break in continuity of a panel, for example using double studs (not touching) instead of large single studs;
viii. Increasing the size of the air gap or cavity between panels; and
ix. Introducing vibration isolated floors to adjacent rooms located on a common slab.

B6.0.0.6

Building construction codes will generally impose limitations on the transmission of sound between adjoining rooms. The *Designer* or acoustical engineer in Australia should ensure compliance with relevant provisions in the *NCC* [6.2] and utilise the standards quoted therein. The following are relevant:

i. *NCC* Part F5 (Volume 1) for Class 2, 3 and 9c building;
ii. *NCC* Parts 2.4.6 and 3.8.6 (Volume 2) for Class 1 buildings;
iii. **AS/NZS ISO 717.1 Acoustics – Rating of sound insulation in buildings and of building elements – Airborne sound insulation** [5.41];
iv. **AS 1191 Acoustics – Method for laboratory measurement of airborne sound transmission insulation of building elements** [5.42];
v. ABCB Handbook “Sound Transmission and Insulation in Buildings” [6.34].

Compliance with the *NCC* provisions can be achieved either through Deemed-to-Satisfy solutions or alternatively through expert opinion or lab testing.

> Whilst providing an expert opinion is a means by which compliance with the *NCC* can be achieved, it does not necessarily imply that the *Performance Requirements* have been met. Testing is the most accurate means of establishing acoustical performance, although the testing procedure should be rigorous; simply testing the acoustic performance of e.g. a new type of wall panel against a Deemed-to-Satisfy solution may not be sufficient if the latter does not in fact meet the Performance Requirements. For example, Specification F5.2 Table 2 provides the Deemed-to-Satisfy solution of 150-mm-thick concrete panels which may not in fact be “sufficient to prevent … loss of amenity to the occupants”, as specified by the NCC Performance Requirements FP5.1, FP5.2, FP5.4 and FP5.5.

B6.0.0.7

The exact requirements will depend on the Class of the building under consideration; only residential buildings (Class 2, Class 3 and Class 9c) have requirements defined in the *NCC* building code. Compliance can be achieved either through Deemed-to-Satisfy solutions or alternatively through expert opinion or lab testing. The *NCC* Section F5.5 mandates the following conditions[3]:

i. $R_w + C_{tr}$ not less than 50 for walls separating sole occupancy units (SOUs). Discontinuous construction is required if the wall is separating a bathroom, sanitary compartment, laundry or kitchen in one SOU from a habitable room (other than a kitchen) in an adjoining unit.
ii. R_w not less than 50 for walls separating SOUs from a plant room, lift shaft, stairway, public corridor and public lobby or the like or parts of a different classification. Discontinuous construction is required if the wall is separating a SOU from lift shafts or plant room.
iii. $R_w + C_{tr}$ not less than 40 for separation of services abutting habitable rooms.
iv. $R_w + C_{tr}$ not less than 25 for separation of services abutting non-habitable rooms.
v. R_w not less than 30 for apartment entry doors.
vi. $R_w + C_{tr}$ not less than 50 and $L_{n,w}$ not more than 62 for floors.

Discontinuous construction is defined as a wall having a minimum of 20 mm cavity between 2 leaves and:

vii. For masonry, where wall ties are required to connect the leaves, the ties are of the resilient type.

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[3] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

viii. For other than masonry there is no mechanical linkage between leaves except at the periphery. Staggered studs are not deemed to be discontinuous.

B6.0.0.8

For building types that are non-residential such as schools, medical buildings, retail spaces, etc. appropriate standards would be required for each specific state or territory.

B6.0.0.9

Modular Construction can involve floor discontinuities, complex connections and lightweight materials. This may lead to significant contributions to sound propagation (particularly between floors) from “flanking paths” (i.e. where the sound takes an indirect path to reach an adjoining volume); generally, the sound propagation will be more complicated than for a conventional construction with continuous concrete slab floors. The available acoustic analysis tools work better for transmission through walls than through floors; rigorous testing is thus advised as the ideal approach to evaluating acoustic performance in this type of construction.

Rigorous acoustic testing is not presently common in the Australian construction industry, and any data collected is not generally openly available. Given the added complexities present in Modular Construction, there is an increased importance that testing is performed. There is the potential here for Modular Construction to provide the opportunity to improve sharing and communication within the industry of acoustical testing data, which may lead to more detailed, efficient and cost effective acoustical solutions.

B6.0.0.10

In addition to noise from adjoining modules, another source of acoustic disturbance for users is the intrusion of noise from the external environment, which may include from the subject building itself or neighbouring buildings. Predictable noise sources may include:

i. Road traffic
ii. Rail traffic
iii. Tram traffic
iv. Aircraft traffic
v. Adjoining occupancy/land use noise as permitted by zoning (whether actually present at the time or not)
vi. In-house mechanised services
vii. Other in-house services from hydraulics or drainage

B6.0.0.11

Finally, consideration should be given to footfall vibration. While the effect of the footfall vibration should be taken into consideration in the airborne and sound impact insulation, it is common to perceive the footfall noise and vibration as a potential issue in modular buildings. For this reason, in the event that this is a critical issue for the type of building, it is recommended to collaborate with the structural engineer in order to model the dynamic response of the floor and dampen it where required.

B7 Sustainable Thermal Regulation

B7.0.0.1

Thermal regulation refers to measures taken to ensure that the temperature in the module does not stray outside a reasonable range for occupant comfort and structural stability. The manner in which this is implemented can have implications for the sustainability of the building. Consideration should be given to what measures could be taken to achieve a sustainable solution.

B7.0.0.2

When considering measures to ensure thermal regulation, the *Designer* may wish to take into account the pressure envelope, which is the primary air barrier enveloping an occupancy volume which reduces air leakage, and the thermal envelope area, which is the total surface area bounding the occupancy volume. The manner in which these envelopes are implemented in terms of materials and structures will have varying effects on the efficiency and sustainability of the solution.

B7.0.0.3

Measures which may be necessary for thermal regulation include condensation control, air infiltration, thermal insulation and heating and cooling.

B7.0.0.4

Building materials and insulation should be chosen in such a way as to maintain a reasonably comfortable temperature within any occupied areas. The *Designer* can make reference to material standards or datasheets to determine coefficients of heat transmission.

B7.0.0.5

Appropriate measures should be taken to limit air infiltration so as to reduce heat loss/gain, including around any envelope penetrations (e.g. plumbing, mechanical, electrical, and window and door frames) and at joints or connections between elements. *Modular Construction* presents an opportunity here, given the factory setting, to perform factory acceptance testing of building modules using thermal imaging or leakage tests.

B7.0.0.6

Sealing of the building environment to prevent heat transfer may have the unwanted side effect of trapping moisture from condensation. The build-up of moisture in an internal space can lead to mould, resulting in property damage and health *risks*. The *Designer* should ensure that there is adequate ventilation in wall cavities, roof cavities and any other enclosed spaces to dissipate condensation.

B7.0.0.7

The *Designer* should be aware of situations where countermeasures against thermal leaks are compromised by thermal bridging between the interior and exterior. For example, double glazed windows which are intended to reduce heat transmission may sit in a metal (e.g. aluminium) frame which could provide a pathway through which heat can travel. Whilst solutions to this may be expensive (such as using frames which are thermally "broken"), it is important nonetheless that the *Designer* is aware of these issues.

B7.0.0.8

Modular Construction can provide the opportunity to develop cost-effective solutions to problems such as thermal bridging, through the repeated manufacture and refinement of modules in controlled factory conditions. The *Manufacturer* should consider integrating research and development into the production process to develop innovative solutions.

B7.0.0.9

The *Designer* should pay careful attention to air movement in the gaps between modules. This is not a consideration that would normally arise in conventional construction. Building regulations typically distinguish between conditioned and non-conditioned zones, and this has implications for thermal insulation requirements. For example, where the building façade is not sufficient to prevent the movement of air into the gaps between modules, those gaps would then be considered a non-conditioned zone, and each module would then need to be more thoroughly insulated. This will be a more expensive solution then ensuring a well-sealed façade.

B7.0.0.10

A modular design may include façade elements pre-fitted to the modules. The *Designer* should consider carefully how to ensure that these façade elements form a proper seal to the movement of air, whilst at the same time accounting for the possibility of differential thermal expansion and contraction which could lead to damage (e.g. where adjacent façade elements impact on one another). A possible solution is to use façade elements which are slightly larger in area than the external module face (so that gaps are minimised) with the use of rubber grommets or silicon seals between façade elements to provide a thorough and yet flexible seal.

Europe generally mandates a higher performance than Australia in the area of controlling the building environment with respect to heat transmission. While a design may meet the *Performance Requirements* mandated by the *NCC* or relevant standards in Australia, the *Designer* may consider aiming higher. *Modular Construction* may present some opportunities for finding cost effective solutions to achieving higher performance.

C

Chapter

Facades

C Façades

C0.0.0.1

The simplest description of the façade of a building is the exterior surface as seen by those outside, typically the vertical wall-like elements. This surface (including others such as a roof) is also the interface of the building with the surrounding environment and must fulfil a range of functions, some of which are addressed by Regulation.

C0.0.0.2

The façade may be incorporated into the main building *load-bearing* structure (e.g. *prefabricated concrete* wall panels) or may be a separate non-*load-bearing* element relying upon the building frame for support (e.g. a curtain wall). In this case it is still required to perform structurally if only to be self-supporting against immediate actions. The façade initially bears all wind actions before transferring these forces into surrounding framing, as is the case for individual windows.

C0.0.0.3

Design and construction of curtain walling for buildings, as a non-*load-bearing* façade, has grown in popularity. This type of façade is a generic description of a light, secondary, rigid framing system filled or covered with a lightweight cladding. This description may be applicable also to typical exterior wall construction detailed for building modules. Curtain walling permits some scope for prefabrication and has arisen from the following demands [8.1]:

i. **Smaller wall footprint** – provides extra floor area
ii. **Parallel scheduling** – enables faster erection
iii. **Lighter structure** – provides material and transportation savings
iv. **Structural flexibility** – easier seismic engineering
v. **Improved light access** – enhances the environment architecturally
vi. **Structural independency** – provides a more flexible architectural layout

These considerations overlap with the drivers and benefits of *Modular Construction* generally. Ideally, the component modules making up a building are each manufactured with their portion of a complete and fully functioning façade already in place (assuming the modules in question are not totally internal within the building). In this approach, it would still be required that continuity of façade performance across junctions between modules be completed on site.

C0.0.0.4

For both the transportation and erection phases of a *Modular Construction* project (particularly in the case of volumetric modular construction), the *Designer* should give consideration to protection of the façade elements. This could potentially take the form of a protective film, or foam packaging.

C0.0.0.5

For the erection phase of modules the *Designer* should consider ways to simplify the completion of façade junctions between modules on-site, accounting for:

i. Coordination of *tolerances*
ii. Ease of completing functional connections and verification
iii. Ease of subsequent inspection and maintenance
iv. Shrinkage and creep issues

C1 Environmental interface effects

C1.0.0.1

According to Kazmierczak [8.1], aside from any *load-bearing* role, and acting purely as a building envelope to protect the interiors, the façade performs the following additional controls:

i. **Rain** – controlled by waterproofing, seals and screens
ii. **Sun** – controlled by shading and coating
iii. **Heat Flow** – controlled by thermal insulation, low emissivity and absorptivity surfacing
iv. **Light** – controlled by shading and coating
v. **Wind** – controlled by a continuous path of structural resistance
vi. **Windborne Debris** – controlled by opening protections
vii. **Blast** – controlled by a continuous path of structural resistance
viii. **Water Vapour** – controlled by configuration of vapour retarding and permeable layers
ix. **Air flow** – controlled by air barriers
x. **Aggressive Airborne and Waterborne Chemicals** – controlled by adequate coatings
xi. **Wildlife** – controlled by bird nets, termite barriers, baffles, etc.
xii. **Dirt Accumulation** – controlled by sloping configuration, hydrophilic surfaces.
xiii. **Snow** – controlled by sloping, parapet, and ledge configuration, heat traces, etc.
xiv. **Flood** – controlled by openings
xv. **Hail** – controlled by resistive layers
xvi. **Earthquakes** – controlled by ductility and movement joints

xvii. **Noise and vibrations** – controlled by addition of mass, damping, skewing and distancing layers
xviii. **Maintenance Loads** – controlled by means of access and a continuous path of structural resistance
xix. **Fire** – controlled by thermal resistive layers
xx. **Smoke** – controlled by smoke and air resistive layers
xxi. **Theft** – controlled by organic glazing layers, shutters, steel plating, and openings hardware
xxii. **Normal Wear and Tear** – requiring maintenance and inspection access

C1.0.0.2

These functions reflect users' expectations and many have related provisions in Regulation. Anecdotally the common façade performance failures typically relate to [8.1]:

i. **Condensation and Frosting** – inadequate heat flow performance
ii. **Glare** – inadequate light control
iii. **Noise** – inadequate sound mitigation or generation of the inborn noise by the wall itself
iv. **Leakage** – inadequate rain water resistance
v. **Glass breakage** – inadequate impact resistance, differential movement, or material failure
vi. **Free fall of wall fragments** – inadequate structural attachment
vii. **Aesthetic imperfections of glass and coatings** – miscellaneous reasons
viii. **Corrosion** – inadequate corrosion protection, galvanic action of dissimilar metals, etc.

Of these, glass breakage and free fall of debris are the most immediate safety concerns, with corrosion as a related causal factor. Since the façade is the ultimate exterior of the building, it is likely there are no additional containment measures to rely upon to control debris.

C1.0.0.3

Although not a corrosion effect, the potential for degradation of materials via ozone cracking should be considered. Typically this may be relevant to sealing systems and those having any content of susceptible rubber compounds.

C1.0.0.4

The *Designer* should give consideration, as a priority, to the safety of people who may be impacted from façade debris. This may include the use of lighter, stronger materials and greater *reliability* or redundancy in connections.

C2 Exposure and Access

C2.0.0.1

Further to these failure sources the attributable causes for these façade performance failures can be categorised as follows [8.1]:

i. **Design Errors and Omissions** – e.g. improper choice of materials and systems
ii. **Materials without proven performance** – e.g. insufficiently tested glass coating technologies
iii. **Deficient Shop Fabrication** – e.g. failure to detect early and prevent through QA and QC.
iv. **Deficient Field Installation** – e.g. inadequately secured connections
v. **Improper or Deterred Maintenance** – e.g. underfunded maintenance budget, improper or missing staff training, omission of commissioning the design to provide an Operation Manual
vi. **Ordinary wear and tear** – e.g. critical, higher risk materials not monitored

C2.0.0.2

The *Designer* should consider the relative expense likely to be involved in correcting any failures on site when compared to the initial economies of *Modular Construction*. A corresponding degree of *Reliability* from the façade system should be factored into the design. That is, an assessment should be made of the probability of façade failure and the consequent repair costs, which may outweigh the benefits of pre-installation of the façade in the first place.

C2.0.0.3

The *Designer* should ensure that material properties and system installations relied upon for façade performance and safety are adequately verified.

C2.0.0.4

In addition to the physical performance of the exposed exterior building components (whether expressed structure or façade cladding), the exposure may also impose appearance requirements. These requirements should be specified for construction, inspection, maintenance and replacement.

C3 Building connectivity

C3.0.0.1

Façade elements and façade systems may or may not be *load-bearing* and to a degree may rely upon the building frame for support. In all cases however, the façade is the most environmentally exposed element of the building. Implications of this for connections to the building include:

i. Wind-induced pull-out loads on façade anchors
ii. Wind-induced compression loads on façade connection fixtures
iii. Thermal distortion gradients between façade elements and building frame
iv. Relatively aggressive corrosion *risk* (compared to internal building components) for the façade exterior and the support connections behind

C3.0.0.2

Regarding wind action, the façade is the element that initially gathers wind load and transfers it to the main structure. This may also involve localised effects should the façade design include features such as louvres or shade screens.

It should also be noted that being the absolute exterior of the building presents issues for façade inspection and maintenance, as well as additional consequent *risk* should any debris become dislodged. The *Designer* should consider the reliability of connection systems accordingly. See **Section A2** for additional guidance concerning connection design.

C3.0.0.3

Where there is potential for relative movement between façade connection locations due to the response of the building frame, the *Designer* should ensure this is compatible with façade performance and capacity.

The corresponding case should also be checked where the façade may respond to certain conditions (e.g. thermal expansion) but is restrained by the building frame.

C3.0.0.4

Sufficient tolerance in connections shall be provided by the *Designer* to ensure that no additional loading that has not been designed for is placed on the façade elements. This requires consideration of the deflection of structural elements (in both the short and long term), and both wind and seismic loading and inter-storey drift. Furthermore the façade system should be designed to accommodate the same dimensional and connection *tolerances* as specified for the structural framing.

C3.0.0.5

Completed junctions between adjoining façade elements (particularly concerning waterproofing) should preferably be formed with minimal additional work on site.

C4 Design to resist loading

C4.0.0.1

The design of façade elements should generally be in accordance with the relevant design codes and should take into consideration all relevant loading, which can be determined from appropriate design standards (see **Section A1**). At a minimum, consideration should be given to the following:

i. Self-weight loading
ii. Wind loading (can be determined from the relevant design code or wind engineer's report depending on the project)
iii. Any thermal expansion or contraction effects
iv. Human impact
v. Projectile impact
vi. Additional loading during transportation and erection

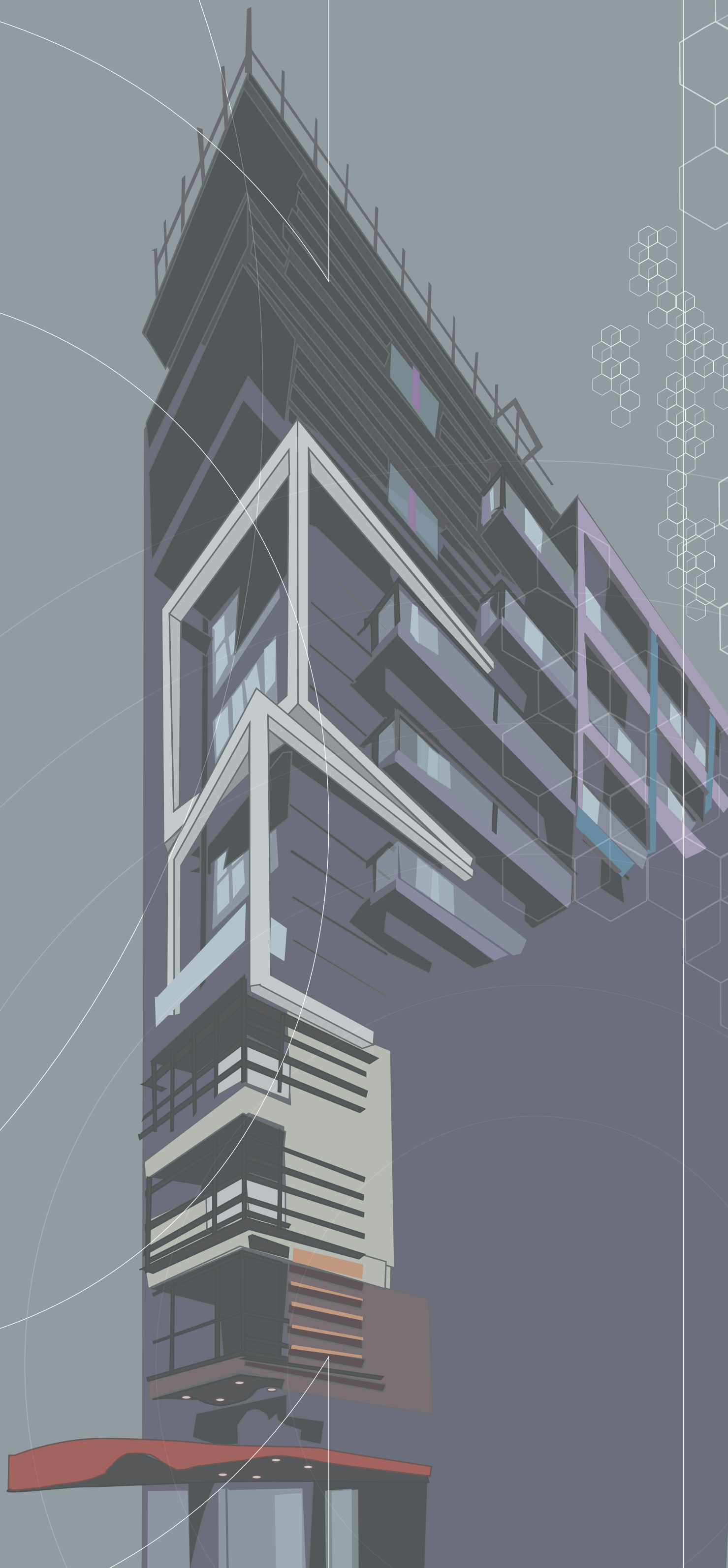
Material design standards can be utilised to determine efficient sizing for structural actions. Guidance on the use of glass in buildings can be found in **AS 1288-2006** [5.28].

C4.0.0.2

Design by testing can also be undertaken. Guidance on the testing of façade systems can be found in **AS/NZS 4284-2008** [5.29].

D Chapter

Architecture



D Architecture

D1 Construction methodology

D1.0.0.1

The choice of construction methodology should be made early in the design process to enable optimal construction solutions. The *Designer* should not generally attempt to adapt an existing project at a late stage to the modular construction methodology. In line with the principles of *Design for Manufacture and Assembly*, the entire building or structure, and the components comprising it, should be considered as part of a holistic design process. With this overarching perspective, possibilities for modularisation can then be sought, which may result in changes to the overall design to fit the modular system. This constitutes an iterative rather than linear process, which emphasises the importance of early design decisions.

D1.0.0.2

Designers and *Manufacturers* should work closely together to ensure that the structural systems and solutions are innately compatible with the intended design.

D1.0.0.3

The *Designer* may or may not wish to expose the construction methodology, depending of a number of considerations. Using structural timber (e.g. cross laminated timber) as an example, in some cases an exposed timber appearance may be desired by the client for its aesthetic appeal; in other cases, the structural timber may be hidden due to perceptions that timber may not be as solid a material as other, more conventional, building materials.

D1.0.0.4

In the case of volumetric modular construction, the appearance of the building need not betray its underlying construction methodology, although this can depend on the *Designer's* intent.

D1.0.0.5

The optimal architectural solution and the potential for a modular construction approach will require consideration of the following factors involving the site context:

i. Accessibility for module delivery and cranes
ii. Proximity to services and site encumbrances
iii. Complexities of urban settings (site access & services restrictions)
iv. Distances from manufacturing centres

It should be noted that the more challenging these elements, the more expensive the construction solution. Some of these considerations are not specific to modular construction; however, the unique requirements of modular construction, e.g. lifting very heavy modules, may present novel challenges.

D2 Module design

D2.0.0.1

The *Designer* should consider how the geometry of the constituent modular components may depend on a range of considerations, including:

i. Limitations to the structural systems needed to develop the architectural solution
ii. Adherence to the desired internal planning and external imagery
iii. Logistical constraints: widths, heights, lengths and weight of the modules being transported

D2.0.0.2

The manner in which the completed structure will be divided into submodules will affect the nature of what internal layouts and floor plans are possible or feasible. The *Designer* should account for this early in the design process.

D2.0.0.3

The *Designer* should consider where external or internal finishes can become part of the modular components. This will depend on the positioning and orientation of such finishes relative to the structural planes of the components, as well as the nature of the materials and whether they can withstand the transportation process.

D2.0.0.4

Government regulations may require certain finishes, for example masonry cladding in built-up urban areas. This will have to be accounted for in the design process. The *Designer* should consult the relevant local standards and codes for their jurisdiction.

D2.0.0.5

Consideration will have to be given to the interface between in-situ and modular components. This may involve:

i. Coordination between footings or sub-structure systems and the modular components

ii. Coordination between lift and stair cores and the modular components on larger projects

D2.0.0.6

For all interfaces, the junctions need to be considered both structurally and architecturally. Structural considerations are detailed in **Chapter A**; for architectural considerations, the *Designer* should consider how the seal for a junction of dissimilar materials may be designed so as to appear to belong to the overall architecture, rather than being an obvious added cover.

D2.0.0.7

The *Designer* should consider how the detailing of the junctions between components may be executed so as to not give the impression of the structure being simply a collection of parts.

D2.0.0.8

The *Designer* should be aware, when considering a modular construction methodology, of the risk that an over-emphasis on standardisation of modules, due to the obvious economic arguments, could unduly constrain other aspects of the design. For example, the use of a single type of bathroom pod, with fixed dimensions, throughout a large construction project, may result in mismatches in dimension with the surrounding structure. The impacts of pursuing such a modular approach on architectural expression and quality should be considered.

D2.0.0.9

Consideration should be given to incorporating parametric design into the modular approach, whereby a “standard module” need not be fixed in every parameter in order to achieve the economies of scale. Rather, the use of advanced digital design tools and fabrication equipment can allow for a reasonable range of variation away from a standard module, so as to allow for somewhat bespoke and individualised modules on a single project.

D3 Modular Form

D3.0.0.1

Modular Construction broadly aims for greater degrees of prefabrication. Maximised prefabrication and elimination of in-situ work might seem to be the goal, except for quite small isolated buildings and other structures (as might fit conveniently on road transport) it is usually the case that further assembly and connection work of modules is done on site. The goal remains maximised efficiency of all resources to meet the project requirements, full compliance with applicable Regulation and management of all *risks*. **Figure D1** illustrates the continuum of prefabrication from simple raw materials processed into basic building fabric (e.g. clay bricks, seasoned/dressed timber) through to completed volumetric buildings.

The differences between volumetric and non-volumetric modular construction are in the extent of prefabrication and timing of the various elemental connections around when the transportation to site and erection/assembly occur.

D3.0.0.2

The appropriate degree of prefabrication will depend heavily on the specifics of the project under consideration. For example, employing a full volumetric modular approach (see **Section D3.1** below) may involve a large degree of structural and material redundancy, since already-structurally-sound modules are placed side by side. This extra material cost may only be offset for projects of a certain nature, e.g. projects such as hotels involving significant repetition of standardised, fully fitted out rooms. In other instances a panelised approach may be more sensible, such as apartments which may involve a substantially lower cost fit out.

D3.0.0.3

The modular form may be constrained by practical issues such as logistical considerations. Volumetric modules (see **Section D3.1** below) occupy a much greater volume relative to the amount of material involved, which presents some challenges when it comes to storage and transportation.

D3.0.0.4

The great variation in conditions and circumstances from project to project makes it difficult to prescribe any particular variant of *Modular Construction* methodology. The *Designer* should make a detailed assessment early in the design phase to determine what methodology, or hybrid of methodologies, may be appropriate, given specific information about the project, including:

i. Location (including transport and site access details)
ii. Building dimensions
iii. Intended building purpose (e.g. hotel, apartment, office)

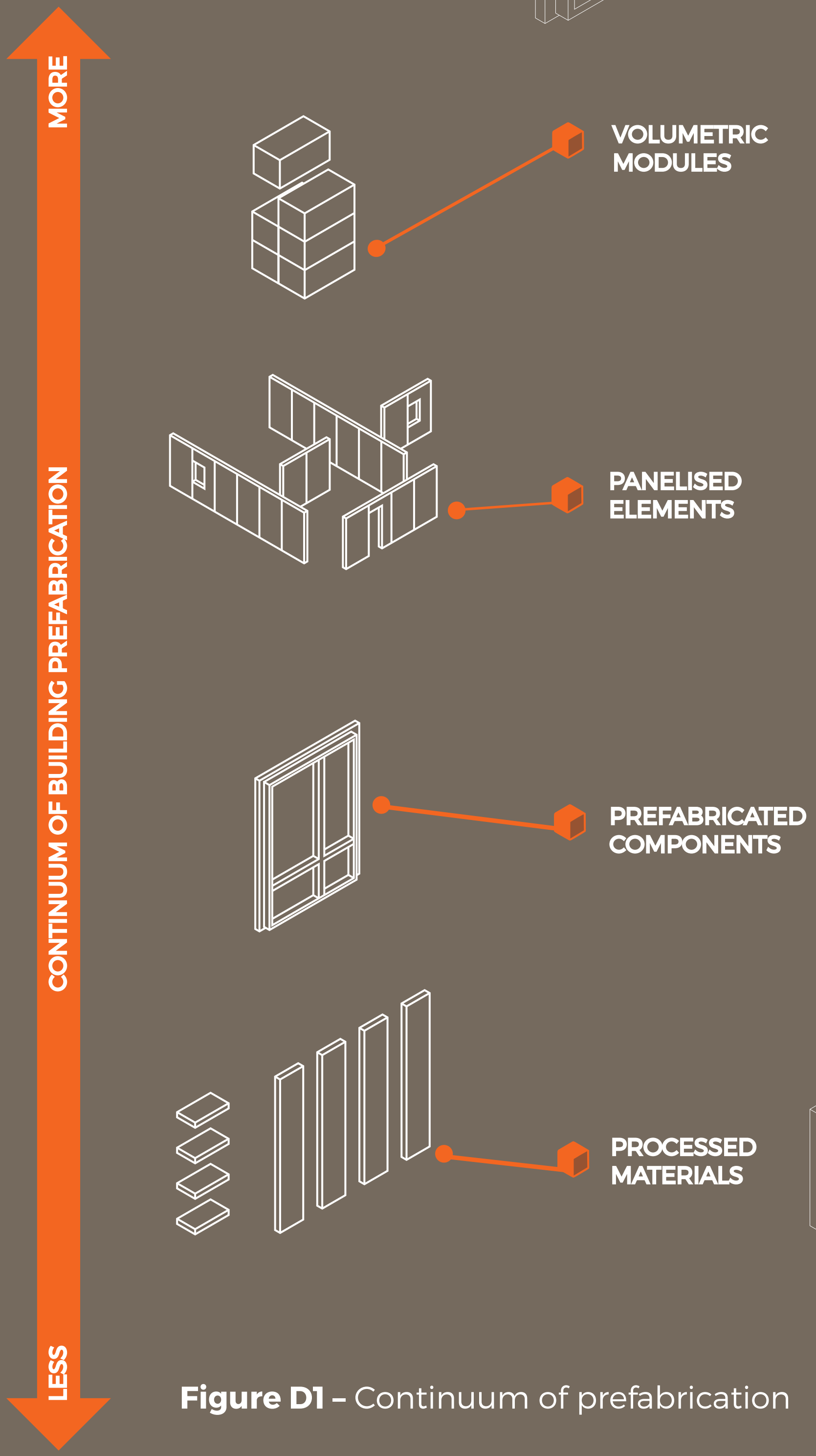


Figure D1 – Continuum of prefabrication

D3.0.0.5

The appropriate degree of prefabrication for a given project requires thorough consideration of a variety of influencing factors such as constructability, cost, quality, safety, productivity, efficiency and ease of engineering design and delivery. The following criteria may be considered:

i. Availability of standard process for the system
ii. Controllable construction tolerances
iii. Site health, safety and security
iv. Quality inspection and supervision
v. Mechanical, electrical, and plumbing coordination
vi. Role in structural performance e.g. stability and integrity
vii. Durability of the system and effect on the entire building
viii. Effects on construction completion time
ix. Repetitive/standardised components
x. Vulnerability to weather conditions
xi. Providing flexibility in time management
xii. Ease of implementation of planning and engineering details
xiii. Onsite maintainability issues
xiv. Required pre-construction time (design, planning, procurement)
xv. Maintenance and operation costs
xvi. Initial capital cost
xvii. Ease of obtaining green/environmental certification
xviii. Level of involvement in waste generation
xix. Level of construction pollutants at site
xx. Amount of disturbance at the jobsite
xxi. Reusability of materials and components
xxii. Complexity of design
xxiii. Design predictability at the early decision-making stages
xxiv. Design flexibility (low limitation in design variation)
xxv. Ease of fabrication
xxvi. Vulnerability to space (space constraints)
xxvii. Availability of skilled labour
xxviii. Ease of manoeuvrability on construction site
xxix. Ease of delivery/supply of components to the site
xxx. Vulnerability to post design changes

D3.1 Volumetric Modular

D3.1.0.1

Volumetric *Modular Construction* describes modules which are complete with enclosed space for the use of occupants. Each module may be a complete structure in itself (e.g. a construction site shed or accommodation unit) or may be one of many units in a larger project requiring inter-unit connections on site (e.g. a multi-storey hotel). The Volumetric form represents the technical peak of *Modular Construction* although it may not always be the optimal approach for project success.

D3.1.0.2

A distinctive aspect of volumetric *Modular Construction* is that the *Designer* should consider is the response of completed modules being subjected to all handling and transportation actions.

D3.2 Non-Volumetric Modular

D3.2.0.1

Non-Volumetric *Modular Construction* describes modules, or more correctly termed **elements**, which are connected once on site to create the enclosed space for occupant use. The elements may be transported more compactly than those for volumetric modular which, for relatively lightweight elements (e.g. timber wall frames or cold-formed steel roof trusses or Cross Laminated Timber panels), may minimise transport costs (albeit offset by additional assembly works and expense on site).

D3.2.0.2

A consequence of non-volumetric *Modular Construction* is that only the elements as packed for shipping must be detailed for transportation and handling, not the assembled modules. Until completed spaces for end-use are created on site, the *Designer* may need to consider all exposed surfaces of all elements as potentially exterior and propose appropriate details.

D3.2.0.3

It is common for non-volumetric *Modular Construction* to require temporary works to provide interim safe support for the site conditions until incorporated into the project building structure. A temporary works *Designer* should specify all measures required and liaise with the project *Designer* concerning staged introduction and eventual removal of any required temporary works.

D3.2.1 Panelised

D3.2.1.1

Panelised non-volumetric *Modular Construction* is typically relatively thin in nature, compared to other major dimensions. Conceptually a panel would span between an arrangement of supports. For this reason individual masonry units (bricks, blocks) would not be included. Common types of panelised non-volumetric *Modular Construction* include:

i. Prefabricated reinforced concrete elements such as wall panels, beams and columns (both cast off-site and cast on-site)
ii. Cross Laminated Timber
iii. Autoclaved Aerated Concrete (AAC) panels
iv. Sections of building façade
v. Sections of safety screen (during construction)
vi. Floor cassettes (typically timber)
vii. Floor planks (typically concrete)
viii. Wall frames (typically timber or cold-formed steel)
ix. Roof trusses (typically timber or cold-formed steel)

Structurally, solid panelised elements offer significant in-plane shear capacity which can be mobilised once connections are complete. Wall frames, based on typical stud, plate & nogging arrangements, can be pre-braced also to harness this performance but often it is preferred to brace them after installation to allow inter-frame joint and connection adjustments.

D3.2.2 Flat Pack

D3.2.2.1

So called “Flat Pack” *Modular Construction* has similarities to the panelised form but with greater coordination required to ensure adjoining panels and elements are supplied together. Further to this the Flat Pack elements should be ordered so that each element may be erected/assembled directly and without the requirement for elements stacked beneath it. Put simply, the Flat Pack elements should be packed in the order that allows the *Builder* to erect them without double-handling.

D3.2.3 Framing

D3.2.3.1

Further to the description of panelised non-volumetric *Modular Construction* other individual framing elements (what might be termed line elements) requiring erection and structural connection on site include prefabricated:

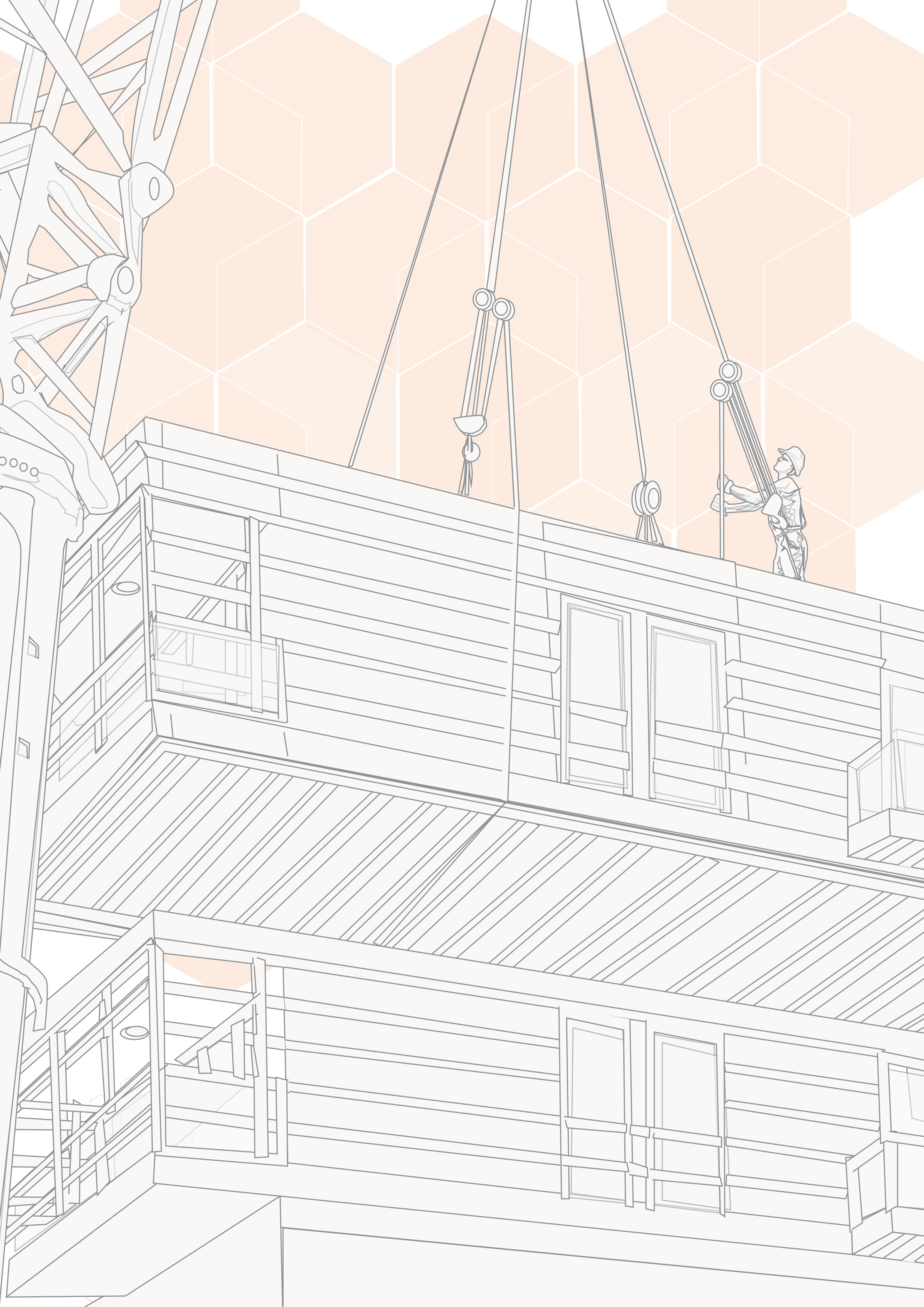
i. Beams
ii. Columns
iii. Portal frames (non-braced)
iv. Bracing
v. Pile caps
vi. Purlins/girts

Physical size and weight of the designed elements, and the availability and value of handling logistics tend to be the main considerations for guiding the *Designer* concerning which modular form to adopt.

E

Chapter

Materials
& Manufacturing



E Materials and Manufacturing

E0.0.0.1

One of the primary aims of *Modular Construction* or *Design for Manufacture and Assembly* is to improve quality, whilst minimising wastes. This is generally achieved by moving from a more traditional in-situ construction model, to a model geared towards manufacturing (i.e. more control over quality and environment). This section provides guidance on the general particulars that may be encountered during the manufacture of a modular system.

E1 Manufacturing

E1.0.0.1

The *Designer* should ensure that any minimum regulatory design requirements are met regarding the *NCC* [6.2] for the completed building, and *WHS* [2.3] for construction & safety in design. The *Designer* should optimise the details of the building fabric, connections for services, commissioning and all inspection requirements (such as ease of access) to serve the purposes of efficiency in manufacture, handling, transport and erection.

E1.0.0.2

The *Designer* should work closely with the manufacturer to ensure they account for the capabilities of the manufacturing facilities. The following considerations are pertinent:

i. The design should minimise the need for construction of special sections and/or details; this is to ensure that the design may be constructed largely with “off-the-shelf” components with minimal fabrication needed, reducing costs.
ii. The design should be able to be manufactured with tools readily available at the place of manufacture.
iii. If special fabrication is required, the *Designer* should work with the manufacturer to develop a fabrication process which is relatively efficient, is realisable with the available facilities and achieves the design requirements.

E1.0.0.3

The *Manufacturer* should ensure that:

i. All components/materials used in the manufacture of modules or modular components meet minimum specified design requirements (e.g. strength, thickness, etc.).
ii. Regulated components (e.g. such as fire-rated walls) used in the manufacture of modules meet the *Performance Requirements* designated as per the relevant Codes, Standards or contractual specifics.
iii. Services installed during manufacture meet the relevant Codes and Standards for the jurisdiction in which the modules or modular components will see final application.
iv. Documented inspection procedures are in place to ensure all workmanship complies with specifications (either from design or from appropriate Codes and Standards).

E1.0.0.4

Depending upon the module, prefabricated system or component being considered, it may be useful, from an erection viewpoint, for the *Designer* or manufacturer to incorporate a placement aid for locating a component within the structure to simplify on-site work.

E1.0.0.5

The *Designer* should make provision for the protection of services (particularly regulated services such as plumbing and electrical facilities) within the modules to withstand the predicted vibration effects from module transportation and handling. Such measures may include the specification of flexible, resilient and/or damped mounts or bushes at supports.

E1.0.0.6

The *Manufacturer* should ensure that all completed modules and products released for delivery and erection are safe for all aspects of required manual handling. *Risks* can arise from:

i. Cut metal edges
ii. Exposed screw tips and nails
iii. Abrasion of insulation materials resting on metal edges (see **Figure E1**, which demonstrates measures taken to protect electrical wiring from abrasion)
iv. Pinch points in connections
v. Surfaces which can retain rainwater
vi. Activities requiring work at heights

E1.0.0.7

Where dimensional control of manufactured components is used (e.g. templates, framing jigs, computer numerical control machinery) from which subsequent connections on site will be made these controls should be checked and/or calibrated at appropriate intervals.

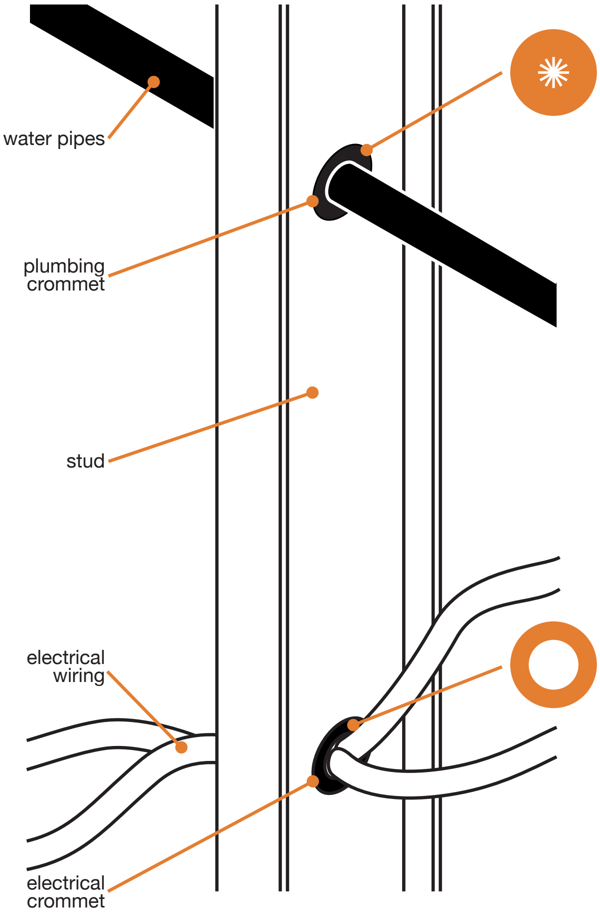


Figure E1 – Typical grommet details to protect from metal abrasion

E2 Tolerances

E2.0.0.1

Tolerances are necessary due to the practical inability to make anything to an exact measure. Further to this there is a distinction between *accuracy* and *precision*. *Accuracy* refers to how close a measure is to the correct value, whereas *precision* refers to the consistency in repeated measurements.

E2.0.0.2

Aspects of *tolerances* applicable to *Modular Construction* which the *Designer* and *Builder* should consider include:

i. Coordination of accepted design *tolerances* between interfacing elements and processes, particularly:
   a. off-site manufactured products for erection and/or assembly on site
   b. *tolerances* for structural erection and those for cladding, services and finishes
ii. Measurement *accuracy* of properties to assess *tolerance compliance*
iii. Calibration to a standard of the means of measurement
iv. Independence of *tolerance compliance verification*
v. Progress hold-points until *tolerance compliance* of previous steps are verified
vi. Suppliers of the processed product should be responsible for specifying relevant *tolerances* and then should demonstrate *tolerance compliance* for their product

Tolerances regarding workmanship similarly require a process for inspection and assessment. Refer to **Section H4.2** regarding dimensional *tolerances* for erection.

E2.0.0.3

The *Designer* should clearly state all design *tolerances* including but not limited to:

i. Required physical properties of all materials
ii. *Tolerances* in physical dimensions (e.g. *tolerances* for bolt holes)
iii. Minimum additional length for electrical and data cables to ensure ease of connection on site
iv. *Tolerances* in service connections (for example, plumbing connections may require some flexibility to account for imperfect alignment)

This will help to ensure ease of manufacture and assembly on-site. The manufacturer should ensure that *tolerances* indicated in the design are incorporated into, and/or met by, the manufactured module or component.

E2.0.0.4

The *Designer* should be aware of prevailing or common industry tolerance expectations and highlight where differences are required for the *Modular Construction* project. Typical *tolerances* for material quality, fabrication and erection dimensions for structural materials are given in various Australian Standards (or equivalents for other jurisdictions). Specifically in relation to erection of building modules the Designer should consider in the manufacturing specification:

i. Connection systems allowing for connected elements to be at opposite ends of the location tolerance range
ii. Connection systems allowing for multiple separated connections of larger elements, assemblies or modules to be at opposite ends of the location tolerance range
iii. In-service control of any slip potential in structural connections where tolerance limits have not been exhausted
iv. Potential for and control of accumulated errors in successive module placements **Figure E2**
v. Compatibility of tolerance limits between all connection systems of materials and services

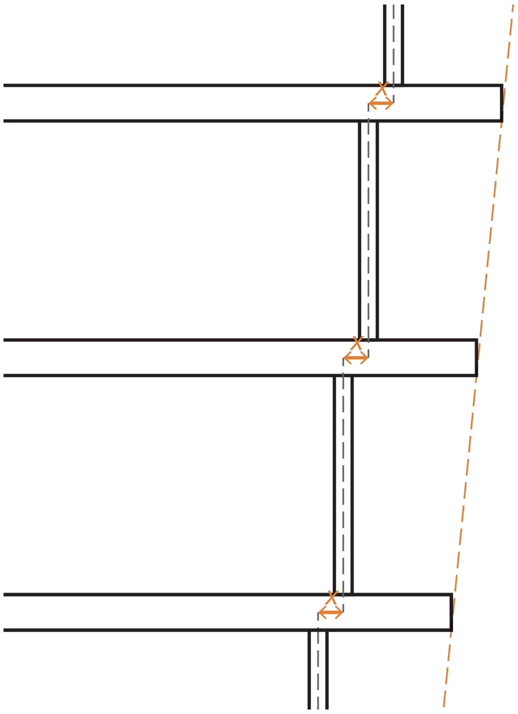


Figure E2 – Depiction of accumulated errors when stacking modules

E3 Material Quality

E3.0.0.1

It is prudent to rely upon the material *Manufacturer* or supplier to verify conformance of the actual product quality to the claimed product quality. In a manufacturing supply chain there would be significant *risk* to a *Manufacturer* from processing unapproved raw material and ultimately this may compromise the required performance and end-user benefit. This may be prescribed by the relevant local regulation. The *Designer* (of the *compliance* process) should require an appropriate *certifier* to be involved.

E3.0.0.2

In order to have confidence that any building material meets the specified quality, an appropriate and independent degree of inspection (including testing) is required. The *Designer* should approve a process for establishing this confidence, which may be relevant to decisions about product supply. For safety-critical products the process may need to be more stringent. Measures which may be considered include:

i. Prequalification of suppliers to an external acceptable standard
ii. A basis for sampling at all levels of testing to ensure valid representation, including specification of sample size, test count, and reproducibility requirements
iii. Initial testing to confirm product *conformance* (to the supplier's claims)
iv. Ongoing production testing (by the *Manufacturer*) to indicate reliability and consistency of the product, with sampling via a validated test plan
v. Market surveillance testing (from an alternate point of supply) for greater confidence in the sampling independence
vi. Independence of the testing firm; where applicable, accredited by an International Laboratory Accreditation Cooperation (ILAC) signatory (such as the National Association of Testing Authorities NATA) in Australia)
vii. The supplier's operation of a reporting, investigation and response process for defective products
viii. Traceability measures in place to relate specific test results to product batches
ix. Reproducibility of the conducted tests by a body independent of the original tester

E3.0.0.3

Where an alternate or substitute material for that specified is proposed, this should be subject to the approval of the *Designer* of the relevant specification concerning both conformance (of actual product quality to claimed quality) and *compliance* (with relevant regulatory controls).

E3.0.0.4

It should be noted that a distinction can be drawn between the implications and responsibilities for *non-conforming building products* and *non-compliant building products*.

E3.0.0.5

The regulatory definition of a "building product" should be noted where applicable. For example, in Victoria, Australia, the Building Regulations [1.2] define "building product", in connection with building work, as including both:

i. The construction method; and
ii. The design component or system.

E3.0.0.6

Material quality is commonly viewed in the context of actual properties assessed in relation to properties specified by the *Designer*. Whether explicitly cited by the *Designer* or not there are overarching health and safety duties imposed on suppliers of building products. Particularly where *hazardous* chemicals may be present (e.g. formaldehyde in pressed wood products or cement in concrete) suppliers are obligated to provide Materials Safety Data Sheets (MSDS) and the *Manufacturer, Builder* or other parties controlling works with affected materials should ensure the receipt and application of such information.

E3.0.0.7

When working with materials for which a *hazard* has been identified as part of the MSDS, all personnel who come into contact with, handle, or are responsible for the material should ensure that safety measures identified in the MSDS are followed. This should be the responsibility of both the person directly working with the material, and their co-workers.

E4 Corrosion and Fire Protection

E4.0.0.1

The *Designer* should clearly state:

i. The corrosion and/or fire protection system that is to be applied to a given component
ii. Any relevant information regarding:
    a. Application or installation methods of the protection systems
    b. Thickness of applied coatings
    c. Curing time and conditions (e.g. relative humidity, temperature) for coatings
    d. Appropriate on-site remedial works if systems are damaged

E4.0.0.2

The *Manufacturer* should take care to ensure that:

i. Any protection systems applied are done as per specification
ii. Damage to protection systems within the manufacturing environment is limited
iii. There is verification that protection is applied as per specification before the module/component leaves for site. It is suggested that any verification procedures be documented in writing and preferably also visually (e.g. photographs or other appropriate means)

E4.0.0.3

Final inspection of any protection system should be done on site by the building *certifier*. Any damage should be rectified as per the *Designer's* specification.

E4.0.0.4

Further guidance on corrosion can be found in **Section F2**.

E5 Certification

E5.0.0.1

Certification is a designated function and thus can be carried out only by a *certifier*. Aside from the required subject competence there must be verifiable independence of the *certifier*, in some cases with regulatory controls. *Certification*, as distinct from routine inspection or monitoring, is most likely justified where regulatory approval is required and also as the basis for the transfer of goods from one contractual party to another and subsequent claims.

E5.0.0.2

The *certifier* should verify that:

i. The modules or components as delivered on-site meet the design and contractual specifications
ii. Any remedial works undertaken on modules or components on site conform to the design specification and allow the system to meet the *Performance Requirements* of the relevant Standards and Codes for the jurisdiction
iii. Any remedial works are done by the party deemed responsible for these (e.g. if the manufacturer is contractually responsible for any remedial works, they or an elected and agreed upon contractor must perform these)
iv. Installation and connection on site meet any relevant specifications
v. Services installed within the modules meet specifications required both contractually and based upon Standards and Codes which apply within the jurisdiction

E5.0.0.3

The *certifier* should provide documents outlining:

i. The unique identifier of the item or works certified
ii. The Standard and Codes for which compliance is claimed and which the *certifier* has verified
iii. The *certifier's* name, contact details, any required regulatory accreditation and indication of professional competence to certify
iv. Location and date of the inspection supporting the *certification* of installed services (e.g. wiring, plumbing, waterproofing)

E5.0.0.4

The *certification* process should require the *Manufacturer* to affix a permanent marking or plate bearing the unique identifier and name of the *certifier* responsible. The *Manufacturer* should also provide the *certification* documents with the module to the receiver.

E5.0.0.5

Guidance about effective and efficient manufacturing *certification* processes may be obtained from **EN 1090** [6.16] which relates to requirements for conformity assessment for structural components (steel and aluminium). This is now mandatory throughout the European Union (EU).

This standard places special emphasis on the provision of a written “Declaration of Performance” from the qualified metal producing and processing manufacturer. This qualification requires the manufacturer to gain *certification* of their “Factory Production Control” via a procedure of “Assessment and Verification of Constancy of Performance”.

In addition to manufacturer requirements **EN 1090** also makes provision for regulating the obligations on agents, importers and distributors.

These processes have been developed to standardise quality control of construction product manufacturing and to guarantee free trade within the EU, given the importance of equivalency of products between different EU states.

E6 Customs and Quarantine

E6.0.0.1

Export and importation of modules between locations having different regulated conditions may present *risks* of unlawful acts, regardless of being intentional or unintentional. The *competent person* responsible for planning the transportation of modules should ensure these *risks* are eliminated. Although typically controlled within national borders there may be more localised domestic conditions which require *compliance* with regulations. For example, within Australia, there may be regulated biosecurity *risk* control regarding the transport of fruit or soil.

E6.0.0.2

Customs and Quarantine requirements are defined by law in each jurisdiction. The parties involved in a *Modular Construction* project should clearly understand the responsibilities for application of the relevant local regulations.

Potential restrictions to be considered separately for forwarding/export, transiting and receiving/import, in the legitimate context of *Modular Construction*, include:

i. Export/import of prohibited building materials (e.g. asbestos)
ii. Export/import of *hazardous* required building materials (e.g. untreated wood which may be a pest host)
iii. Export/import of incidental contaminants (e.g. soil, plant matter, airborne insects)

In some jurisdictions, such as the European Union, there are selling restrictions on construction products (including fabricated structural steelwork) which may have implications for importation controls. This is to minimise the risk of unapproved materials contaminating the construction product supply chain. The European Union requires and controls the “CE” marking system for this purpose.

E6.0.0.3

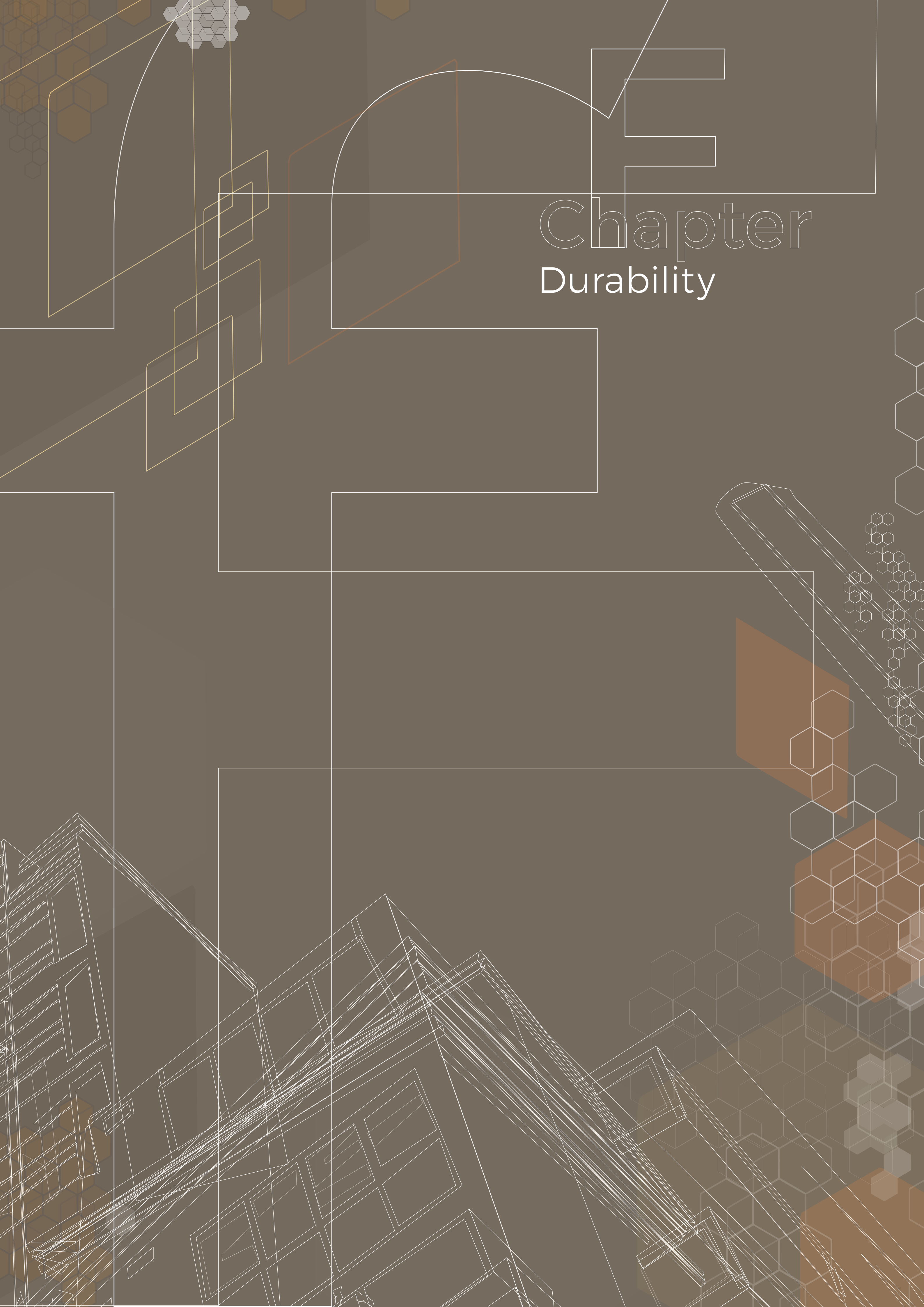
Volumetric modules, in particular, may present a *risk* for unauthorised access and opportunistic transport of prohibited products. The *competent person* responsible for planning the transportation of modules should consider how to eliminate such *risk* via the use of security seals or similar systems.

E6.0.0.4

Upon arrival of a module at any stage of transportation it should not be accepted for delivery unless and until there is confirmation it is as specified on the transport documentation. If fitted, any security seals should be inspected for signs of tampering or unauthorised access. Any irregularities should be notified to the carrier and sender and, if applicable, to Customs or law enforcement agencies before removing the seal. See **Chapter L** for more guidance on traceability, which will be important in this context.

E6.0.0.5

If any chemical treatment of a module is required on account of building materials being susceptible to deterioration by pests, there may be *risk* of chemical absorption into materials and the subsequent release into the air and exposure to any occupants. The *Designer* should consider specifying the use of pre-treated materials so as avoid the need for any fumigation of completed modules.



Chapter F

Durability

Table F1 –Design life of building installations and their components, taken from the ABCB Durability in Buildings Handbook [6.29][1].

Building Design Life Category	Building Design Life (years)	Design life for components or sub systems readily accessible and economical to replace or repair (years)	Design life for components or sub systems with moderate ease of access but difficult or costly to replace or repair (years)	Design life for components or sub systems not accessible or not economical to replace or repair (years)
Short	1 < dl < 15	5 or dl (if dl < 5)	dl	dl
Normal	50	5	15	50
Long	100 or more	10	25	100

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[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

F Durability

F0.0.0.1

Durability relates to the longevity of performance capacity for building elements to perform their function over a specified period of time. This time period is typically described relative to the required service life. Durability requirements should be specified as a part of the design process along with other design criteria.

F0.0.0.2

The *Designer* should consider where long-term changes in material properties may improve or diminish the required performance of the structure. For example, service conditions which encourage hygroscopic materials (those that tend to absorb moisture from the air, such as timber) to dry out excessively compared to ambient environmental levels may affect properties such as strength, stiffness, ductility and flammability. Many materials exhibit degrees of dimensional instability with changes in internal moisture content.

F0.0.0.3

The *Designer* should be aware that a project specific "Durability Management Plan" may be developed. These document how the selected design, materials and construction processes will achieve the durability objectives of each element of the works. Specifically, they can be used to define the corrosivity and aggressivity of the environment, the mechanisms of deterioration and the minimum durability requirements for the materials of each element, such that the element will be suitable for the nominated design life with planned maintenance.

F1 Design Life

F1.0.0.1

Design life refers to the period for which a building is expected to fulfil its intended function. The intended *design life* for a building or structure should be stated by the *Designer* as part of the conditions upon which the design is based. The intended *design life* represents the required duration of exposure to time-dependent environments of actions and conditions which have varying degrees of intensity, frequency and duration. Some actions and conditions are a function of probability, rather than being deterministic; that is, one can only predict the likelihood that certain actions and conditions will occur, rather than predicting exactly which conditions will occur and when.

F1.0.0.2

The *Designer* is required to account for reasonable and foreseeable conditions for the whole life cycle. This may include the lifetime performance of *load-bearing* structural elements (e.g. beams, columns, etc.), non-*load-bearing* structural elements (e.g. curtain wall façades), and non-structural elements such as coatings (whether architectural or anti-corrosion in nature). Implicit in the definition is the assumption that regular maintenance will be carried out and that there will be no unusual events such as a large earthquake.

F1.0.0.3

A guide for the minimum design life for building components and their sub systems is shown in **Table F1**, taken from the ABCB Durability in Buildings Handbook [6.29].

F1.0.0.4

The New Zealand Building Code [6.31], Section B2 "Durability" provides a detailed guide to durability requirements in that jurisdiction, including a straightforward flowchart (see Figure 1 of [6.31]) to determine the design life of a building that would be classified as "normal" according to **Table F1**, as well as a comprehensive list of specific building elements and their durability requirements (see Table 1 of [6.31]).

F2 Corrosion

F2.0.0.1

Corrosion is a material degradation effect arising from surface chemistry, typically relating to metals. Where potential for corrosion is foreseeable and adequate resistance is not assured via material specification then the *Designer* should make provision for monitoring of material condition and performance. This may include key points of visual inspection or other appropriate measures of continued material integrity. In this case structural connection locations are of critical importance.

F2.0.0.2

Corrosion will typically be quantified by the rate at which the material is removed, i.e. thickness of material surface lost per unit time. As an example, corrosion of steel in a moderately sea-proximate location might be somewhere around 25 to 50 μm/year (see for example **AS/NZS 2312.1 Table 2** [5.14]). If the steel contributes to the load-bearing capability of a structure, then this corrosion would result in decreased resistance, and hence implications for the reliability or probability of failure of the building.

This can be challenging, as generally the structural steelwork requiring monitoring is quite inaccessible once the building has been completed. One option is to use an industrial type borescope to access cavities while minimising damage to finishes and structure.

F2.0.0.3

Corrosion is of particular importance in modular structures where a variety of microclimates may evolve within the structure. This is dependent upon the ability for moisture, from rain or condensate or drainage leaks, to ingress behind building façades and overall structural geometry. In modular construction empty volumes and crevices are likely to be created between completed and assembled modules. Prefabricated single dwellings often sit atop screw pier foundations, leaving a gap under the module where corrosive conditions may occur.

F2.0.0.4

Modular Construction may also involve an increased prevalence of bolted-together components. Whilst the individual components may conform to corrosion protection specification, the connection points and connection process may induce unforeseen corrosion and reduced durability.

The effect of microclimate upon structural durability can be demonstrated with the example of the collapse of the roof of an indoor swimming pool in Uster, Switzerland in 1985. A microclimate had evolved as warm, humid and chloride-containing air was passed between the building ceiling and the suspended ceiling. While the suspension hangers (fastening components) were stainless steel, the formation of an acidic, chloride-containing moisture film on their surface resulted in corrosion damage. This damage, combined with the high stress, resulted in stress corrosion cracking causing the brittle failure of 94 of the 108 fasteners which failed (Faller & Richner, 2003 [8.5]).

Consider this example in the context of *robustness* as presented in **Section A3.4**. The corrosive environment which evolved resulted in the stainless steel becoming brittle instead of ductile (i.e. a reduction in the plastic region of material behaviour), in addition to reducing the capacity of the *anchors*. As this reduction of capacity resulted in the overload of a single *anchor*, which then failed in a brittle fashion, this total loss of resistance then increased the load on adjacent *anchors* significantly, leading to their (often brittle) failure which propagated through many of the fasteners which failed. This is a characteristic case of a *progressive collapse* which had consequences significantly greater than those of the initial local failure.

This is a case where application of the principles presented in this section would aid the *Designer* in identifying potential durability issues affecting the long-term behaviour of structural materials. This may then be combined with other design concepts such as *robustness* or *reliability*. This demonstrates that the design of structures should be a holistic process, where the *Designer* considers how numerous individual factors may need to be considered as a whole in order to achieve the required performance.

Consider further the effect of corrosion upon the *reliability* of a structural component (discussed in more detail in **Section A3.5**). Typically, corrosion may be viewed as the degradation of material i.e. the reduction in its resistance to an applied action. This may be viewed as a reduction in the mean value of resistance, and an increased spread of its distribution (i.e. the reduction of the characteristic/nominal value). **Figure**

F1 shows the shape of the load (Q) and resistance (R) as degradation progresses from times t_1 to t_2 to t_3 (under certain assumptions about the distribution of the variables).

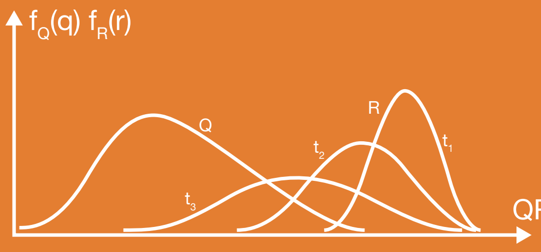

Figure F 1 — Load (Q) and resistance (R) distributions in the presence of degradation, at times t_1, t_2 and t_3.

The increasing overlap between the load and resistance distributions as the material degrades indicates that the probability of failure is increasing. Recall from **Section A3.5** that the reliability index can be defined under certain assumptions as

$$\beta = \ln\left[\left(\frac{R_m}{Q_m}\right)\sqrt{\frac{C_Q}{C_R}}\right] / \sqrt{\ln(C_R \cdot C_Q)} \qquad \textbf{(F1)}$$

where Q_m and R_m are the mean values of the load and resistance respectively, and C_Q and C_R are the coefficients of variance of the load and resistance respectively. Degradation of material through corrosion reduces the mean value of resistance R_m and increases the coefficient of variance C_R, thereby reducing the *reliability* of a component and increasing the probability of failure.

An important result of this is that a design which is acceptable at the start of a structure's life may become unacceptable through the action of durability issues (i.e. the *reliability* index decreases over time below the design value). Therefore, it is important that the *Designer* appropriately protects elements within the design against corrosion and other durability issues to ensure adequate performance throughout the design life.

F2.0.0.5

There are numerous standards which can be referred to considering corrosion, including **AS 2312** [5.14], **AS 4312** [5.13], **ISO 12944-2** [6.11] and various **NACE** standards. These standards are similar in many ways and cover similar topics, but may not be entirely consistent with one another. The *Designer* should be careful to ensure that there are no inconsistencies in their rationale for the durability of the structure. Ideally, only a single standard would be referred to where possible.

F2.1 Corrosive Environments

F2.1.0.1

Atmospheric corrosive environments are broadly broken down into the classes shown in **Table F2** (including some typical environments).

Table F2 – Atmospheric corrosivity categories taken from AS 2312 Table 2.1[1]

Category	Typical Exterior Environment	Examples of Interior Environment
C1: Very low	Few alpine areas	Offices, shops
C2: Low	Arid/rural/ urban	Warehouse, sports halls
C3: Medium	Coastal	Food processing plants, breweries, dairies
C4: High	Sea-shore (calm)	Swimming pools, livestock, buildings
C5-I: Very high (Industrial)	Within chemical plants	Plating shops, chemical sites
C5-M: Very high (Marine)	Sea-shore (surf)/offshore	N/A
CX	Shoreline (severe surf)	Adjacent to acidic processes
T: Inland Tropical	Non-coastal tropics	N/A

These definitions appear in a wide range of Standards (including Australian). Some standards (such as **AS 4312** [5.13]) even provide further guidance in the form of maps designating an environmental classification of different geographic areas, as in **Figure F2**, which depicts a portion of Melbourne, Australia with shading to indicate corrosivity categories.

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[1] © Standards Australia Limited. Copied by the MCCB with the permission of Standards Australia under Licence 1703-c123

While **Table F2** and maps such as **Figure F2** provide a guideline for the corrosivity of environments when selecting anti-corrosion systems/coatings, it will not capture the specific conditions which may be encountered during the service life of the modular structure. As such, the following guidance is offered.

F2.1.0.2

The *Designer* should consider the effect of the following factors upon the corrosive environments experienced by components during the life of a structure:

i. Built and natural environment
ii. Climatic cycles and conditions
iii. Distance from nearest source of airborne salinity
iv. Nearby industrial activity
v. Intended use of the structure
vi. Chilling of building materials in the presence of humidity, which can potentially lead to the formation of unexpected moisture films
vii. Galvanic corrosion from dissimilar metal contact
viii. Conditions conducive to the occurrence of stress corrosion cracking (including specific chemical or metal contact combination, tensile stress levels, elevated temperature)

Industrial Galvanisers (Australia's largest hot-dip galvanising company) have developed a free Corrosion Mapping Tool. This tool was developed in conjunction with CSIRO and enables the Designer to establish the corrosivity of an environment, accounting for climatic and environmental conditions, on the basis of particular Eastings and Northings.

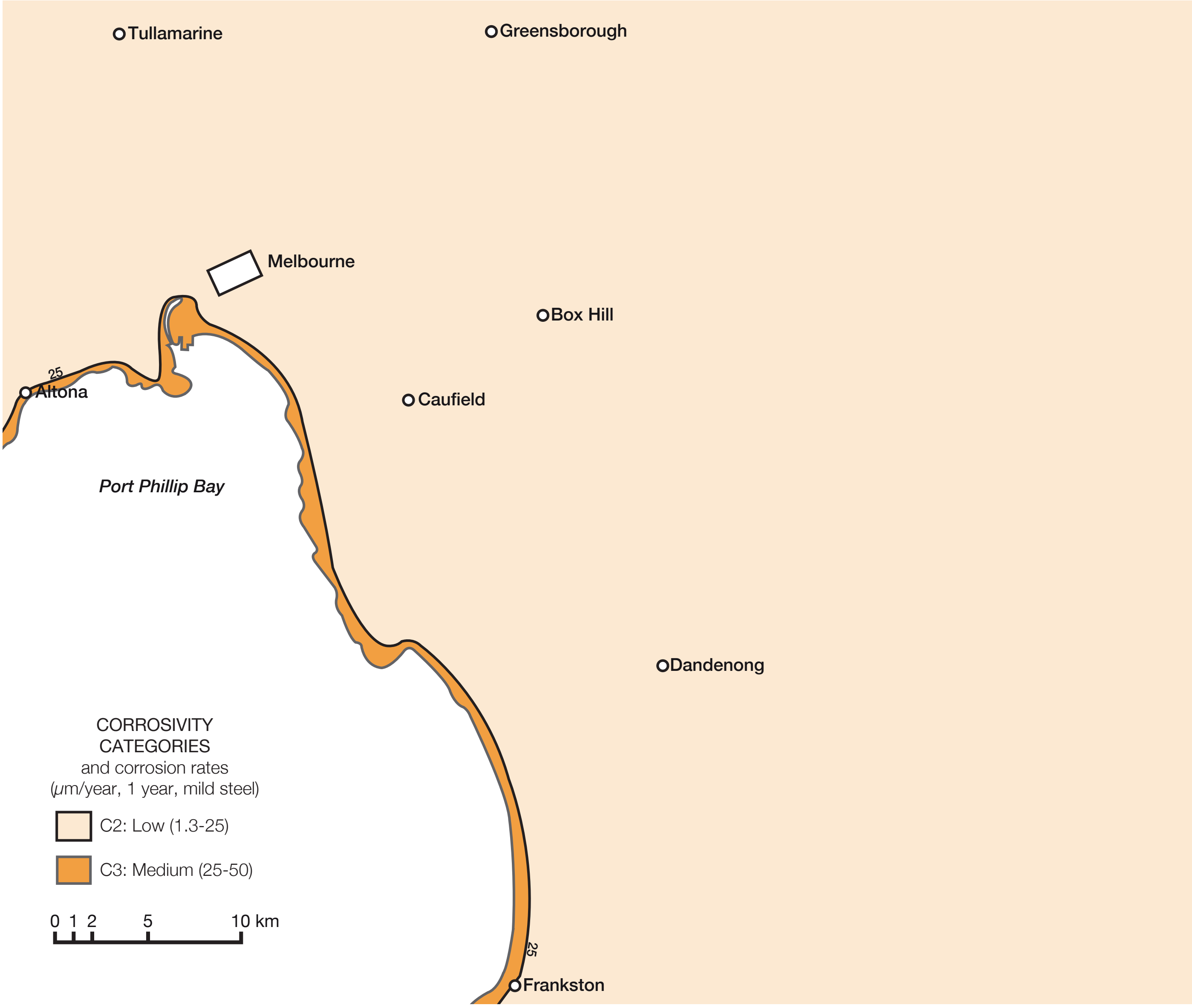

Figure F2 – Typical ISO corrosivity category map for Melbourne area (from AS 4312, Appendix A)[2]

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F2.1.0.3

It should be noted that for Australia and many other countries, deposition of salts and pollutants on metal surfaces generally occurs by the transport of aerosol droplets from ocean sources, making this a primary source of corrosion. However, for many inland countries or regions, industrial activity may be the governing factor.

F2.1.0.4

When developing a strategy to mitigate corrosion and ensure durability of the structure, the *Designer* should consider all environments in which the components of the structure, and the structure itself, might be located, even temporarily. This may be a more significant consideration in modular construction with the associated transport of partially assembled structures, e.g. completed volumetric modules being shipped through saltwater environments.

Various sources have noted the wide range of conditions which influence corrosion rates. Works have been conducted which identify the factors affecting the production and transport of marine aerosols (Cole et al. 2003a [8.6]), the effect of natural and man-made structures on the deposition of these (Cole et al. 2003b [8.7]) and the mechanisms of surface wetting (Cole et al. 2004 [8.8] & Corvo et al. 2008 [8.9]). Typically corrosion is said to progress whenever a surface is wet and oxygen is present within the electrolyte layer formed. An oft-quoted definition is the Time Of Wetness (TOW) in relation to corrosion rates for surfaces, defined in **ISO 9223** [6.12] as the time at which ambient relative humidity exceeds 80%. However this can often lead to the underestimation of total TOW due to increased relative humidity at the metal surface.

Typical factors which have an effect upon total corrosion rate are:

i. Shielding due to man-made and natural geographic features
ii. Cycles in ambient relative humidity
iii. Pollutants deposited and retained upon the surface
iv. Use and environment of structure

Factor (i) for many countries involves the reduction of deposited salinity by shielding effects of the nearby man-made and natural environment. For Australia, this may be quantified similarly to the shielding factor introduced in **AS/NZS 1170.2** [5.2] for wind loadings (Cole et al. 2003b). Typically, this will influence the effect of factor (iii) through direct reduction of deposited salinity, however factor (iii) also depends upon the intended use of the structure (e.g. commercial, residential, industrial) and the ability for retention of pollutants upon the surface, which may be reduced by cleaning of surfaces or the ability for pollutant-laden moisture to drain from the surface.

In addition to ambient relative humidity as per factor (ii) above, typical rainfall patterns and other factors may play a key role in the corrosivity of an environment. Rainfall events may result in the cleaning of retained salts from surfaces (Cole & Paterson 2007 [8.14]) meaning that regular rainfall can, perhaps counter-intuitively, result in a reduction in total corrosion. This is illustrated in **Figure F3**.

Figure F3 –Internal and external corrosion compared at Air on Broadbeach (Gold Coast, QLD). The protected façade has a markedly higher corrosive microclimate as rain does not clean off contaminants.

The Perth Stadium roof truss (**Figure F4**) was designed as a modular component to allow for ease of transport and erection. Significant cost savings were realised for stakeholders through consideration of the factors mentioned heretofore, as the corrosivity of the environment was discovered to be significantly below that originally designated.

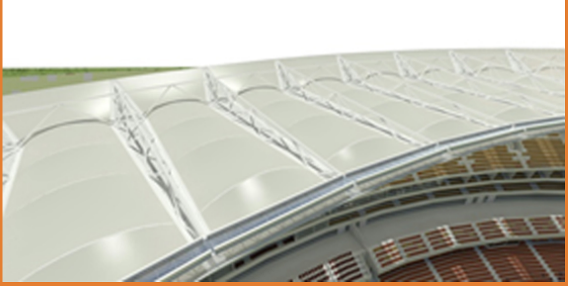


Figure F4 – Perth Stadium roof: An example of a modular structure with corrosion considerations

Factor (iv) typically has an effect when considering it in combination with factors (ii) & (iii), where the use of the structure may significantly alter the total TOW of components. For example, a residential or commercial structure may make use of cooling systems which result in a reduction of steel components' surface temperature, resulting in the formation of a moisture film when none is expected on the basis of ambient relative humidity. Further, it is possible for microclimates to evolve during the transient (i.e. transport) stage of modular components. Finally, the use of modular components such as precast elements within road tunnels or similar may be subject to corrosive actions resulting from exhausts (in Australia and abroad) or the presence of de-icing salts and moisture resulting from their use (such as in Europe, the US or Canada). As such, it becomes important for the *Designer* to consider the effect of microclimates that might evolve during transport, erection and long-term use of their structures.

For highly corrosive environments it is recommended that a specialist corrosion engineer is engaged to develop a project specific coating system. Such a consultant will also prescribe an approved sampling procedure to ensure compliance.

It should be noted that while the above discusses these factors primarily from the perspective of design in Australia, the concepts used are universally applicable.

F2.2 Corrosion Protection

F2.2.0.1

Corrosion protection will be necessary for a range of materials, including steel and concrete. The extent of the required protection will depend on both the desired time to first maintenance and the required service lifetime, as well as the environment to which the structure will be exposed (as detailed in **Section F2.1**).

F2.2.0.2

The types of corrosion protection vary; as an example, for steel, the protection will involve surface preparation (typically abrasion by various means) followed by coatings of different thickness and composition. As many as three coats could be used. These coatings serve multiple purposes, including to present a barrier to corrosive conditions or to serve as a sacrificial layer.

F2.2.0.3

For detailed design of anti-corrosion systems (whether galvanization or paint coating), the Designer should consult with manufacturers for detailed information on products offered. Basic guidance for the selection of protection systems for structural steel may be found in Standards such as **AS/NZS 2312** Part 1 and Part 2 [5.14].

F2.2.0.4

Corrosion protection may be tested via measurement of the Dry Film Thickness (DFT). This process provides information on the expected life of the underlying material and the conformance of the corrosion protection system with the design specification.

F2.2.0.5

The level of corrosion protection deemed sufficient may vary depending on which stakeholder has the decision responsibility. For example, the asset owner will be concerned with longevity and reduced ongoing maintenance costs while the material supplier has a primary interest in meeting volume targets. It is crucial that sufficient consultation is performed to ensure that optimal design decisions are made and to ensure that requirements are communicated clearly.

An important concern relating to corrosion protection is traceability and verification along the logistical chain. This is an even more significant concern for *Modular Construction*, since the individual elements comprising a structure are not constructed in place. Mishandling and damage may occur subsequent to application of the corrosion protection, and it is in the best interests of all stakeholders (e.g. the supplier, transport personnel, builders, asset owner) that accurate apportionment can be made for any shortcomings in a component. Ideally this would be achieved through the use of digital record keeping and communication systems, which offer accessible, secure and integral data management. Such systems are in use but are currently still in their infancy. This can be thought of as falling under the umbrella of Digital Engineering (see **Section R2**).

F2.2.1 Warranty Considerations

F2.2.1.1

Prescriptions of the durability duration do not constitute a "warranty time". Durability is a technical consideration which can feed into a well thought out maintenance programme. A warranty time is a separate matter which will form part of the contractual agreement between parties. The durability duration and the warranty time have no mandatory correlation, although at a maximum one would expect the warranty to last about one-quarter to one-third of the estimated durability period.

F2.2.1.2

The purpose of the warranty may not necessarily relate to the durability of the coating system, but could rather be for faulty products or workmanship.

F2.2.1.3

Various issues can arise with long term warranties for coating systems, as outlined by Clause 1.7 of **AS/NZS 2312.1** [5.14] and should therefore be avoided in the interests of all parties.

It is common practice for painted coatings to be applied on top of hot dip galvanised coatings. However, it should be noted that this is typically not warranted by paint suppliers. Furthermore this can be seen as a wasted expense since the painting system will typically be maintained, meaning the galvanising layer is not functioning at all. Although typically having a shorter lifespan to first maintenance, paint systems are easier to plan for maintenance than galvanising, which requires removal to regalvanise or a paint system retrospectively coated.

F2.2.2 Inspection

F2.2.2.1

Inspection to verify the adequacy of corrosion protection measures will typically be required by regulation, and furthermore is desirable to all parties to ensure that quality and safety is achieved.

F2.2.2.2

One potential subtlety affecting modular construction in this regard is the possibility of localised corrosivity conditions within the module manufacturing facility. Inspections may involve tests of atmospheric conditions, but these tests may significantly underestimate the corrosivity if not performed in the appropriate area. For example, the corrosivity may be much higher in a corner or sheltered area of the facility where air flow is reduced, and components assembled in these areas may be subjected to higher than anticipated corrosion.

F3 Fatigue from Long-Term Cyclic Loading

F3.0.0.1

Fatigue from long-term cyclic loading requires a combination of a fatigue-susceptible material and an appropriate loading environment. The loading environment is essentially described by the number of load repetitions up to a given intensity of material stress as a ratio of its strength.

F3.0.0.2

The emphasis in *Modular Construction* on *lean construction* concepts encourages greater material efficiency and thus increases the likelihood that stress/strength ratios are higher in the service life of a given component. Modules are also more likely to be exposed to dynamic loading effects from transportation in which imposed combinations of stress intensity, frequency and duration may need to be defined. The *Designer* should account for these concerning fatigue potential.

F3.0.0.3

The *Designer* should consider dynamic effects due to the following during the life of the structure:

i. Imposed actions
ii. Wind actions
iii. *Seismic* actions
iv. Snow & *precipitation* loading where appropriate
v. Dry thermal cycles
vi. Freeze/thaw cycles

F3.0.0.4

Different structures will have various governing parameters in terms of fatigue/cyclic loading. See **Section A1.2** of this document for details on typical dynamic loadings experienced by modular/pre-fabricated components during transport and erection. Further information on dynamic analysis for *seismic* actions is available in Section 7 of **AS/NZS 1170.4**.

F3.0.0.5

The *Designer* should consider the effects of climatic variations (particularly in relative humidity) upon the long-term performance of components. This involves in particular the effects of moisture content changes in various materials. For example, these variations may cause mechano-sorptive creep in timber components, leading to failure which might not otherwise be predicted.

F3.0.0.6

Fatigue effects may have significant impact upon the *reliability* and *robustness* of a structure. This is typically due to the reduction in ductility of elements through strain hardening, and the corresponding changes in the distribution of materials properties. The *Designer* should remain cognisant of these effects when the design is detailed.

F4 UV Degradation

F4.0.0.1

UV degradation refers to the discolouration or loss of properties as a result of exposure to *UV* radiation (i.e. sunlight). While the most common and ubiquitous form of this is the discolouration and peeling of architectural paint coatings, *UV* degradation may affect the long-term performance of components, depending upon material and application. A number of potential issues surrounding *UV* degradation are summarised in **Table F3**.

F4.0.0.2

The *Designer* should consider any effects upon the long-term performance of any component or system which will be exposed to *UV* radiation.

F4.0.0.3

A number of tools are available to the *Designer* to combat the issues surrounding *UV* degradation including, but not limited to:

- i. Appropriate provision of maintenance schedules
- ii. Appropriate material/coating selection, including:
  - a. Selection of paint coating systems to be sufficiently resistant to *UV* degradation
  - b. Anti-UV additives to polymer mixes
  - c. Selection of polymers with sufficient *UV* resistance without additives
  - d. Inclusion of additional materials on the structural surface, for example inclusion of a vale on the surface of FRP members
- iii. Coating with *UV*-resistant paints where appropriate

F4.0.0.4

Typically, it is suggested that the *Designer* consult closely with all stakeholders in the project to determine the required performance, including that of discolouration. Material selection may then be accomplished both through consultation of material data and with manufacturers to determine the material/coating best suited to the *Designer's* requirements.

This particular durability issue may have flow-on effects to Corrosion (**Section F2**) and maintenance (**Section F5**). Given this, it is possible that the *UV* degradation of components (particularly paint coatings) may have effects upon the long-term performance of components typically considered resistant to *UV* (such as steel which has been coated with anti-corrosion systems).

Note that most laboratory facilities can conduct accelerated *UV* age testing to prove long-term performance. If the material surface performance under *UV* is unknown, this is highly recommended for most applications exposed to *UV* in Australia. Most clients are wary of using products without an established record of performance in Australia, so accelerated testing of such products is also often a sensible investment.

Table F3 – Summary of UV degradation issues for a number of materials/components

Material/ Component	Issues
Façades	i. Discolouration and peeling of architectural paints ii. Degradation of any plastic components
Plastics/Fibre-Reinforced Polymer (FRP)	i. Reduction in material properties (such as strength) ii. Cracking, disintegration and discolouration of polymers iii. May lead to failure of components under previously acceptable loads
Anti-corrosion paint coatings	i. May lead to a performance reduction, which can reduce the time to first maintenance for a particular coating ii. Degradation of performance may result in more pronounced corrosion of structural members exposed to the elements

F5 Maintenance

F5.0.0.1

Maintenance refers to the total set of activities performed during the design life to retain a building in a state in which it can fulfil its intended function.

F5.0.0.2

In the case that maintenance of material conditions and quality is foreseeable in order to maintain material performance for the design life, then the *Designer* must make provision for required access and egress to inspect and carry out maintenance as required. This should take the form of a safe work method statement, detailed within the Safety in Design register and issued to the owner/manager. This should detail any residual risks and describe how these are managed.

F5.0.0.3

The *Designer* and/or *Manufacturer* should clearly state the expected lifetime to first maintenance for all components which make up a module or modular/pre-fabricated system. These may include, but are not limited to:

i. Any anti-corrosion systems which are employed for components
ii. Connections or components which are susceptible to long-term fatigue due to cyclic loading
iii. Connections or components whose service environment may promote material degradation due to effects such as corrosion or creep

F5.0.0.4

The *Designer* and/or *Manufacturer* should develop maintenance plans for all modular components or systems. Such plans should cover at a minimum the following aspects:

i. How do maintenance personnel gain access to components?
ii. What maintenance activities should be performed?
iii. What documentation is necessary for maintenance activities?
iv. What checks are required to ensure maintenance has been performed in a timely and effective manner?
v. Who is responsible for conducting and checking maintenance activities?
vi. What level of competence is required for maintenance personnel?

F5.0.0.5

Following maintenance activities, the personnel responsible should identify:

i. If any follow-up action is required for any issues identified during maintenance
ii. The time until next maintenance should be conducted

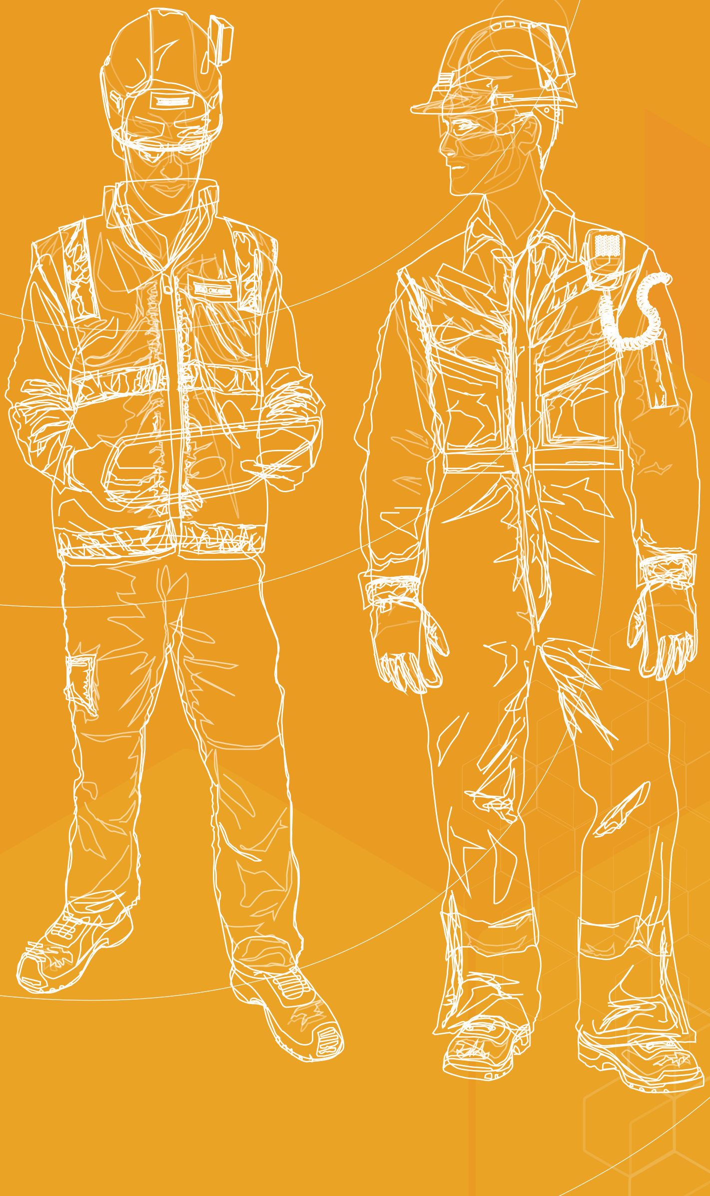
F5.0.0.6

Modular structures may present difficulties for maintenance due to their nature; assembly of completed individual modules will typically result in gaps between modules with access complications. The *Designer* should consider this during the design process; either by modifying parameters to push back the expected time to first maintenance, or by designing in such a way as improve accessibility to susceptible areas. See commentary after **F2.0.0.1**.

G

Chapter

Safety



G Safety

G0.0.0.1

Modular Construction departs from traditional construction methodologies and thus opens up the possibility of unusual or unforeseen safety *risks* and *hazards*. This may arise due to:

i. Lack of familiarity of management or operators with the novelties of the *Modular Construction* methodology
ii. Increased *risk* associated with the lifting, transportation and storage of heavy modules
iii. Increased *risk* associated with work performed in close proximity to modules; in some cases this may occur without the scaffolding measures typically utilised in traditional construction

G0.0.0.2

At the same time, *Modular Construction* presents many opportunities for improvements to safety and reductions in *risks* and *hazards*, including:

i. Reductions in on-site work, including work at height
ii. Reduced on-site construction programme, resulting in reduced hazards to areas adjacent to sites
iii. The shift of labour to a controlled off-site environment, with protection from weather and the opportunity to continually refine the processes involved
iv. The potential for some processes involving toxic materials to be performed using fume hoods

G1 Safety Regulations

G1.0.0.1

Health and safety of people in the built environment is a primary community expectation and is thus reflected in legislated duties for *Designers*, *Builders* and other relevant persons. In Victoria the *OHS* Regulations [1.1] apply to all workplaces, including construction sites, and make additional provisions for designated “high-risk construction work”. *Modular Construction*, as such, is not specified but works “involving tilt-up or precast concrete” and “involving demolition” are, all of which may involve modular concepts. It is recommended that the regulated safety provisions for high-risk construction work are consulted in relation to *Modular Construction* generally.

G1.0.0.2

In relation to a structure which is a work place the *Work Health and Safety* (*WHS*) Act [2.3] may be applicable and includes the document Safe Design of Structures [4.1], an approved Code of Practice. According to that Code of Practice (section 1.1):

> “Safe design means the integration of control measures early in the design process to eliminate or, if this is not *reasonably practicable*, minimise *risks* to health and safety throughout the life of the structure being designed”.

Aspects to be considered include:

i. The intended purpose of the design
ii. The materials to be used
iii. The possible methods of construction, maintenance, operation, demolition or dismantling and disposal; in the case of *Modular Construction* the *Designer* may need to pay particular attention to how maintenance staff may gain safe access for routine inspection and/or repair (see **Section F5**)
iv. What legislation, Codes of Practice and Standards are to be complied with

G1.0.0.3

Deciding what is “*reasonably practicable*”, as commonly defined in *WHS* Regulation [2.3], requires weighing up all relevant matters including:

i. The likelihood of the *hazard* or the *risk* occurring
ii. The degree of harm that might result from the *hazard* or the *risk*
iii. Knowledge about the *hazard* or *risk*, and ways of eliminating or minimising the *risk*
iv. The availability and suitability of ways to eliminate or minimise the *risk*, and
v. After assessing the extent of the *risk* and the available ways of eliminating or minimising the *risk*, consideration of the cost associated with eliminating or minimising the *risk*, including whether the cost is grossly disproportionate to the *risk*

Relevant Duty Holders should note, from iii) above, that this *Modular Construction* Handbook is part of the body of available knowledge in the industry that ought to be known. That is, even if the Duty Holder is unaware of the existence of such a document, they are not absolved of their Duty to have sought out and applied knowledge as a part of due diligence.

G1.0.0.4

Further to this (referring to **Section 1.2** of reference [4.1]), various persons have work health and safety duties in relation to the design of structures, as follows.

The broad duty of the *Builder* and related parties is to:

> *"ensure, so far as is reasonably practicable, that workers and other persons are not exposed to health and safety risks"* arising from the building activity.

The broad duty of the *Designer* and related parties is to:

> *"ensure, so far as is reasonably practicable, that the structure is without risks to health and safety. This duty includes carrying out testing and analysis and providing specific information about the structure".*

This duty relates to what could be reasonably expected to be the workplace use of the structure designed. For instance, the manner in which the structure is designed may prohibit certain works or work methods from being carried out, and the *Designer* must therefore provide information to that effect.

G1.0.0.5

Once any employer-employee relationship is involved between parties in connection to a location it may signal the application of *WHS* law. The commissioning client for a project, as distinct from the *Builder* or *Designer* or others involved with the provision of a building, may also have *WHS* duties should that client remain the building owner or operator, or remain the owner while leasing it to others, or even sell the building to others.

In relation to the *WHS* Act the description of a *Designer* involves documenting plans and decisions about the design "that may affect the health and safety of persons who construct, use or carry out other activities in relation to the structure". *Designers* may include:

i. Architects/Building *Designers*
ii. Engineers
iii. Building surveyors
iv. Interior *Designers*
v. Landscape architects
vi. Town planners
vii. Building service *Designers*
viii. Contractors providing supplementary design work
ix. Temporary works engineers
x. Specifiers of structural alterations, demolition or dismantling

There are separate design safety provisions for all buildings (including non-workplace functions) as classified under the *NCC* [6.2]. Refer to Part A3 of *NCC* Vol. 1 for complete list of building classifications.

G1.0.0.6

For structures classified via their function as Buildings (as regulated by the *NCC*) the *Designer*, *Builder* or other relevant *competent person* must satisfy stated Performance Criteria which include provisions about structural safety, fire safety and occupation/movement safety.

G1.0.0.7

For a structure deemed a workplace there are additional obligations via *WHS* legislation. This extends beyond the intended in-service function of a building, whose classification may be described as a dwelling or office or factory or public retail venue or others via the *NCC*. All structures are a workplace during the construction phase. There may be further workplace implications even for residential projects since they may again become temporary workplaces during subsequent use, maintenance, demolition or dismantling activities (See **Chapter N**). Where such activities are foreseeable the *Designer* should ensure the designed aspects are without *risk* to health and safety.

Referring to Safe Design of Structures [4.1] the following areas of Design Consideration are highlighted relating to reasonably foreseeable activities:

i. Design for safe construction
ii. Design to facilitate safe use
iii. Design for safe maintenance
iv. Modification
v. Demolition and dismantling

G1.0.0.8

There is a broad duty on all relevant parties that consultation must occur on matters pertaining to *WHS* arising from the building project and its reasonably foreseeable uses and life cycle.

The *Designer* should consider a systems approach that integrates the *risk* management process in the design phases and encourages collaboration between a client, *Designer* and constructor.

A design may be scrutinised at any time for compliance with safety regulations independently and regardless of any analysis of actual building behaviour in an adverse or unsafe event affecting a structure.

G1.0.0.9

Safe Design of Structures [4.1] also offers a "Safety in Design Checklist" which lists potential *hazards* under the following headings to assist the *Designer* of a structure to control *risks* throughout its lifecycle:

i. Electrical safety
ii. Fire and emergencies
iii. Movement of people and materials
iv. Working environment
v. Plant
vi. Amenities and facilities
vii. Earthworks
viii. Structural safety
ix. Manual tasks
x. Substances
xi. Falls prevention
xii. Specific *risks*
xiii. Noise exposure

The Specific *Risks* (xii) may include:

a. Exposure to radiation e.g. electromagnetic
b. Exposure to biological *hazards*
c. Fatigue
d. Working alone
e. Use of explosives
f. Confined spaces
g. Working over and under water, including diving and work in caissons with compressed air supply

G1.0.0.10

The *Builder* should ensure that all necessary and regulatory controls are used on site so that construction activity is without *risks* to health and safety.

Practical control of and responsibility for safe construction on site during erection of modules is provided for via *WHS* Regulations. A common tool to manage construction safety *risks* is the Safe Work Method Statement (SWMS) which is mandatory in some cases. In Victoria, designated High Risk Construction Work (HRCW) requires the preparation of a prescribed form of SWMS. The principles involved may be beneficial also to other construction work in any jurisdiction that may not be compelled by local regulation to use a SWMS.

Where regulated the SWMS must:

i. Identify work that is designated High Risk Construction Work
ii. State the *hazards* and *risks* to health and safety from that work
iii. Clearly detail the measures selected to control those *risks*
iv. Describe how the *risk* control measures will be implemented

The SWMS should also identify the date and location of work, the persons responsible and the persons consulted in the SWMS preparation.

G1.0.0.11

Where there is a *risk* to health or safety, persons with a duty of control should first seek to eliminate that *risk so far as is reasonably practicable* (e.g. by having overhead power lines de-energised). If a *risk* cannot be so eliminated it must be reduced *so far as is reasonably practicable* by implementing one or more of the following:

i. Implementing any *hazard-specific* controls required by law
ii. Substituting a lower *risk* activity, procedure, plant, process or substance (e.g. using scaffold in preference to ladders)
iii. Isolating persons from the *hazard* (e.g. fence off areas for mobile plant operation)
iv. Using engineering controls (e.g. trench shields, guard rails, mechanical ventilation)

If, after the above steps, a risk to health and safety remains then administrative controls, *so far as is reasonably practicable*, should be considered (e.g. safety training, work instructions, warning signs, supervision).

If, after implementation of administrative controls, a risk to health and safety remains then use of personal protective equipment (PPE), *so far as is reasonably practicable*, should be considered (e.g. hearing protection, high visibility clothing, respiratory protection).

G1.0.0.12

Regulated duties may be assigned but the key compliances to be fulfilled include:

i. To develop the SWMS
ii. To implement the SWMS
iii. To monitor work performance in accordance with the SWMS
iv. To cease high risk construction work when and while non-compliance is detected
v. Review the SWMS if the high *risk* work changes, if there is any indication the controls are not adequate, and after any adverse safety incident
vi. Retention of the SWMS for the duration of high *risk* work

G1.0.0.13

Even where the completed *Modular Construction* has a function which does not warrant a work-related classification (e.g. a dwelling) it may necessarily become a workplace when persons attend for work-related purposes e.g. building inspections, services operation and maintenance. The site also becomes a workplace before intended occupancy (during construction) and after (during demolition or dismantling).

These activities are likely to be foreseeable and so should be accounted for by the *Designer* under the usual *WHS* provisions. See **Section G2** concerning the elimination of need for hazardous manual tasks.

G1.0.0.14

Any parties responsible for safety management should acknowledge that the conditions and context of a repeated process, task or job are subject to variation. Safety management plans should follow a risk-based approach which considers the particulars of each job.

G2 Erection

G2.0.0.1

The *Designer* should provide evidence in the documentation of having conceived at least one safe method of performing the necessary steps to build the structure as it has been designed. Should this conceived method require any temporary works, the erection and operation of these should be subject to the same *WHS* requirements .

Guidance may be obtained by referring to “Safe Design of Structures” [4.1]. Where *reasonably practicable* a structure must be designed to eliminate the need for any *hazardous* manual task.

G2.0.0.2

Prior to erection of modules they will require safe transportation. The *Designer* should liaise with the transport controller to ensure the necessary load restraint conditions are advised regarding their effects on the module and the means of transport (e.g. via lifting, road, rail or ship).

All relevant parties should consider how additional horizontal or vertical loading on modules, for example while stacked in temporary storage or in stowage during shipping, might cause stresses leading to damage and consequent *hazards*. The necessary measures may include prescribing a maximum permissible stacking of modules.

G3 Robustness

G3.0.0.1

The concept of *robustness* relates to prediction and limitation of structural behaviour after the initiation of a notional failure. See **Section A3.4** for detailed guidance about designing for *robustness*. The goal of *robustness* is focused on safety. It is applied to control the *risk* of failure so that consequences of failure are not disproportionate to their cause or to the extent of the immediate precipitating collapse. The *NCC* describes minimum standards for assessing *robustness*.

G3.0.0.2

Robustness design for a completed building is regulated (See **Section A3.4**) but the principles should also be observed by the *Designer* for the construction phase under the scope of temporary works (see **Chapter H**). The *NCC Performance Requirements*, from which the *robustness* provisions are derived, apply also to the construction (pre-completion) phase of buildings and structures.

The *NCC* verification method for Structural *Robustness* (Vol. 1, BV2) requires that the building must remain stable and any resulting collapse must be limited after the notional removal of any one:

i. Supporting column
ii. Beam supporting one or more columns
iii. Segment of *load-bearing* wall of length equal to its height

The definition of *load-bearing*, as relating also to column function, is to be noted.

For example, consider small but framed shade structures (Class 10b structures via *NCC*). The structure shown in **Figure G1**, should it rely on a single column element, may have unsatisfactory *robustness* under current *NCC* provisions. In contrast, the structure shown in **Figure G2**, should it rely on the cluster of column elements, may have satisfactory *robustness* under current *NCC* provisions.

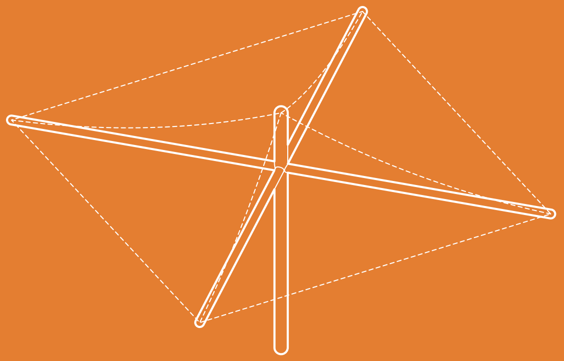


Figure G1 – Structure with single column support

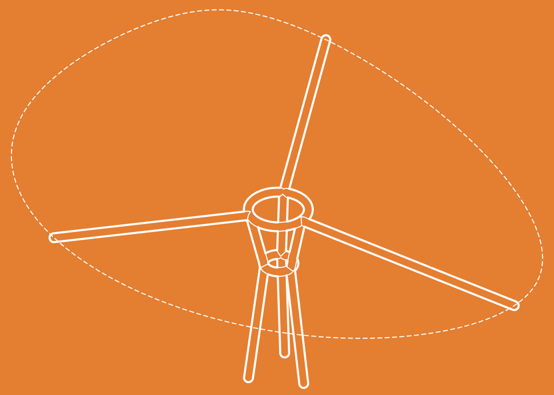


Figure G2 – Structure with multiple column support

G3.0.0.3

In the broader context of *risks* to safety (personal injury and property damage) the potential consequences from any limited collapse scenario should be considered. For example:

i. limiting the severity of structural displacements
ii. impact from dislocation of materials and released debris
iii. stability consequences from removal of any one non-*load-bearing* element (e.g. a brace)
iv. stability consequences for suspended structures and progressive collapse (e.g. where the failure of one connection point in the suspension system might lead to progressive collapse of the suspended structure; see commentary in **Section F2**)

Consider further the way in which the intended use of the structure may affect its performance (especially with regards to *robustness*) and therefore safety. Should durability issues (see **Section F**) arise as a result of climates evolved due to use, this may have implications for the safety of users and/or occupants.

Although such aspects may not be prescribed by the *NCC robustness* provisions these scenarios and consequences may be foreseeable and reasonable and as such should be considered by the *Designer*.

G3.0.0.4

Similar to the Separation and Compartmentation concepts for fire-resisting design it may be a consideration to provide discontinuities at nominated locations in large structures to ensure the disruption of any collapse mechanisms. This might be described as a structural fuse. Such fuses will likely fail in a ductile manner and provide a viable load path to redistribute load following yielding, aiding in preventing the overload of adjacent and/or other elements.

When building with prefabricated concrete wall panels, during the construction phase, temporary bracing is typically required until the panels are incorporated into the permanent structure. Even for relatively narrow panels, whose temporary lateral design actions may not require the capacity of multiple braces, it is typically mandated that a minimum of two braces are used. This may provide satisfactory *robustness*. See **Figure G3**.

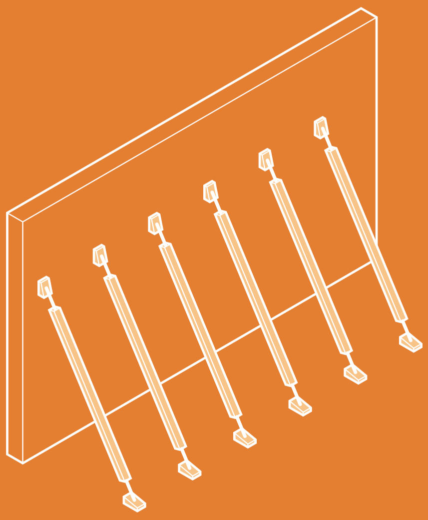


Figure G3 – Temporary bracing of prefabricated concrete wall panels.

G4 Safety by Design

G4.0.0.1

Whilst safety regulations such as those described in **Section G1** provide guidance and procedures to improve safety, it should be emphasised that safety cannot always be engineered into a system as an intrinsic property. The use of documents such as Safe Work Method Statements represents a valuable exercise in considering hazards, risks and mitigation methods. However, all relevant personnel, including both management and operators, should consider that some circumstances simply cannot be anticipated in advanced. Safety can instead be viewed as emerging from the ability of operators and managers within the system being able to adapt appropriately to local conditions.

G4.0.0.2

A comprehensive safety management plan should consider that the repetitive nature of many tasks in construction (which may be even further exaggerated in *Modular Construction*) may result in adaptations by operators to local conditions which can result in a gap between procedure and practice. Measures should be put in place to ensure that this gap can be monitored. This may include:

i. Regularly scheduled meetings, such as pre-start or post-shift meetings, which aim to shine a light on how the practice is evolving;
ii. Critical analysis of adaptations to determine what learnings and value can be derived from them.

G4.0.0.3

Feedback systems that form a part of the safety strategy should include awareness of normalised deviance, where small safety incidents are underreported. This is not only important when failures are occurring but also in situations where safe outcomes are preceded by potentially dangerous deviations from procedure.

G4.0.0.4

The fundamental goal conflict between productivity and safety should be acknowledged in the safety management plan, and should feed into a management culture that does not encourage safety to be compromised in the name of productivity.

G4.0.0.5

The Australian Steel Institute, in conjunction with Multiplex Constructions Pty Limited, has developed a “Practical Guide to Planning the Safe Erection of Steel Structures” [6.43]. This guide aims to support best practice outcomes to mitigate health and safety risks for the erection of steel structures. The principles therein generalise in a straightforward way to many other situations, particularly *Modular Construction* which will generally involve more complicated lifting and erection procedures and thus warrants more rigorous safety practices. The guidance includes an emphasis on:

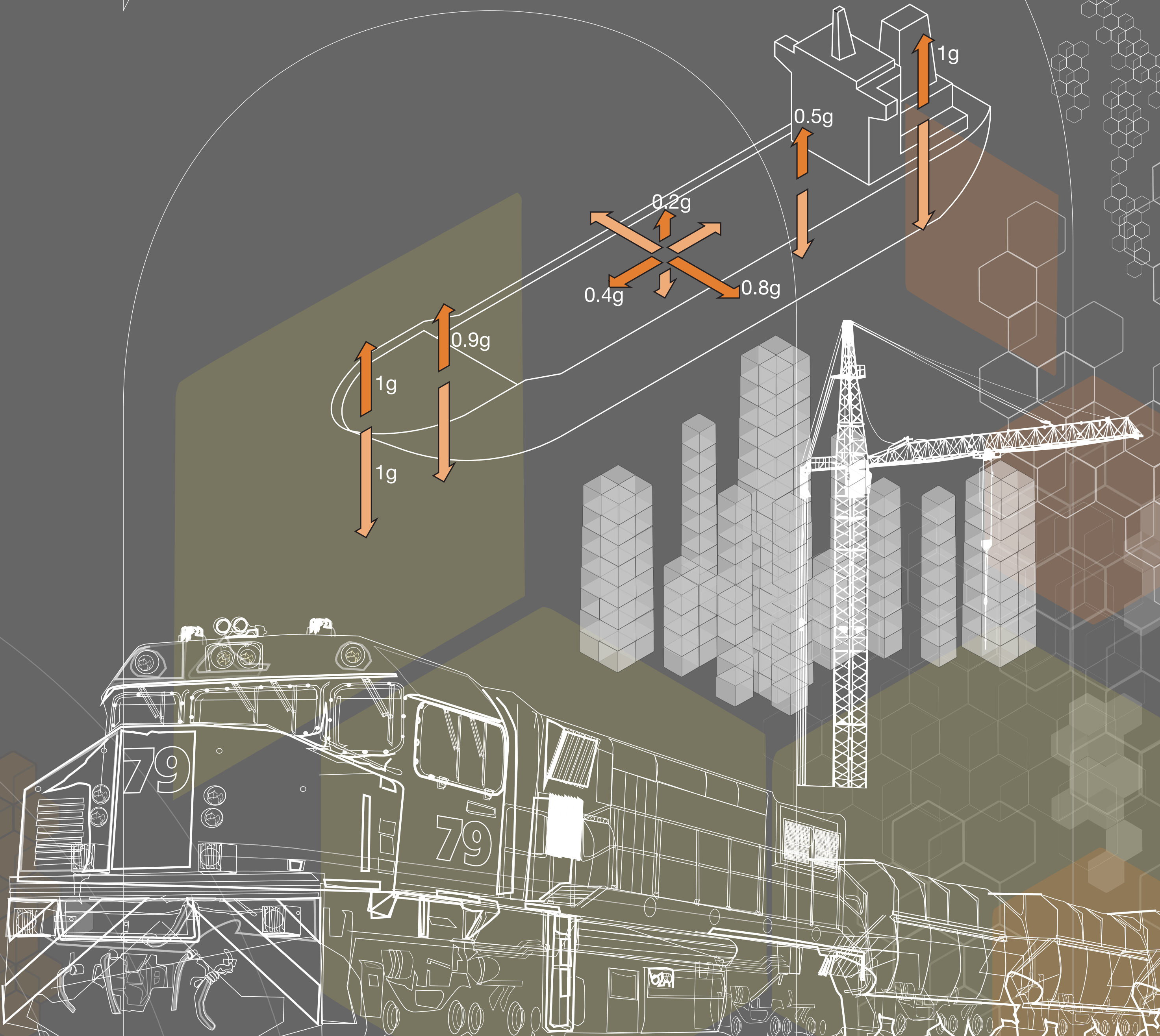
i. Communication and consultation between all of the safety stakeholders
ii. An emphasis on safety by design, including risk planning workshops and consideration of the entire chain of events involved
iii. Detailed plans for erection, termed the Erection Sequence methodology, which include highly readable, colour-coded and straightforward visual depictions of the erection sequence at different stages
iv. Work shift meetings to assess previous progress, account for variations and ensure that all stakeholders are fully informed of what is intended for the next shift

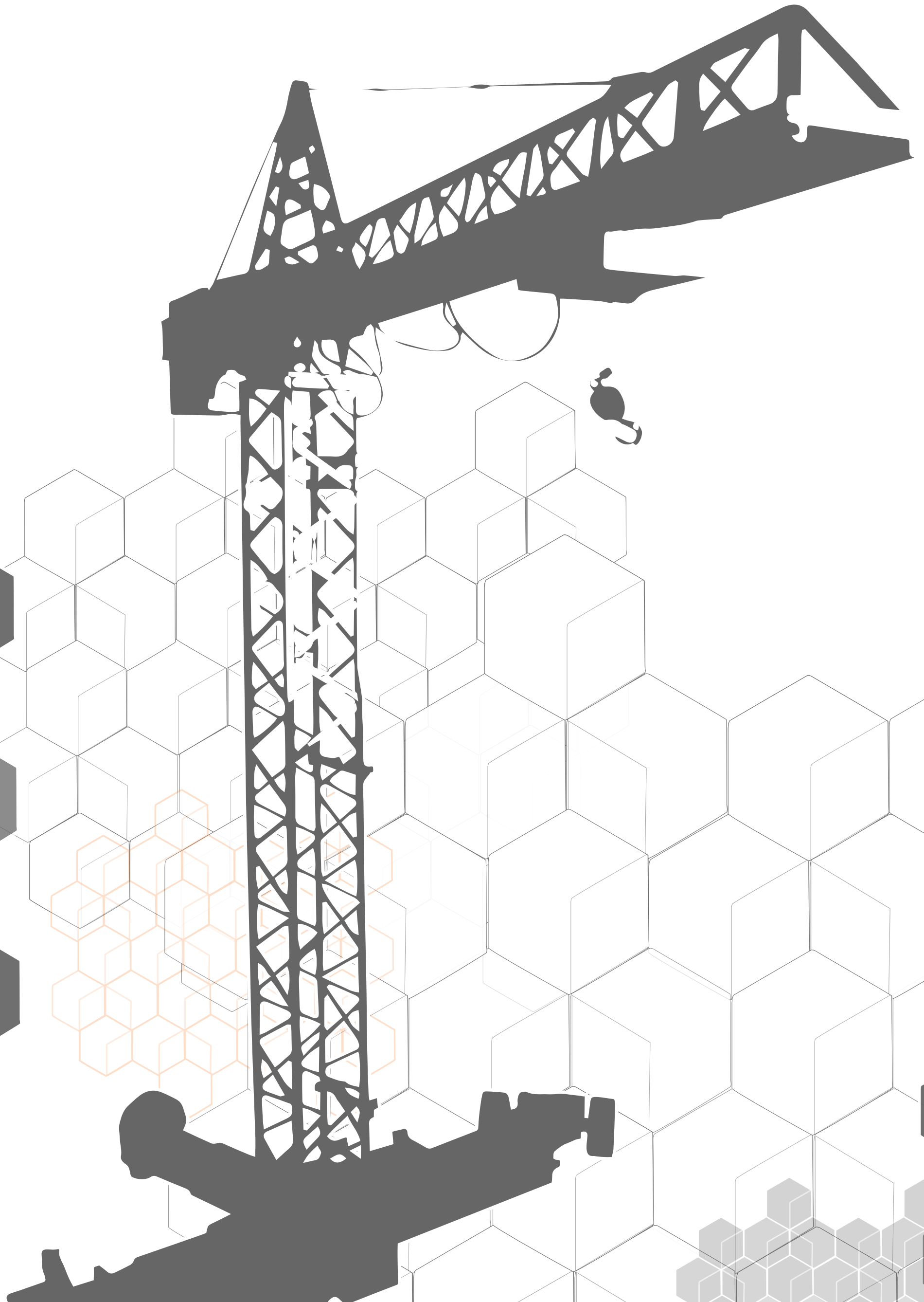
G4.0.0.6

A well-designed safety management plan for a *Modular Construction* project must consider all stages of the construction process, from off-site manufacture and storage through to transportation and assembly. This will be aided by integration of the safety plan with the structural design of the modules and consultation with relevant stakeholders for all of the stages.

H Chapter

Transportation, Erection & Temporary Works





H Transportation, Erection and Temporary Works

H0.0.0.1

The fast growth and adoption of modular construction in Australia has led to the need for a code for moving modules safely and efficiently to ensure the quality, integrity and efficient completion of the end product.

H0.0.0.2

A successful transport, lifting and erection plan should include consideration or inclusion of the following points:

i. Developing a build process based on manufacture and installation rather than construction.
ii. Preparing a detailed plan based on end-to-end solutions, starting with completion and working back to the production line. The plan should incorporate all design aspects, ensure cost-effectiveness and eliminate *risk* through a detailed *risk* management approach.
iii. Managing design and workflow planning according to industry codes and standards, making use of Lean tools and processes where appropriate.
iv. Engaging competent people with strong leadership skills to manage operations over the whole of the building lifecycle, from design and installation through to demolition and dismantling.
v. Collaborating and involving all stakeholders early in the project to address solutions holistically and ensuring commitment to the end result.

H1 Lifting

H1.0.0.1

All *Modular Construction* involves one or more phases of lifting partial (e.g. a panelised system) or complete (e.g. volumetric) modules, typically by crane. Except for the limited case where modules or components may be manufactured at the site where they are to be erected (e.g. on-site *prefabricated concrete* elements) all forms of *Modular Construction* also involve one or more modes of transport, typically via road, rail or sea. The regulatory requirement to consider the whole lifecycle for buildings including demolition and dismantling (Safe Design of Structures [4.1]) may entail at least a second phase of lifting to be accounted for after many years of building service. The combined lifting history for a completed module may involve:

i. Removal from the manufacturing shop floor to storage while awaiting delivery to site (may be two lifts if not handled with gantry crane)
ii. Loading onto road transport
iii. Loading onto intermediate transport methods, if necessary
iv. Erection at the project site
v. Eventual demolition

H1.0.0.2

Lifting materials involved in manufacturing or construction, generally via the use of mechanised plant, is frequently the highest *risk* phase in the life of a structural element. Structural demands on modules commence from the first lifting operation and must be designed and controlled at every stage (including multiple and incidental lifts) by a competent person. In what follows, guidance is presented on the technical and safety aspects of lifting design and operation.

H1.0.0.3

The *Designer* should consider the intended support configurations for lifting based on assessments of: proposed cranes or lifting plant; centre of gravity; slings and compression forces; stability; and lifting and connection/stacking arrangements.

H1.0.0.4

For specialised elemental modular forms, such as most *prefabricated concrete* panels manufactured on-site and off-site, the designed lifting frequently involves changing the panel orientation and static conditions during a lift. This is unlikely with volumetric *Modular Construction* but the point should be made that the structural demand on any module usually commences with its first lifting operation and this must be designed and controlled at every stage by a *competent person*.

H1.0.0.5

Some modular elements, again commonly from the off-site *prefabricated concrete* industry, have an intended service life which may involve regular multiple lifting operations. For example, the modules may be repetitively hired out to multiple locations. This also needs to be accounted for in the design. In the case of *prefabricated concrete* a Service Life Factor of 1.6 may be applied to design lifting loads (see **AS3850.2** [5.12] for more details).

H1.0.0.6

For further extensive guidance about design for lifting of *prefabricated concrete* elements, much of which is applicable to *Modular Construction* generally, see **AS3850.2** [5.12].

H1.0.0.7

During manufacture there may be a requirement for incidental lifts of the incomplete module and these also should be closely controlled. The casual or uncontrolled use of forklifts creates a different environment of lifting forces than that from suspension by a crane and rigging. Every lift is a new application of loads and involves *risk* which must be eliminated through appropriate design and practice.

H1.0.0.8

The *Designer* should ensure that all intended lifting activities are identified and designed for. Where an individual module has more than one lifting arrangement (e.g. to suit differing arrangements at the factory and at the project site) these should be specified (and clearly documented) so as to avoid confusion.

H1.0.0.9

It should not be left to riggers to determine how a module is to be lifted. The *Designer* of lifting should be *competent* in structural engineering and be informed about common and efficient rigging practices and incorporate these where suitable.

H1.0.0.10

By definition any lifting activity involves movement of materials and/or people and typically the use of mechanised plant (e.g. cranes, forklifts). The use of plant is usually regulated and in addition there is much complementary guidance for lifting and handling of specific materials (e.g. structural steel, *prefabricated concrete*, prefabricated timber frames). Although generally of short duration, any necessary lifting operations are frequently the highest *risk* phase in the life of any modular structural element and such *risk* warrants corresponding control from the *Designer* and *construction compliance supervisor*.

H1.0.0.11

Technical and safety aspects to be considered in the lifting design and operation include:

i. Observation of any regulatory requirements concerning competencies and documentation, and clarification of responsibilities for any *certifications* required
ii. Where any proprietary equipment or products are specified (e.g. rigging, *anchors*/connection fittings), the suppliers may also have obligations to provide information about capacity ratings, safe design and use.
iii. Different proprietary products or components should not be combined without validating their compatibility, either by testing or supplier *certification*.
iv. Clarification and communication of responsibilities for information to be relied upon (e.g. module mass, pick-up and set-down conditions [including any requirement for reorientation], capacity of crane set-up area, rigging configuration)
v. For reusable lifting devices periodic proof-testing may need to be performed and verified.
vi. Clarification of the intended module stability and support conditions for the completion of the lift (e.g. connections, temporary bracing). If a satisfactory completion is not detailed so as to permit safe disconnection of rigging then the lift should not commence.
vii. Modules must never be used for any purpose when being lifted, especially not to transport people or to transport materials not allowed for in the lifting design.
viii. Modules must never be lifted or suspended over persons below.
ix. All materials within a module must be directly secured.
x. The lifting design should specify the intended rigging configuration, especially the use of any angled *slings*. Where angled *slings* are specified this commonly transfers additional axial compression loads into the module/lifting spreader for which the module/lifting spreader must be designed.
xi. The lifting design should account for the static load distribution between multiple *slings*. Where multiple lift points are used and the lifting device is not self-equalising, the majority of the load may be supported by a single lift point, leading to an increased *risk* of failure.
xii. The lifting design must show the *Centre of Gravity* (*CoG*) for the module. To ensure the module does not swing as it separates from supports, the crane lifting hook (to which the rigging attaches) should be positioned vertically above the *CoG*.
xiii. The lifting design must show the actual mass of the module so the crane operator can detect if there is a problem which might lead to destabilising or damaging the crane or the module.
xiv. The ability of a module to tolerate distortion during a lift should be assessed and the rigging detailed accordingly. Load equalisation mechanisms may be required for multiple *slings*.

xv. Potential behaviour at overload and ductility of materials should be reviewed. If insufficient ductility is available then it is recommended to consider increased redundancy, alternate load paths or increasing the design load factors (i.e. design the module for *robustness* at overload).

xvi. A process for capacity assurance for non-proprietary systems, especially for connections and even relying upon proprietary products (e.g. on-site welding, post-installed concrete *anchors*)

xvii. A contingency plan should be documented should a lift, once commenced, not be completed as intended and the module needs to be laid down elsewhere. The support conditions should be noted.

xviii. Where a module is to be placed in proximity to others the sequence is to be detailed, accounting for working space and temporary works clearances, especially for required connections.

H1.0.0.12

Design loads for lifting are derived from material self-weight onto which loading factors may be applied which determine the specification of the lifting points and rigging. The rigging configuration itself (e.g. inclined *slings*) may impart additional loads to the module during the lift. The following should be considered where applicable for load factors:

i. **Dynamic allowance** – for crane winch speed and braking and minor impacts, the load factor should not be less than 1.2.

ii. **Sling angle** – for the included angle between slings to a common point, load factors should be applied as in **Table H1**, with an example depicted in **Figure H1**. Note that induced compression in the module will also increase as *sling* angle increases.

iii. **Support adhesion** – to overcome adhesive effects of concrete to the casting bed. See **AS3850.2** [5.12].

iv. **Service life** – to account for intended multiple lifting in-service. Typically to be assessed on a case-by-case basis, although for *prefabricated concrete* use 1.6.

Table H1 – Sling angle factor applied to lifted element and lifting points (2-dimensional)

Included Angle	Sling angle factor
0°	1.00
30°	1.04
60°	1.16
90°	1.42
120°	2.00

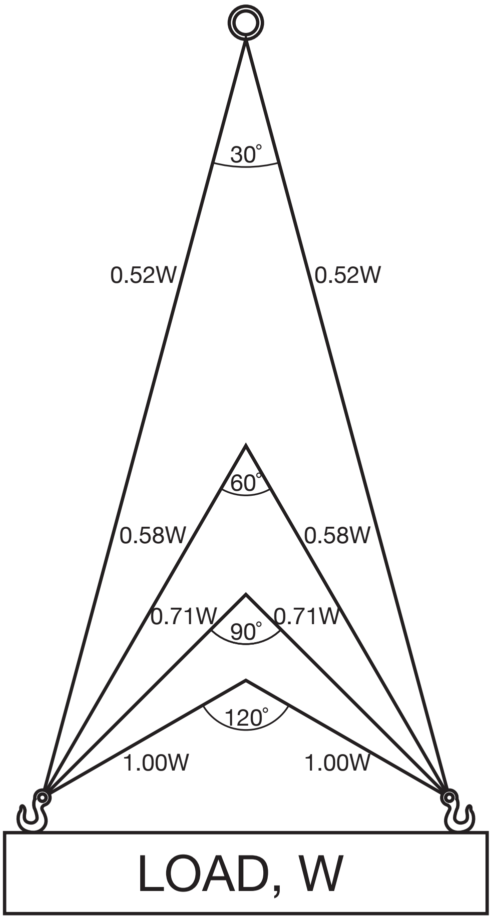


Figure H1 – Effect of sling angle on loads in slings and lifting points.

H2 Procedure

H2.0.0.1

Construction safety in Victoria is regulated under the general provisions of *Work Health and Safety* law, as is the case in many other jurisdictions. In addition, there are other provisions for designated “high-*risk* construction work”.

Before attending to the technical requirements for proposed transportation, erection and temporary works for *Modular Construction* it should be emphasised that this can be a complex process of specialised competencies and accountabilities and the interfacing among them.

H2.0.0.2

The Heavy Vehicle National Law [2.2] seeks to codify transport safety under provisions for *Chain of responsibility* and identifies several active participants in this Chain, in short any person with an influence and/or control in the transport chain. It recognises the actions and requirements of on-road and off-road parties in the transport and supply chain, and assigns their accountability. As with building law (reflected in the *NCC*) the Heavy Vehicle National Law is performance-based, with a primary requirement for loads to be restrained to prevent unacceptable movement during all expected conditions of operation. Therefore load restraint systems must prevent:

i. Load dislodgement from the vehicle
ii. Unlimited load movement, such as may adversely affect vehicle stability and weight distribution

H2.0.0.3

Under the Heavy Vehicle National Law [2.2] *Chain of responsibility* duties may apply in the following examples:

i. A heavy vehicle driver breaches fatigue management requirements or speed limits
ii. A heavy vehicle driver breaches mass, dimension, or loading requirements
iii. Where any instructions, actions or demands by any parties in the supply chain cause or contributes to an offence

H2.0.0.4

It is noted that, as with all contracts generally, transport-related contracts that may require a driver or others to break the law (e.g. concerning road safety) are illegal.

H2.0.0.5

For additional guidance the **CTU Code** [6.5] also provides for a *Chain of responsibility* across all transportation modes.

Regardless of whether such a regulated *Chain of responsibility* process exists in all areas of logistics the ultimate aim should be to ensure heavy vehicle movements (via road, rail or sea), as are required for *Modular Construction*, are safe and efficient.

H2.0.0.6

The *Builder* should ensure that a process is agreed for assigned responsibilities in the transportation and supply chain, at least ensuring regulated duties are assigned and communicated.

H2.0.0.7

All activities involving transport, erection and temporary works for modular structures should have a documented procedure as approved by an identifiable *competent person*. Safety in road transport is comprehensively regulated in Australia at Federal and State levels, including the restraint of loads.

H2.0.0.8

The Load Restraint Guide [6.4] outlines the minimum regulated Performance Standards that must be satisfied concerning safe carriage of freight including prefabricated modules. The *Designer* should make provision not only for the support connection and restraint of modules on the vehicle but also for the corresponding restraint loads on a module where tie-down methods are used.

H2.0.0.9

It may be prudent for any inspections required before transport from one location/contractor/jurisdiction to another to be repeated on arrival before subsequent works. In the case of inspections for regulated systems (e.g. plumbing, electrical) this is strongly recommended for quality *compliance* reasons and to manage accountability. The *Designer* and construction *compliance supervisor* are reminded that the Heavy Vehicle National Law includes provision for *Chain of responsibility* to ensure that off-road parties with influence over on-road behaviour are held appropriately accountable.

H3 Transportation

H3.0.0.1

Transportation is one area in particular where *Modular Construction* introduces novel considerations. In conventional construction, raw materials are transported to the site, where they are processed and built up to form sections of the building. In *Modular Construction* however, sections of the building are manufactured off-site and are transported to the site where they are connected to other modules and structural elements.

Some aspects of transportation have already been discussed in **Sections A1.2.3–A1.2.6**, specifically with regards to structure and loads. In this section, more attention is given to the general logistical aspects of transportation.

The nature of the transported materials is very different in modular construction, and guidance is necessary everywhere along the logistical chain to ensure that the product retains its integrity, and that safety is observed.

H3.0.0.2

Transportation practices for freight are regulated for many of the same reasons applicable to vehicle design and manufacture—primarily for personal safety and damage protection. It should be remembered that any conveyed load becomes part of the vehicle (on road, rail or sea) and affects its behaviour. Given the actual and potential effects of conveyed freight on the behaviour of transportation vehicles it is worthy of detailed consideration.

H3.0.0.3

The *Designer* of the modular structure should assess what information and competence is required for specifying satisfactory transportation details, including that for regulatory *compliance*.

H3.0.0.4

The goal is to complete any transportation of goods without damage to the modules or to the vehicle/transport infrastructure, without *risk* to transport workers and the adjoining public, and without delay or dispute of accountability among the multiplicity of parties who may contribute to the required transportation.

H3.0.0.5

Considering transport internationally as potentially the most complex case, the chain of logistic activity and responsibility from the module manufacturer to receipt by the *Builder* at the project site may include the following:

i. Loading onto a truck (at origin)
ii. Domestic carriage to port of export
iii. Export customs declaration
iv. Unloading of truck in port of export
v. Loading onto export vehicle (via ship/road/rail)
vi. Carriage to port of import
vii. Unloading at port of import
viii. Import customs and taxes
ix. Loading onto a truck
x. Domestic carriage to project site
xi. Unloading at destination

Steps (i) to (vii) are frequently the contracted responsibility of the Shipper (Sender), and steps (viii) to (xi) the contracted responsibility of the Consignee (Receiver).

H3.0.0.6

See **Section A1.2** for structural design considerations for modules in their temporary state (i.e. during manufacture, lifting, transportation etc.) and specifically **Sections A1.2.3–A1.2.6** for considerations where transportation and structure intersect. This includes, for example, dynamic loading, effects of cargo restraints and wind loads which differ from what might be expected in the module's final resting place.

H3.0.0.7

There are other relevant issues surrounding the practicalities and logistics for transport of modules up to and including delivery/pre-erection/acceptance for building inclusion. It is not feasible to describe here all of these issues or to prescribe detailed solutions; it should be an essential consideration from the beginning of a *Modular Construction* project that a detailed logistical solution is necessary, and it is important that it is taken into account in the design of the individual modules or components.

H3.0.0.8

Successful design for *Modular Construction* requires a holistic view of the design, manufacture and assembly process. This involves, in a primary sense, detailed application of knowledge of the modular form to guide the design of the completed building. A secondary, but still important, aspect of the process is detailed application of knowledge of the necessary transport and handling modes being employed. In some cases (e.g. volumetric modular construction) the transportation vehicles and lifting apparatus provide a restrictive upper bound on the dimensions and weight of the module. The *Designer* must work carefully to comply with the client's specification, whilst at the same time respecting these limits.

H3.1 Transportation modes

H3.1.0.1

The transportation modes which are most likely to be employed in modular construction, and indeed in any form of construction, are shipping, road and rail transport. Different *Modular Construction* projects may employ these modes in different proportions. For example, one project may involve off-shore manufacture and shipping of completed volumetric modules, while another project might employ a domestic manufacturing facility, in which case the transportation may be limited to road or rail. The mixture of these modes and the routes taken by each will have ramifications for the success of the project.

H3.1.0.2

Common issues for all transport modes are the potential exposure of modules to conditions of relatively severe acceleration and tie-down forces, air pressure, water impact and humidity, and dust impregnation. For transport across jurisdictional boundaries there may also be issues concerning quarantine and protection of modules from unauthorised access, biosecurity, presence of contaminants and contraband.

H3.1.0.3

Where load restraint of modules relies upon friction effects, the *Designer* should allow for tie-down forces applied to each module.

H3.1.0.4

The *Designer* may consider the option of limiting exposure of the most sensitive building materials (e.g. glazing, plasterboard, HVAC plant) to the most adverse transport impacts by completing manufacture with sensitive materials close to the project site.

H3.1.0.5

The *Designer* should consider the *risks* to material conditions and safety resulting from the transportation process. While modules should be packed and sealed to prevent unwanted intrusion of foreseen external influences there may be some *hazard* from volatile chemical components of building materials being released internally. Appropriate ventilation should be considered, without compromising any required barrier to external sources.

H3.1.0.6

Generally speaking, it is difficult to prescribe a detailed logistical solution for transportation of modules or components, since it is highly dependent on the specific *Modular Construction* project. Each project will require a detailed *risk* assessment at the outset to ensure that the project can be completed within the allowed time and cost windows.

H3.1.1 Shipping

H3.1.1.1

Shipping transport commonly (though not exclusively) involves international carriage between national jurisdictions and increased *risks* of adverse conditions through open seas. Domestic shipping (e.g. around the Australian coast) is likely to be simpler on both counts.

H3.1.1.2

The *Designer* and *Builder* should be cognisant of the logistic constraints applicable to shipping transport, including:

i. Standardisation preferences for cargo dimensions
ii. Tie-down/lashing requirements
iii. Specialised/certified packing within units as acceptable cargo
iv. Lead time *risks* for transit and handling delays up to export and from importation
v. Implications of stowage location regarding movement accelerations and weather exposure
vi. Control of security *risks* (for customs related matters) from international shipping

H3.1.1.3

Additional guidance is contained in the **CTU Code** [6.5]. The guidance includes advice on safe packing of cargo, condensation damage, and supply chain management. See also **Section A1.2** concerning restraint of cargo.

H3.1.2 Road

H3.1.2.1

At some point, most modular systems will need to be transported by road. It is therefore important to optimise the system to allow for an efficient and safe road transport method. Road transport will typically involve transport of precast, flat pack or volumetric modules on the back of a heavy cargo transport vehicle. Important considerations include how the load is distributed with respect to the carrying capacity of the vehicle, how the cargo is restrained, and dynamical loading.

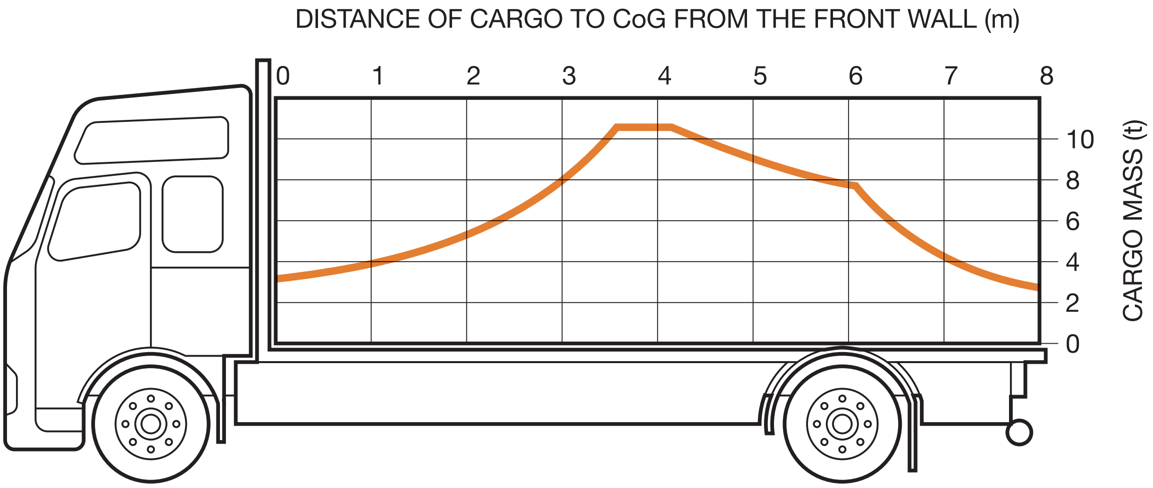


Figure H2 – Example of a load distribution diagram for a rigid truck (**CTU Code** [6.5]).

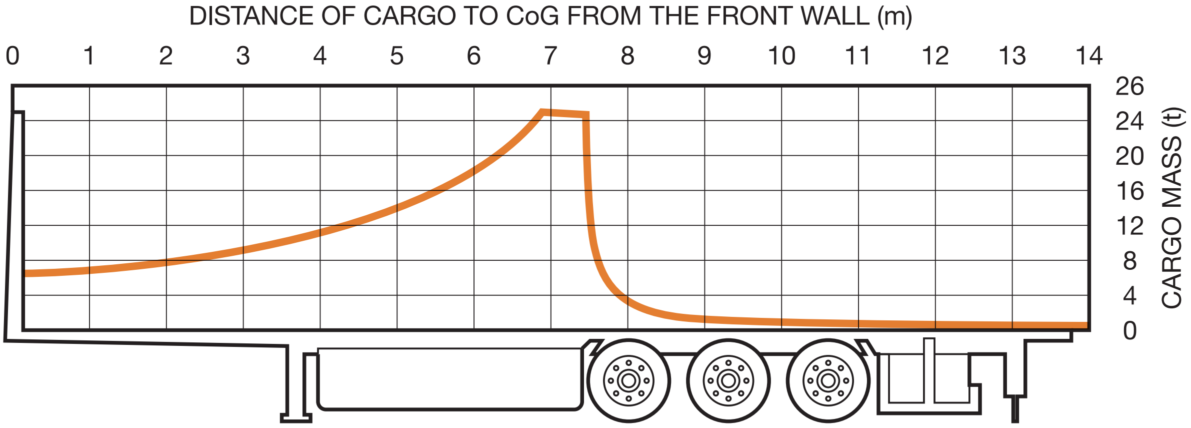


Figure H3 – Example of a load distribution diagram for a semi-trailer (**CTU Code** [6.5]).

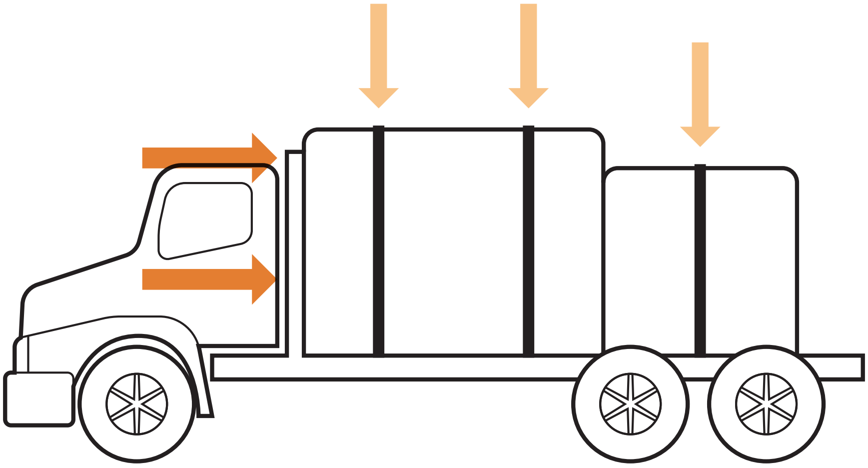


Figure H4 – Example of load restraint

H3.1.2.2

In most jurisdictions there will be regulations covering road transport of cargo, particularly with respect to restraining loads. In Australia, the **Load Restraint Guide** [6.4] from the National Transport Commission should be complied with or alternate measures employed which are verified to meet the Performance Standards in the Regulations. See in particular Section F in [6.4]. Additional guidance is contained in the **CTU Code** [6.5].

H3.1.2.3

The maximum size of transported modules is limited by individual state laws governing semi-trailer transportation. As well, city and county governments sometimes impose additional regulations. These laws place various restrictions on transportation such as permit requirements, maximum dimensions, times of day, roads, route reporting requirements, and maximum weights. Modules can be most economically transported if they do not require a permit and/or escort. There are differences between states in Australia in terms of permit requirements, so a detailed assessment of these requirements is advised at the outset of a *Modular Construction* project.

H3.1.2.4

Acceptable loading characteristics of road truck types need to be understood in relation to proposed loads before detailing the transport of specific modules. For example, the nominal cargo capacity of a truck is dependent upon the load placement and distribution. See **Figures H2** and **H3** which have been extracted from the **CTU Code** [6.5]. Note the significant and sudden capacity reduction for a semi-trailer where the load centre-of-gravity is not forward of the first axle.

H3.1.2.5

Load restraint is achieved via direct bearing/force transfer to the truck body or by friction or by combining them. Friction resistance is the product of the vertical force applied (from weight of goods plus from any tie-down lashings) and the friction factor at the two surfaces in contact. Friction forces will oppose the tendency of the cargo to slide along the flatbed, which occurs during acceleration as when the vehicle accelerates, brakes or turns. Tables of friction factors for various material combinations are given in the **CTU Code** [6.5].

As an example of friction forces in cargo transport, the friction factor for a wooden pallet against grooved aluminium is 0.3, which means that under typical conditions, the friction at the interface between these surfaces can provide at most a resistance of 0.3 times the total down force on the pallet (including goods weight and tie-down forces).

H3.1.2.6

Direct restraint may be achieved by mechanical connection with the load (e.g. using twist-locks onto a shipping container or connected chains) or by blocking/containment between the load and truck body in the direction to be restrained. In **Figure H4** the load is restrained:

i. From forward movement by a combination of friction produced by the load weight and lashing tie-down force, and also blocking against the headboard
ii. From rearward and sideways movement by friction only
iii. From upward movement by direct restraint of the lashings

H3.1.2.7

Additional guidance is contained in the **CTU Code** [6.5]. See also **Section A1.2** concerning actions to be restrained. The *Designer* should note that road transport for significant distances at high speed may initiate fatigue effects. This is caused by cyclic loading due to vibrations and regular oscillatory motion during transport.

H3.1.2.8

Restrictions of oversize and/or overmass load-carrying vehicles apply in Australia and other jurisdictions. In Australia this falls under the auspices of the National Heavy Vehicle Regulator (NHVR). The NHVR has made available detailed guidelines for the transport of oversize/overmass cargo. Some state road authorities have also issued guidelines that make specific comments relating to restrictions and considerations in those regions.

H3.1.2.9

The *Designer* should take into account the mass limits that may be imposed on the modules or components by regulations throughout the logistical chain. Particularly in the case of transporting large volumetric modules over great distances it may be preferable to employ the services of a logistics expert who has a thorough understanding of all the pertinent issues.

H3.1.2.10

The Heavy Vehicle National Law (HVNL) provides for **three classes** of heavy vehicle as a means of managing the different access requirements of different types of heavy vehicles. Some, but not all, jurisdictions had similar classes under previous legislation. Vehicle classes will appear on legal documents such as permits and notices, and while beneficial, it is not necessary for operators to remember or know what class of vehicle they operate. Common terminology describing heavy vehicles, such as B-doubles and mobile cranes, will continue to be used by the National Heavy Vehicle Regulator (NHVR).

H3.1.2.11

Class 2 general freight carrying vehicles have been designed to efficiently transport 20 and 40 foot container sized freight. These vehicles provide the most cost effective means of transporting standard-sized freight. However, many modular structures are oversized and cannot be transported within a 20 or 40 foot container envelope. The transport of oversized freight will be managed by Class 1 Oversize/Overmass vehicles (OSOM). Although the NHVR has been set up to administer a national set of heavy vehicle laws, OSOM vehicles still require access permission from each state and territory road agency. These are described in the following clauses.

H3.1.2.12

Class 1 Oversize/overmass vehicles: An oversize or overmass vehicle is a heavy vehicle or combination which alone, or together with its load, exceeds prescribed mass or dimension requirements, and is a heavy vehicle carrying, or designed for the purpose of carrying, a large indivisible item. This does not include road trains or B-doubles, or vehicles carrying a freight container designed for multi-modal transport. Examples include a prime mover and extendable trailer or a prime mover and low loader combination.

H3.1.2.13

Class 2 Freight-carrying vehicles: General freight carrying vehicles that are longer than 19 m require specific networks that are capable of handling these larger vehicles. This is usually managed by declaring route networks in gazette notices, but where a network does not exist, an operator may apply for a permit. There are a number of common Class 2 heavy vehicle combinations.

A B-double is a class 2 heavy vehicle that consists of a prime mover towing two semitrailers, with the first semitrailer being attached directly to the prime mover by a fifth wheel coupling and the second semitrailer being mounted on the rear of the first semitrailer by a fifth wheel coupling on the first semitrailer. A B-double must comply with prescribed mass and dimension requirements.

B-triples are categorised as road trains (HVNL s5 - definitions) and must comply with prescribed mass and dimension requirements. B-triples sometimes have dedicated networks declared that may be different to road train networks.

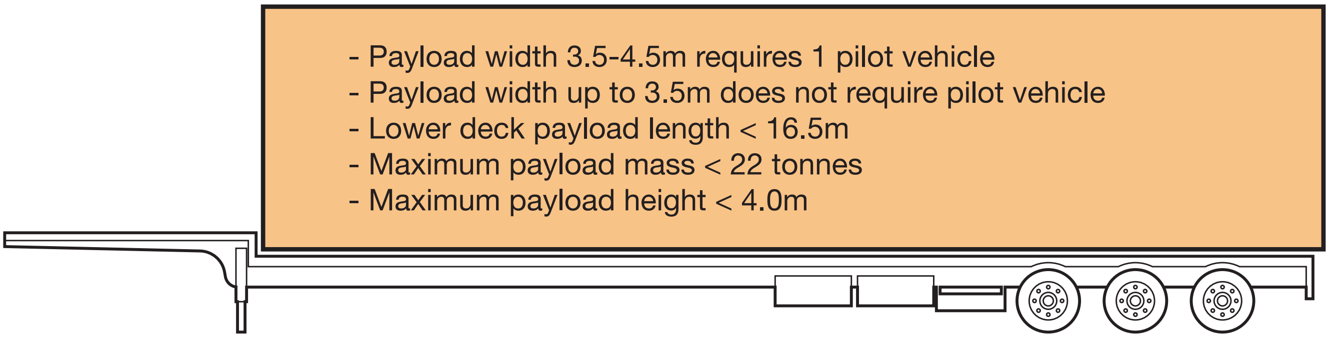
A road train is a Class 2 heavy vehicle that consists of a motor vehicle towing two or more trailers (excluding converter dollies supporting a trailer). Road trains must comply with prescribed mass and dimension requirements.

H3.1.2.14

Performance-Based Standards (PBS) vehicles: Performance-Based Standards (PBS) vehicles are defined as Class 2 heavy vehicles. There are four levels within the PBS Scheme, and these vehicles must meet twenty safety and infrastructure standards and are designed to offer higher levels of safety and productivity. PBS vehicles are able to operate on road networks that have been classified as suitable for their level of performance.

H3.1.2.15

Class 3 heavy vehicles: A Class 3 heavy vehicle is a heavy vehicle which, together with its load, does



- Payload width 3.5-4.5m requires 1 pilot vehicle
- Payload width up to 3.5m does not require pilot vehicle
- Lower deck payload length < 16.5m
- Maximum payload mass < 22 tonnes
- Maximum payload height < 4.0m

Figure H5 – Typical module size constraints when using a drop extendable trailer not comply with prescribed mass or dimension requirements and is not a Class 1 heavy vehicle. A truck and dog trailer combination consisting of a rigid truck with 3 or 4 axles towing a dog trailer with 3 or 4 axles weighing more than 42.5 tonnes is an example of a Class 3 heavy vehicle. Other examples might include a B-double or road train transporting a load wider than 2.5m.

Class 3 heavy vehicles do not include PBS vehicles or heavy vehicles complying with prescribed dimension requirements but operating under Concessional Mass Limits (CML) or Higher Mass Limits (HML).

H3.1.2.16

Figure H5 indicates typical module size constraints when using a drop extendable trailer. These size and mass constraints may factor significantly into the design process, since they will either restrict the use of modular construction techniques to lighter individual components, i.e. moving more towards flat-pack modular form, or will otherwise restrict the nature of what open spaces will be possible in the completed structure limited by the size of modules that can be transported.

H3.1.2.17

In addition to size and mass considerations, it is also important to consider further requirements for transport of large cargo, for example requirements for warning devices and escort vehicles. Personnel involved in the transport process should refer to materials published by the relevant authorities as to what measures must be taken (for example, the NHVR in Australia).

H3.1.3 Rail

H3.1.3.1

When considering the use of rail transportation for modules the *Designer* should consider the specific rail corridors and rolling stock operators being proposed. Even for rail track of the same gauge (distance between rail running faces) the permitted envelopes within which transported cargo must fit may vary in different locations and networks.

H3.1.3.2

Rail corridor operators specify a Loading Gauge (static) or Dynamic Envelope which is the dimensional limits within which loaded rolling stock must fit. The dynamic envelope includes factors allowing for suspension movement, lateral overhang on curves (between bogies and at end projections), and lateral motion around curves or through permitted rail alignment tolerances at speed. Outside this there is also a Structure Gauge within which no structures ought to encroach (e.g. station platforms, tunnels, trackside furniture). Between these outlines is the required clearance, which is needed not just to avoid geometric obstruction but also for acceptable aerodynamic flow (through tunnels and especially for passing trains) and electrical separation from any overhead wiring.

It follows also that security and integrity of the exterior surface of the rail cargo should be assured to avoid unintended clearance encroachments.

H3.1.3.3

The *Designer* should account for combinations of train/wind speeds and rain as it may simulate cyclonic effects. The *Designer* should also account for peak accelerations/impacts from rail yard shunting, and peak air pressure waves when transiting tunnels. See **Section A1.2.6** for more details.

H3.1.3.4

Additional guidance is contained in the **CTU Code** [6.5] concerning rail transport of modularised cargo.

H4 Erection

H4.1 Sequence

H4.1.0.1

Sequencing and planning the order and progress of the modular erection sequence is critical to the site build as well as to the manufacturing supply line. The role of the *Designer* includes:

i. Coordinating tolerance specification and control for all stages of connection
ii. Applying *risk*-based checks and continuous improvement processes to ensure quality output
iii. Addressing issues relating to module exposure to a range of conditions and localised environments over the module life cycle

H4.1.0.2

The *Designer*, in consultation with the *Builder*, should specify the erection sequence and ensure the integrity of structural staging and any necessary temporary works. The temporary works may also extend to progressive weatherproofing for the exposed modules and particularly for any surfaces not forming part of the building exterior.

H4.1.0.3

Where the lead time for module supply is long (e.g. from overseas) the *Builder* should have contingency activities on-site for the workforce (even multiple options for erection sites on larger projects) and/or pre-delivery storage close to site as a lead time buffer.

H4.2 Tolerances

H4.2.0.1

Whereas generous erection *tolerances* might seem to aid construction, it creates problems for completion of connections and assurance of connection performance. This applies to all systems requiring connection – e.g. structure, services, insulation, weatherproofing.

H4.2.0.2

Concerning *Modular Construction* in particular the *Designer* should allow for connection systems which can accommodate fit-up misalignments within the range of specified *tolerances*. In multi-story buildings for example, where a dimensional verticality *tolerance* over a storey height is specified the *Designer* should consider an inter-storey connection system which can correct for any misalignments so they do not accumulate over several levels.

H4.2.0.3

There should be consultation between *Designers* of various aspects (structural, mechanical, electrical, etc.) to accommodate the permissible *tolerances* between modules in all building systems.

H4.2.0.4

Reference should also be made to **Section E2** which discusses *tolerances* in manufacturing, and stresses the necessity for the *Designer* to coordinate *tolerance* specification and control for all stages.

H4.3 Checks

H4.3.0.1

Processes for checking of work could arguably be inadequate and thus *risk* an assured project outcome or lead to an inefficiently burdensome cost providing poor value — both outcomes risking project success for all parties. The adopted checking process should be developed on a *risk*-based approach and be open for review, seeking continual improvement. In many cases better design can simplify and streamline inspectorial costs without compromise of quality output.

H4.4 Corrosion and Fire Protection

H4.4.0.1

During transportation and construction activities modules and elements within modules may be exposed to conditions and localised environments which may not be repeated during the service life once the structure is complete. Even so, the *Designer* should account for such exposure as a foreseeable phase of the module lifecycle.

H4.4.0.2

In relation to moisture exposure the effects of any short-term absorption or adsorption prior to erection (due to free water ingress or hygroscopic dampening of materials) may be worsened after the erecting and sealing-up of the modules as they are incorporated into the building. Poor ventilation may nurture conditions for progress of corrosion (see **Section F2**) and/or mould growth.

H4.4.0.3

As in the case of structural safety, the service life of the structure must maintain stability at all times during the construction before, and demolition after. Similar provisions apply to fire resistance in the construction phase. The *NCC* [6.2] mandates a *Performance Requirement* (Vol1, EP1.5) that:

> “suitable means of fire-fighting must be installed to the degree necessary in a building under construction to allow initial fire attack by construction workers and for the fire brigade to undertake attack on the fire…”[1]

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[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

J

Chapter

Compliance with Building Codes

J Compliance with Building Codes

J1 Procedures

J1.0.0.1

This Handbook has no inherent legal status. It is not a regulation (as would be enacted by Government) nor is it referenced from legislation but may assume some influence in particular circumstances where there is agreement among participating parties. It may, for example, be referenced from contractual documentation for specific construction projects.

The Building Codes referred to in this section are those regulatory controls based upon the *National Construction Code* (*NCC*) [6.2] and enforced across Australian jurisdictions which focus on **prevention** of *risks* to:

i. Personal safety and health; and
ii. Property damage; and
iii. Amenity (functions and facilities with health and safety impacts); and
iv. Sustainability outcomes

These objectives are to be applied in the design, construction and performance of buildings.

The principles behind these controls are replicated to a similar extent in many jurisdictions internationally.

J1.0.0.2

There are further implications directly for the *Designer*, *Builder* and other relevant persons (in addition to those from the *NCC*) on account of *WHS* [6.3] regulation. These relate to risks arising from the construction, operation, maintenance and demolition of a structure. Refer to **Chapter G** for more details on safety, but note that the *Designer* must provide adequate information with the design about any conditions necessary to ensure the structure is without *risks* when used as intended through its life cycle, as per regulation.

Other regulatory *compliance* is required for matters relating to transport, which also is typically an activity applicable to *Modular Construction*. See **Chapter H** for more details about transport and related matters.

Separate regulatory *compliance* issues may arise from any pertinent consumer laws should there be problems with *non-conforming building products*. All parties should be aware of the distinction between *non-conforming building products* and *non-compliant building products* and the requirements associated with each, including responsibility to prevent occurrence.

In common with *compliance* matters generally there should be an effective form of recorded verification (refer also **Chapter K**).

J1.0.0.3

The regulatory framework around the Australian construction industry is controlled by the States and Territories. A structure is assigned a Building Classification on the basis of its intended function. If it is proposed to vary a building's function then its classification should be reviewed. There are uniform **technical** provisions in building regulations across all jurisdictions in Australia. These are embodied in the *NCC* which is formed by the Australian Building Codes Board (ABCB), a Council of Australian Government (COAG) standards writing body comprised of the Building Code of Australia (BCA) and Plumbing Code of Australia (PCA). The *NCC* is adopted in each jurisdiction, whereas for **administrative** provisions (e.g. permits, licencing, offences) each jurisdiction makes its own arrangements independently under their respective Building Acts and regulations.

J1.0.0.4

The *BCA* is performance-based regulation such that the only mandatory terms for *compliance* are the stated minimum *Performance Requirements*. These define various aspects of interaction between building design/construction with occupant requirements and wellbeing.

The *Performance Requirements* arise from the aspects noted in **Table J1** (see *NCC* for specific details) which summarises the stated *NCC* Objectives for each aspect of performance. It should be noted that the *NCC* is a minimum standard, not "the standard" that should be adopted. A Safety in Design (SiD) review may identify design outcomes that exceed the requirements of the *NCC*.

J1.0.0.5

The building must meet the *Performance Requirements* and so the *Designer*, *Builder* and other relevant persons should ensure this is done. The only options are to propose any verifiably acceptable **Performance Solution** (formerly termed **Alternative Solution**) or to apply a **Deemed to Satisfy** (or **DtS**) **Solution** as described in the *NCC* (see **Figure J1**). There is no assurance that a DtS solution is optimal, most efficient or the best possible solution. However, clause A0.4 specifies that a DtS solution complying with DtS provisions is automatically deemed to comply with *Performance Requirements*. References to Australian Standards frequently form part of the DtS provisions in the *NCC*. If DtS solutions are met, it is not usually necessary to consult further design guidance. It may however be pertinent for the *Designer* to consult with international Standards or Codes for subjects which are not adequately covered by the DtS provisions.

Table J1 - Aspects of regulated building Performance (from NCC [6.2])[1]

Aspect of Performance	Objective Summary
Structure	Safeguard people from injury and other property from damage due to structural failure (including from glazing) and safeguard people from loss of amenity caused by structural behaviour.
Damp and weatherproofing	Safeguard building occupants, the building and other property from damage caused by external and internal water sources.
Fire safety	Safeguard building occupants and other property from a building fire and protect the building from bushfire effects.
Health and amenity	Safeguard building occupants from injury and loss of amenity from wet area use, and inadequacies in room size, hygiene facilities, lighting, ventilation and sound insulation.
Safe movement and access	Provide people with safe access to and within a building and safeguard people from injury associated with swimming pools.
Energy efficiency	Reduce greenhouse gas emissions

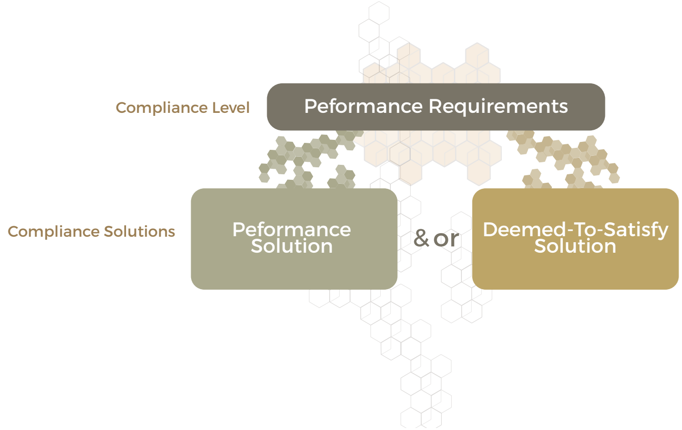

Figure J1 – Extract from NCC 2016 Vol 1 illustrating Performance Requirements and compliance solutions generally[1].

Building-related regulations extend also to hydraulics (water supply and drainage) and electrical services to cover both technical aspects and the licenced workers who provide construction services. The Plumbing Code of Australia (PCA) is covered by *NCC* Volume Three.

J1.0.0.6

The *NCC* provides for formalised methods to verify compliance of some *Performance Requirements* including, under the Structural Provisions, for *Reliability* and *Robustness* in all buildings.
The *Designer* should be conversant with these obligations. See **Chapter A** for more details on these topics.

J1.0.0.7

Although the main focus in the *NCC* is on the performance of the completed building there are also aspects applicable specifically to the construction phase. These include:

i. Structural stability (*NCC* Vol1, BP1.1(a))
ii. Fire-fighting equipment (*NCC* Vol1, EP1.5)

There is also a specific fire resistance *Performance Requirement* concerning failure behaviour and stability of concrete external walls in a fire (see *NCC* Vol1, CP5, Clause C1.11 and Specification C1.11).

It is important to note again that *Modular Construction* is just a form or method of construction around which design detailing has been customised. The *NCC* takes little account of the method of construction, only the performance of the building in-service and during construction. A similar example of this is typical precast concrete which is just a method of construction with reinforced concrete. In the Australian context the NCC makes minimal reference to aspects specific to precast concrete but in all aspects precast concrete must comply with the technical design provisions of the main guidance for concrete structures. **AS 3600 Concrete Structures** is referenced in the NCC whereas **AS3850 Prefabricated concrete Elements** is not.

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[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

J1.0.0.8

The *Designer* should ensure that the design details comply with any relevant regulatory provision and should document with clear accountability how *compliance* has been verified. The issuing of a prescribed form of ***design certification*** by a *certifier*, for example under Regulation 1507 in the Victorian Building Regulations [1.2], does not verify or document the basis for assessment and issuing of the *certification*.

J1.0.0.9

Designers/Owners should consider the need for *Builders* to be formally certified to the internationally recognised **AS/NZS ISO 9001 Quality Management Systems standard** [5.11], or at a minimum, work in accordance to this standard. This requirement may need to take into account the industry, risk, *WHS* requirements, complexity etc.

Designers/Owners are advised to conduct evaluations and assessments on suppliers/subcontractors to ensure that they have the appropriate facilities, personnel, *WHS* systems, quality systems etc. to effectively manufacture or fabricate the intended design. The level of evaluation can be dependent on the risk/cost and could simply involve the completing of a questionnaire or the *Designer*/Owner undertaking a contract pre-award audit of the preferred supplier/subcontractor.

J1.0.0.10

Local authority and state-based regulations must also be complied with. This may include specific codes, guidelines and frameworks for licensing and standards of workmanship.

J1.0.0.11

A *certifier* who issues a prescribed form of inspection *certification* should document with clear accountability how *compliance* has been verified. The issuing of a prescribed form of inspection *certification* by a *Certifier*, for example under Regulation 1507 in the Victorian Building Regulations [1.2], does not verify or document the basis for assessment and issuing of the *certification*.

A separate assessment of *compliance* is required to verify that all of the *Designer's* specifications have been fulfilled, possibly as a contractual requirement. See **Chapter K** for more details.

Although unlikely, it is conceivable that a design may or may not comply with regulation independently of the as-constructed structure which itself may or may not comply. It is a separate consideration again, with contractual implications, as to whether the as-constructed structure complies with the design, as may be verified by the *construction compliance supervisor*.

There are other aspects of administrative *compliance* with Building Regulation which on various projects at times might be overlooked if not enforced but which may offer tangible benefits. Being codified in regulation makes such measures not only straightforward to mandate on a project but establishes an onus on any relevant duty-holder concerning compliance regardless of what may or may not be agreed for a specific project. This should improve confidence in outcomes and the prevention of unsafe results.

Using the Victorian Building Act and Regulations [1.2] as an example, the range of provisions include:

i. The Building Surveyor must state on the Building Permit the stages of construction (some of which are mandatory) for which notification must be given to allow inspection for approval, prior to work continuing to the next stage.
ii. The *Builder* must call for inspections for the designated notification stages, noting that a given stage could be reached more than once in each project.
iii. The Building Inspector must properly inspect designated works and not approve them where non-compliant.
iv. Except for specified minor works exempt from requiring a Building Permit all building work requires a Permit to be issued prior to work commencing.
v. The Building Surveyor must assess an application for a Building Permit for compliance with the Act, the Regulations, and the relevant *Performance Requirements* of the *NCC*.
vi. The Building Surveyor is responsible for the inspections at mandatory stages.
vii. The *Builder* should maintain a full set of most updated approved plans and other relevant documents on site for the Building Surveyor to view during inspections.
viii. Should the *Builder* propose

any variation to the design or construction process that differs from approved documents as per the Building Permit they first require approval by the Building Surveyor before the relevant work is undertaken.

ix. Professional standards of competence, independence and vigilance regarding conflicts of interest where actual or potential.

In the case where the *Builder* or another person alters or modifies a design without consulting the original or subsequent *Designer* it is likely that person will be deemed to assume the duties of a *Designer*. Note that this would be illegal under the Engineers Act 2002 if the alteration involves the provision of professional engineering services.

The process of assessing an application for a Building Permit would require assessing the design documentation for compliance with relevant regulatory provisions. Where the Building Surveyor is not appropriately competent regarding the required technical matters he should obtain any relevant certification of design compliance from a *competent person*. The issuing of a Building Permit can be an effective Hold Point to prevent construction with *non-compliant building products*.

J1.0.0.12

The mandatory notification stages in the State of Victoria which must be set out in the Building Permit are:

i. Prior to placing a footing
ii. Prior to pouring an in-situ reinforced concrete member as nominated by the Building Surveyor
iii. Completion of framework
iv. Upon completion of all building work

The *Designer* and *Builder* should be aware of the equivalent stages in their own local jurisdiction.

The significance of in-situ reinforced concrete members being cited is that other structural load-bearing materials (e.g. steel, timber, masonry) are incorporated to the building works with their intended physical properties already present. The manufacture of in-situ reinforced concrete is exposed to variations from on-site workmanship and conditions, and pre-pour inspection is preferable for verifying the embedded reinforcement, which is more difficult after concrete pouring.

Where prefabricated elements from any materials are used, as might be maximised with *Modular Construction*, the mandated inspection and verification of framing completion should account for the material integrity of those prefabricated elements and integrity of connections between elements formed on site.

The process of assessing building works for approval would require inspection and verification that constructed materials conform to the approved Building Permit documents. Where the Building Surveyor is not appropriately competent regarding the technical matters he should obtain any relevant certification of inspection compliance from a competent person. The issuing of an inspection approval can be an effective Hold Point to prevent construction with *non-compliant building products* and also with *non-conforming building products*.

J2 Material Performance

J2.0.0.1

Strength of materials, and other important related properties such as elasticity, ductility and durability, is critical to all aspects of required material performance. Even for non-*load-bearing* and nominally non-structural applications (e.g. glazing, paint coatings, interior wall cladding, insulation) the materials require strength to maintain continuity.

J2.0.0.2

A primary focus of the *NCC* and this Handbook is on structural behaviour and design. The structural *Performance Requirements* include the following:

i. During construction and use a structure must perform adequately under all reasonably expected design actions and extreme/frequently repeated design actions, and avoid damaging other properties
ii. Actions to be considered must include (but are not limited to) those prescribed by the *NCC* or relevant local Codes
iii. Analysis of the structural resistance of materials must rely upon the five percentile characteristic values

iv. Special consideration for glazing at *risk* of human impact
v. Special and conditional consideration in flood *hazard* areas for safety in flood waters
vi. Other considerations include cyclonic and earthquake loading

J2.0.0.3

As of 2016 the *NCC* includes provisions for complying with structure *Performance Requirements* specifically concerning *Robustness* and *Reliability* (which are related to structural strength). The *Designer* is reminded that *Robustness* relates to a nominal failure initiation from which subsequent damage is not disproportionate to the cause, and that *Reliability* relates to an acceptably small probability of failure. See **Sections A3.4** and **A3.5** for more details about *Robustness* and *Reliability* respectively.

J2.0.0.4

Concerning *Robustness* (*NCC* Vol1, BV2), for the notional removal of any described building element the building must remain stable and the extent of any surrounding collapse must be limited. Specific *risk* assessment is required for elements supporting more than 25% of the total structure.

J2.0.0.5

Concerning *Reliability* (*NCC* Vol1, BV1), an assessment of the Annual Structural *Reliability* Index (β) for structural components and connections is calculated and must not be less than prescribed values.

J2.0.0.6

All structural behaviours during construction and use which might cause personal injury or cause loss of amenity for use or cause damage to other property are regulated by the *NCC* [6.2] *Performance Requirements* for Structure. This includes actions and induced behaviours such as racking, vibration, lifting (erecting of modules), dynamic transportation loading and material fatigue. The *Designer* should consider all reasonably foreseeable effects. At all times the building, and incomplete structure during construction or demolition, must be structurally safe and stable.

J3 Design by Testing

J3.0.0.1

Compared with conventional construction, the design of modular buildings is more complex and presents considerable risks due to a great deal of uncertainties in the structural behaviour of the assemblies of modular systems. It is therefore recommended that *Designers* consider performance-based design through testing, in order to mitigate the risks associated with those uncertainties.

J3.0.0.2

Design based on data derived by testing may support a Performance Solution in response to mandatory *Performance Requirements*. It may also be a means of justifying greater efficiencies and optimisation of design than is otherwise delivered via following a prescriptive solution.

J3.0.0.3

Specific guidance can be found in Appendix B of **AS/NZS1170.0** [5.2] concerning:

i. appropriate methodology for testing including set-up, specimen preparation and calibration of apparatus
ii. data evaluation and use
iii. statistical assessment of variables and uncertainties
iv. reporting
v. modelling and correlation with reality
vi. criteria for acceptance

Further checks and assessment of constituent material properties may be required for which accepted testing Standards may be used.

J3.0.0.4

The *NCC* (Vol1, A2) makes specific provision for acceptable evidence of suitability to support that the use of a material, form of construction or design meets a *Performance Requirement*. Such evidence may include:

i. A report issued by a Registered Testing Authority (as defined in *NCC*)
ii. A current Certificate of Conformity or current Certificate of Accreditation (as defined in *NCC*)
iii. A certificate from a professional engineer or other appropriately qualified person in the prescribed form (including for calculation methods)
iv. A current certificate as accredited via JAS-ANZ (Joint Accreditation System of Australia and New Zealand)
v. Any other documentary evidence that correctly describes the properties and performance necessary for suitability

J3.0.0.5

It is a stated priority for the Australian Building Codes Board (author of the *NCC*) to develop further the quantification of performance, both as a codified requirement and to build the capacity, knowledge and skills of *NCC* users to embrace the performance-based code.

J3.0.0.6

Additional and complementary guidance for the basis of structural design can be found in **EN1990.0** [6.8] and **Section A2.6** of this document.

K
Chapter
Inspection & Verification

K Inspection and Verification

K0.0.0.1

Without evidence of *conformance* with a stated requirement there can be no reliable confidence that an activity or output:

i. Will achieve the required level of performance
ii. Will achieve *compliance* with relevant regulations
iii. Will enable determination of the progress of contracted duties
iv. Will enable assessment of related claims or disputes
v. Will enable review of what has been done in order to develop improvements, especially after adverse outcomes, structural alterations, functional change of space usage, etc.

K0.0.0.2

The key elements of a valid and effective inspection (e.g. of materials, of a process, of workmanship, of calculations) are:

i. An organised examination (e.g. visually or via sensing technologies, sampling of test specimens like reinforcement bar, concrete, witnessing the test, etc.).
ii. Relevance of the observations (with graphical or photographic record if deemed required) to a specified outcome.
iii. A valid measurement process. Inspection equipment should be calibrated in accordance with manufacturer requirements and operated only by suitably trained personnel.
iv. Competence of the inspector, according to regulation where required (including professional independence).
v. Accountability of the inspector. The inspector must be independent of the construction process or team. They may work for the same company but need to have different reporting lines and responsibilities (e.g. quality of workmanship) as opposed to that of the construction team sho may be driven by cost/schedule.
vi. Traceability of inputs in a documented inspection record (see **Chapter L**).
vii. A uniquely identified inspection record.

If the inspector does not make an assessment of the inspection results to declare *compliance* or non-*compliance* with the required outcome, then the record of inspection should either state that such a declaration has not been made or contain provision for a suitable *competent person* subsequently to do so.

Given that in many cases there are staged demarcations of service provisions and potential liability involved it is also essential to be able to trace personal accountability for the inspections and verifications done. See **Chapter L** for more details about traceability.

During the required project consultation between relevant duty holders, it should be noted that the costs to carry out inspection, verification and traceability activities are to be weighed against the complexity of manufacturing, strict tolerances of design and potential costs (including regulatory, legal, commercial, reputational, critical path impact, rework costs etc.) of correcting non-*compliance* and, worse still, of any consequences it may cause. In practice over time total costs are minimised and value maximised where activities (design and construction) are organised to minimise non-*compliance* especially at its source. This in turn will require less onerous inspection & verification processes and costs.

For example, should an exterior cladding system for a building be designed then the specification should be checked for regulatory *compliance* (with *Performance Requirements*), which may reveal an issue. If found to be non-compliant, then its correction before detailing progresses onto contractual arrangements may prevent non-compliant construction (with respect to regulation) and minimise the *risk* of additional costs beyond that for verification.

Similarly, should the physical cladding system proposed for use, or perhaps an offered substitute, be assessed (via testing or acceptance of *certification*) for regulatory *compliance* then this may reveal an issue. If it is in fact a *non-compliant building product*, then its rejection prior to supply may prevent non-compliant construction and minimise *risk* of additional costs.

Further to this, another complication may arise where the building product is claimed to comply with regulation, perhaps with incorrect documentation, but in fact it does not, in which case it is also *non-conforming building product*. This may have implications with Consumer Law.

Should any of these scenarios progress adversely without timely and effective verification steps the costs to achieve *compliance* later, and for any loss incurred, may be significant.

K0.0.0.3

By means of appropriate processes of inspection, verification and traceability, *compliance* and liability is value-managed:

i. Between design and regulation
ii. Between construction and regulation
iii. Between construction and design

K0.0.0.4

Due to the greater degree of prefabrication in *Modular Construction* it encourages more attention to design detail to accommodate the essential and varied stages of manufacture, transportation and on-site construction. These, in turn, encourage so-called Lean Manufacturing practices which are more likely to produce better end product and process efficiencies.

Without a corresponding increase in the controls to ensure all levels of *compliance* via processes of inspection, verification and traceability the *risk* increases for problems with:

i. Safeguarding people
ii. Protecting property
iii. Regulated building performance
iv. Regulated work health and safety
v. Regulated transport safety
vi. Commercial success

This is better defined on a state-by-state basis. For example, according to Queensland Building and Construction Commission (QBCC)'s Rectification of Building Work Policy (2014), 'structural defective building work' is defined as defective building work (other than residential construction work causing subsidence) that is faulty or unsatisfactory because it does one or more of the following:

vii. Adversely affects the structural performance of a building;
viii. Adversely affects the health or safety of persons residing in or occupying a building;
ix. Adversely affects the functional use of a building;
x. Allows water penetration into a building.

A non-structural defect is defined as anything that sits outside that definition and is subject to much less stringent defect liability periods.

K0.0.0.5

The activities of inspecting and verifying *compliance* should be recorded and also be traceable to the *competent person* carrying them out. *Certification* of *compliance* to regulations typically requires a professional registered person as per those regulations.

K0.0.0.6

For constructed works that require verification, for example critical connections or completion of framing, the *Designer* and *Builder* should make provision for necessary clear access at points of inspection.

K0.0.0.7

Practices based on principles for inspection and verification controls should meet the requirements of **AS/NZS ISO9001** [5.11] particularly concerning Monitoring and Measurement (Clause 8.2). This describes the use of Inspection and Test Plans (ITPs), Inspection and Test Records (ITRs) and Inspection Checklists – noting they are not the same thing. See [5.11] for further details about appropriate Hold Points, Witness Points and Review Points.

The essential elements of an ITP include the statement of:

i. Clear title/description for the ITP
ii. What inspection is to be performed (referring to any Inspection Checklist and reference drawings)
iii. Work package/module(s) the ITP relates to
iv. When the inspection is required – the ITP should be set-out in order reflective of construction sequencing
v. Frequency with which samples are to be collected
vi. Extent of testing required (e.g. x-ray test on welded connection, etc.)
vii. Acceptance criteria that the inspection needs to meet
viii. Related reference to a Works Method Statement and following the sequence of works where possible
ix. Person(s) responsible for the inspection
x. Definition of agreed Hold, Witness and Review Points and records of any agreed notice given
xi. Any precedents required
xii. Any requirement for completed ITRs/ Checklists to form part of the as-built or handover packages
xiii. Document status and revision

K0.0.0.8

An Inspection and Test Record (ITR) is a document that records the inspection and test data on a formal, controlled document template to prove compliance to a specified standard or acceptance criteria. Essential elements involved include:

i. Inspection item description with reference to drawings etc. (and preferably following the sequence of works as in the Works Method Statement)
ii. Method of inspection
iii. Name, date and signature of person accountable for carrying out inspection
iv. Acceptance criteria and reference
v. Inspection/observation record and reference (all non-applicable items marked as "N/A" – no items left as blank)
vi. Document currency and control

Recorded results including performance parameters should be clearly recorded so that the person completing the ITR knows immediately if it is compliant or not.

An Inspection Checklist contains similar information to the ITR items above, but can comprise a tick box and does not need to incorporate specific test results. They should not contain information that is not relevant to the inspection.

K0.0.0.9

Refer to **Table K1** for suggested Hold Points generally for incorporation into a *Modular Construction* ITP regarding technical aspects (in addition to typical on-site project measures). Other items concerning contractual, financial, human resources matters or the like may also be appropriate.

K0.0.0.10

The practical objective of inspection and verification is to record *compliance*, and to ensure that:

i. *Compliance* (to regulation) and *conformance* (of actual quality to claimed quality of products) is assessed and documented
ii. *Compliance* of the design with regulatory controls is achieved
iii. *Compliance* of the built product with the specified design intent is achieved
iv. *Compliance* of the manufacturing and construction process with regulatory controls is achieved

K0.0.0.11

Where a product or component is specified to a Standard the supplier should provide verification of compliance with that Standard from an approved and appropriately independent source. Where tested properties are reported such reports should be issued by a third-party accredited from a signatory to the International Laboratory Accreditation Cooperation (ILAC) such as the National Association of Testing Authorities, Australia (NATA).

Where a supplier does not provide acceptable verification of product performance the *Designer* should consider devising suitable means to verify product quality as required, or seek and alternative.

K0.0.0.12

To prevent the *risk* of using *non-compliant* or *non-conforming building products*, critical aspects to verify are those of identification of product/model type (by the manufacturer/supplier) and the performance level claimed by the manufacturer/supplier. Suppliers of products made by others still have onerous duties under Consumer Law and *WHS* Law in Australia.

The Australasian Procurement and Construction Council publishes a guide "Procurement of Construction Products: A guide to achieving compliance" [6.32]. Assisting with Australian construction product conformity and conformance assessment, the Guide is intended to reduce confusion and provide greater clarity for all stakeholders involved in building and construction project delivery.

K0.0.0.13

The *Builder* should consider making it a condition of product supply that the supplier provides all necessary information and product markings to allow verification that the product is what it claims to be (*conformance*) and satisfies the specification set by the *Designer*, primarily that required by regulations (*compliance*). The *Builder* should inspect all incoming or free issue materials for both quantity, quality and damage upon delivery. Items that do not meet these criteria should either be returned to the supplier or segregated until the correct items have been provided.

Table K1 – Modular Construction suggested Hold Points

Hold Point	Verification Required
Prior to commencement of detailed design	1. Compliance with Safe Design of Structures provisions regarding foreseeable hazards and consultation. 2. Compliance with NCC Performance Requirements as solutions are proposed.
Prior to commencement of manufacture	1. Regulatory certification of design or approval permits. 2. Compliance with NCC Performance Requirements as materials or systems are procured. 3. Preparation of a manufacturing or construction Method Statement. 4. Verification by suppliers of material conformance.
Prior to commencement of high-value additions (e.g. specialist services or subcontracts)	1. Confirmation regarding acceptable existing module conditions (e.g. interior finishes, plant and equipment).
On completion of regulated works (e.g. plumbing, electrical)	1. Regulatory certification as required.
Prior to transport from factory	1. Regulatory certification of inspection (including regulated works). 2. Compliance with the Heavy Vehicle National Law. 3. Confirmation of acceptable existing module conditions.
Prior to export	1. Confirmation of acceptable existing module conditions. 2. Confirmation of required export and security approvals.
Prior to forwarding after importing	1. Confirmation of acceptable existing module conditions
Prior to erection	1. Confirmation of acceptable existing module conditions. 2. Confirmation of fit-up of inter-modular connections for structure, services and temporary works for staging.
During/After the installation	1. Confirmation of acceptable existing module conditions. 2. Confirmation of fit-up of inter-modular connections for structure (including any additional/external attachments onto the modular building) prior to covering up and services.

Chapter

Traceability

L Traceability

L0.0.0.1

Traceability includes all the practical aspects of Inspection and Verification (see **Chapter K**) but with added emphasis on the recording of accountability sequences for constructed materials and design decisions for anywhere in the structure.

The purpose of traceability is not just to manage better the quality of construction at the time of construction but also to provide reliable as-built information to the building owner and operator during the service life.

L0.0.0.2

For *Modular Construction*, traceability is vital in determining and rectifying sources of manufacturing errors. Due to the repetitive nature of most *Modular Construction*, delays or misdiagnosis of these errors can have severe cost and time ramifications. For example, if a non-conforming product is identified but does not have traceability records, it would not be possible to determine where that product has/has not been included in the manufacturing process.

L1 Design

L1.0.0.1

At the project outset, clear responsibilities and requirements for various *Designers* involved should be determined.

L1.0.0.2

Designers must ensure that both the company and the relevant persons involved in any document, drawing or communication are clearly identified. This helps to ensure both traceability and accountability.

If there is a regulatory or contractual requirement that the *Designer* is to be registered professionally, or semi-professionally, this must be established at the outset.

L1.0.0.3

Records of critical communications (e.g. design meeting minutes, project related emails and design change instructions) should be kept on file.

L2 Construction

L2.0.0.1

During construction, the *Builder* should ensure a record is kept of all design changes or variations that occur. This should include the cause of the variation, the approved alternative and who has approved it.

L2.0.0.2

Records of critical communications (e.g. site meeting minutes, project related emails, material schedules, etc.) should be kept on file.

L2.0.0.3

Prior to commencement of construction, the *Builder* should clearly define the role and responsibility of both suppliers and the various sub-contractors employed to complete works. The *Builder* should also request/retain copies and obtain approval for all employees assigned to carry out or inspect the works. This will enable the *Builder* to clearly allocate tasks and identify at-fault parties in the event of any problems.

L3 Materials

L3.0.0.1

The *Builder* should retain as-built records for the constructed structure and provide a copy to the building owner. This may be in conjunction with the provision of a Build Manual (see **Section M2**). These records should include verification of supplier accountabilities for materials used.

L3.0.0.2

Regarding the acceptability of products and materials used in the building fabric, the *Builder* should require from any supplier all such justifying information and/or *test reports* to verify *compliance* with that specified by the *Designer*, and *conformance* with the supplier's product claims.

L3.0.0.3

Nothing should vary from what has been specified by the *Designer* and upon which the approved Building Permit is based. Where alternative details are proposed they should be considered and approved only by the specifier responsible for the detail for which an alternative is sought. This approval and the actual product used should be recorded accordingly.

L3.0.0.4

Except where supplied product(s) have undergone satisfactory proof testing, the *Designer* and *Builder* should agree on a process of assurance testing with the supplier. This testing is to manage any *risk* that satisfactory *test reports* based upon product samples may not be representative for the product actually supplied to the project. Any such assurance test samples should be selected randomly.

L3.0.0.5

Where a supplier is required to have product traceability, or offers to provide such beyond what the *Designer* specifies (e.g. batch numbering for *anchor* products), such product information should be recorded with as-built records for the related locations in the structure.

L3.0.0.6

In the case of proprietary products and components that are critical to health and safety (e.g. prefabricated framing elements and connections, electrical assets) the building materials themselves should bear markings which permit unique identification and reference to relevant performance data. For certain products in Australia this is mandated by regulation and/or industry standards (e.g. hot-rolled steel sections, lifting/anchoring hardware in concrete, electrical and plumbing components). As a minimum, the markings should identify the manufacturer or supplier and a key performance claim such as a capacity or reference to a Standard to which compliance is claimed.

The *Designer* should specify only products which are verified to comply where regulations are applicable. Where regulations may not be specific but the *Designer* decides it is beneficial for the control of *risk* which is specific to a project, then appropriate marking of nominated components may be considered.

L3.0.0.7

In the case of a critical building product for which there is some degree of manufacture on site (e.g. concrete or grout poured in-situ, field-welded steel connections, installed post-tensioning systems, etc.), special attention is required to maintain control and traceability of outputs. Should there be any unacceptable results, which may not become apparent for some time, then accurately locating the extent of the detected and potential quality problem will be critical to rectifying it with confidence. Measures of traceability should be derived concerning:

i. Raw materials supply and the supplier
ii. Quality of workmanship processing those materials on site
iii. Specification and quality of any preparatory or follow-up works

L3.0.0.8

It is recommended that primary responsibility for verification of conformity of building products (where actual quality meets claimed quality) should rest with the manufacturer and supplier of materials.

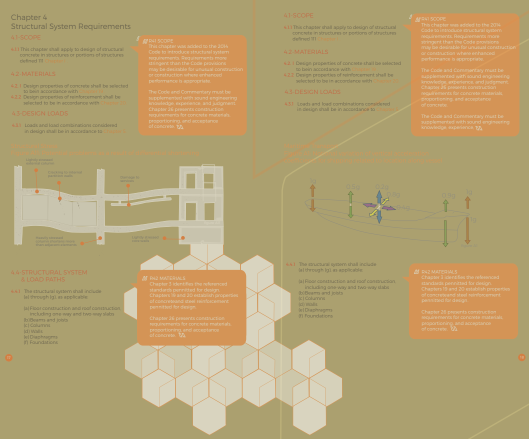
L3.0.0.9

Other considerations should include validation of fire protection (passive and/or active) and *compliance* with Access Codes and the Disability Discrimination Act.

M

Chapter

Documentation



Chapter 4
Structural System Requirements

4.1-SCOPE

4.1.1 This chapter shall apply to design of structural concrete in structures or portions of structures defined 111 Chapter 1.

4.2-MATERIALS

4.2.1 Design properties of concrete shall be selected to bein accordance with Chapter 19.

4.2.2 Design properties of reinforcement shall be selected to be in accordance with Chapter 20.

4.3-DESIGN LOADS

4.3.1 Loads and load combinations considered in design shall be in accordance to Chapter 5.

R41 SCOPE
This chapter was added to the 2014 Code to introduce structural system requirements. Requirements more stringent than the Code provisions may be desirable for unusual construction or construction where enhanced performance is appropriate.

The Code and Commentary must be supplemented with sound engineering knowledge, experience, and judgment. Chapter 26 presents construction requirements for concrete materials, proportioning, and acceptance of concrete.

Structural Stress
Figure A11: Potential problems as a result of differential shortening

4.4-STRUCTURAL SYSTEM & LOAD PATHS

4.4.1 The structural system shall include (a) through (g), as applicable:

(a) Floor construction and roof construction, including one-way and two-way slabs
(b) Beams and joists
(c) Columns
(d) Walls
(e) Diaphragms
(f) Foundations

R42 MATERIALS
Chapter 3 identifies the referenced standards pennitted for design. Chapters 19 and 20 establish properties of concreteand steel reinforcement pennitted for design.

Chapter 26 presents construction requirements for concrete materials, proportioning, and acceptance of concrete.

17

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Maritime Transport
Figure A1: Notional variation of vertical acceleration coefficients for shipping related to location along vessel

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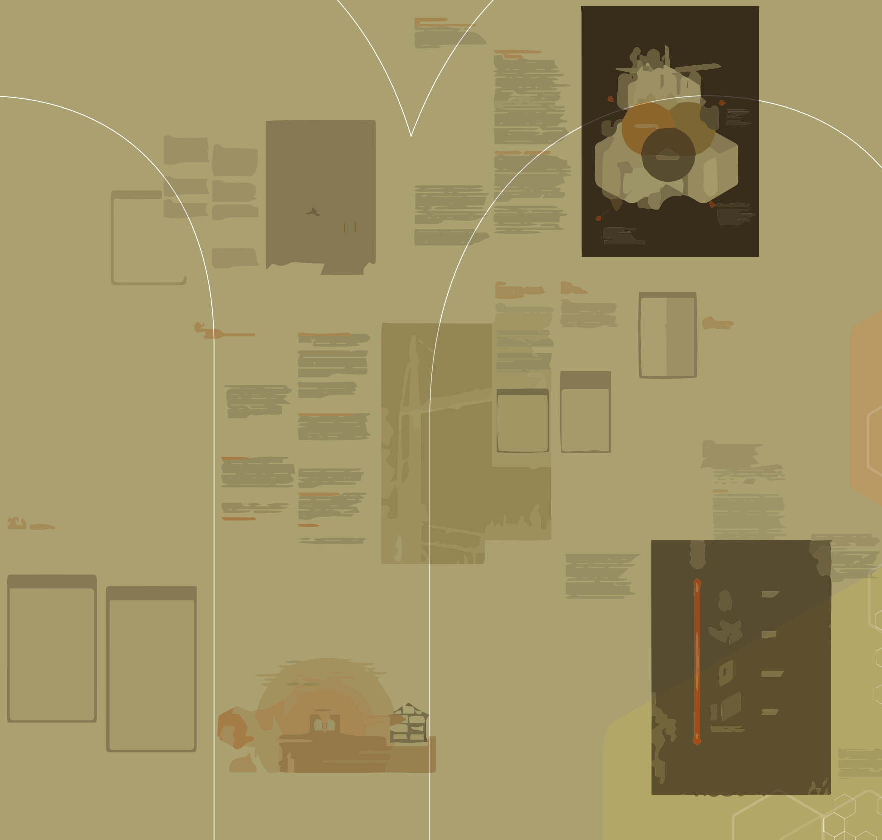
18



M Documentation

M0.0.0.1

It is accepted practice in construction culture to document anything which is specified or ought to be specified, and also to document that which is carried out. This is the basis for communication of intentions, establishment/administration of contracts, and verification of conformance/ *compliance*. It is commonly the case that construction documentation before, during and after construction activity is attached to contractual and legal queries. As with legal requirements, construction success is served by clarity and *compliance*.

M0.0.0.2

An important aspect of documentation is co-ordination between *Designers*, which requires an appropriate level of consideration. The responsibility of this co-ordination can vary depending on the circumstances and management of the project (by architect, project manager, *Builder*, client etc.); however, ensuring proper communication between *Designers* is always critical. Establishing clear communication channels should assist in minimising issues experienced during design co-ordination.

Furthermore, clear and early communication between the Designers, Builder and Suppliers will generally improve the constructability of the project design; leading to more successful outcomes of better quality.

M0.0.0.3

Project documentation should not contradict itself. In the case of conflict, this should generally be resolved through a Technical Query or Request for Information. However, most projects usually also determine a documentation hierarchy. Generally this will be in order of contract; Specification; Drawings; Procedures, though this should be determined on a project by project basis.

M0.0.0.4

Project Document Control requirements should be carefully considered to facilitate clear and effective communication, with ordered management of document revisions. Quality Management Systems Requirements (**AS/NZS ISO9001** [5.11]): Section 7.5.3 gives suggested detail on information that should be included.

M0.0.0.5

Note that in addition to permanent works design documents, other required documentation should cover:

i. Mould design.
ii. Documentation of material sources and certificates / tests, etc.
iii. Quality assurance and control of the production processes.
iv. Production planning (including timeframes, coordination of time required for design, material procurement, assembly, testing and despatching to site).
v. Unique identification of the produced units (requires a key document outlining ID convention) with traceability back to mould, batch and production day/shift, material source, mix designs, etc.
vi. Management of relationship between sub-assemblies and main assembly (as delivered to site).
vii. Procurement controls on productivity and efficiency of production process (e.g. labour productivity, material wastage etc.).
viii. Logistics, transportation, temporary works and storage.
ix. Post assembly documentation to for performance and commissioning.

M0.0.0.6

With regards to point v. above on identification of units, a convention for assigning unique identification numbers should be developed, ensuring consistency and unambiguity across the range of documentation involved in the project.

M1 Specification

M1.0.0.1

The purpose of specification is to state what is acceptable to achieve the intention of the *Designer*. Any regulated design aspect must be controlled or approved by a correctly registered or licensed *Competent person* which usually entails appropriate professional insurance.

Designers are reminded that from the range of typical documentation (drawings, specification, contracts) it should specify clearly and uniquely:

i. What is to be done
ii. Who is accountable for what has been specified
iii. The basis or source information of what is specified so that independent checking/ *certification* can be carried out

M1.0.0.2

A design specification should be provided by each *Designer* that highlights their design philosophy, intent and how they plan to meet criteria set by planning requirements, relevant building codes/regulations and the client. Some examples of expected content for a design specification of structural and architectural *Designers* are listed below. This is not intended as an exhaustive list.

M1.0.0.3

Examples of the typical contents of a structural design specification include:

i. Structural design philosophy
ii. Adopted design criteria, including references (loading, deflection limits, durability, robustness, fire, etc.)
iii. Material requirements
iv. Modular structure details, i.e. all assembly components
v. Building structural performance
vi. Transportation, lifting and handling requirements
vii. Construction requirements

M1.0.0.4

Examples of the typical contents of an architectural design specification include:

i. Architectural design philosophy (including materiality)
ii. Government planning (as set by local and state government)
iii. Building functionality (including maintenance)
iv. Adopted design criteria, including references (occupancy, acoustics, durability, structure and services, emergency access evacuation, etc.)
v. Occupational health and safety considerations

M1.0.0.5

Differentiation should be made between a performance based specification and prescriptive specification. Obligations of contractors working under each will vary.

i. **Performance Specification** — A performance specification is a set of instructions that outlines the functional requirements for elements (such as hardened concrete) depending on the application. The instructions should be clear, achievable, measurable and enforceable, including a clear description of test methods and acceptance criteria. For example, the performance criteria for interior columns of a building might be compressive strength and weight since durability is not a concern. Conversely, performance criteria for external load bearing elements might include strength, permeability, scaling, cracking and other criteria related to durability since the concrete will be subjected to a harsh environment.
ii. **Prescriptive Specification** — A prescriptive specification is one that includes clauses for means and methods of construction and material composition (e.g. concrete mix), rather than defining *Performance Requirements*. These may often conflict with the intended performance, but the producer would generally not be liable for any issues as long as the material conforms with the prescriptive specification.

Performance specification with prescriptive limits (e.g. water-cementitious material ratio) are therefore often used.

M2 Drawings

M2.0.0.1

Construction drawings communicate the intention of the *Designer* to all relevant parties Where there is a design brief the construction drawings should reflect it faithfully having first ensured *compliance* with the requirements of any relevant Regulation.

M2.0.0.2

Modular Construction enlarges the envelope of specifiable aspects which need to be controlled (and thus which fall within the scope of contractual obligations) and so the range of drawings, including views and notes, needs to reflect this. The documentation should address:

i. All assumptions and references for design input. This includes assumptions relating to fabrication, lifting and transportation that have impacted the design.
ii. Specification of material quality, any processing operations (e.g. fabrication, coatings) and the governing *tolerances* which apply.
iii. Necessary details for manufacture including unique numbering of assemblies.
iv. Necessary details for all lifting, transport, storage and handling. Special attention may be required concerning waterproofing in transit.
v. Necessary details for site works including connections and building fabric interfaces.
vi. Necessary details for staged construction on site including module delivery schedules and any required temporary works or supports.

vii. Necessary details for *compliance* processes to minimise handling without stage approvals.
viii. Verification (with traceable accountabilities) of all aspects which have been specified. This includes the design itself and its *compliance* with Regulations.

M2.0.0.3

Generally, drawings produced by *Designers* are translated by fabricators into what are commonly referred to as "shop drawings". These drawings essentially form a parts list of what is to be made for various components. Due to the nature of *Modular Construction*, an increased amount of work is completed by fabricators off-site, and therefore the accurate production of shop drawings is critical. The *Builder* should ensure that the *Designers* and fabricators work closely together during the development of these shop drawings to ensure the design intent is adhered to and that any issues or clashes are resolved as soon as possible, and well before arrival on-site.

It should be noted that although the *Designer*'s review of shop drawings is generally a hold point, this does generally not mean that the *Designer* takes responsibility for the content of these drawings and relieves the fabricator/subcontractor from liability.

M2.0.0.4

While it is not within the scope of this document to provide detailed advice on the preparation of design drawings for various disciplines, the following suggestions are made:

i. Ensure both the *Designer* and draftsperson (where applicable) are identified on the drawing
ii. Ensure company contact details are provided
iii. Ensure the issue type (For Tender, For Construction etc.), revision number and date of issue are clearly labelled
iv. Ensure any modifications between issues are clouded for ease of reference

M2.0.0.5

"As built" drawings reflect what was actually built on-site, including any changes made during construction. In the case of *Modular Construction*, ideally changes during construction should be minimal. It is important to note that any changes or variations during fabrication should be captured within "as built" drawings. Nevertheless it is important to ensure that "as built" drawings are provided—particularly in the case of temporary structures or structures designed with disassembly in mind.

M3 Build Manual

M3.0.0.1

The *Designer*, pursuant to *WHS* duties [2.3], must supply adequate information concerning any conditions necessary to ensure that there is no unacceptable *risk* arising from intended use of the design or foreseeable related activity.

Under *WHS*, the *Builder* (and/or fabricator) also have a duty of care to ensure no outstanding unacceptable risk and outline any residual risks. Documentation to communicate residual risks and how they have been managed should include inclusion of the Safety in Design register and Work Methods for maintaining and demolishing building elements within the Build Manual.

M3.0.0.2

The *Builder* should compile drawings and other specification material attached to or referenced from a Build Manual which is drafted to provide guidance and background information to the building owner and the building manager or maintenance supervisor. This serves to reinforce to the property owner their obligations to eliminate foreseeable *risks* to health and safety for any occupant.

As a minimum the Build Manual should contain:

i. The design philosophy
ii. A summary of the building (including design and analysis undertaken)
iii. Features and key physical aspects (e.g. dimensions) of the building and site
iv. The contact details of all the involved specifiers, building lead contractors (following the specification) and *certifiers* engaged
v. Module assembly sequence (if required)
vi. Transportation methodology
vii. Construction methodology and sequence
viii. A schedule of all plant facilities and items to be monitored in the building and references from which effective inspection and maintenance plans can be prepared

M4 Compliance

M4.0.0.1

The principle of verifiability for anything which has been specified is outlined in **Chapter K**. Similarly unless any such verification is documented there can be no confidence or ability to demonstrate to any interested party that it is factual nor can accountability be assigned or confirmed regarding verification. This applies to all construction forms and may be more pertinent for *Modular Construction* wherein subcontracted components are completed off-site but then exposed to the *risk* of contact and handling by others before project completion.

M4.0.0.2

There are two distinct areas in which demonstrable *compliance* is required to afford an effective measure of accountability for satisfactory building performance:

i. The design, including the specification of the entire building fabric and supporting documentation, must comply with all regulatory provisions. See **Chapter J** for more details.
ii. The construction must comply with the design and specification. See **Chapter K** for more details.

It is a separate issue again, and beyond the scope of this document, as to whether the design accurately satisfies, reflects and complies with the wishes of the project client.

M4.0.0.3

A generic framework is herein proposed which the *construction compliance supervisor* should customise for a specific project. This framework relates the design to regulatory requirements only (*NCC* [6.2], *WHS* [2.3]) but not to the specific project brief. It also relates the constructed works to the design intent.

The framework should address the following key elements:

i. Identifiable individual accountability for actions.
ii. Documentary evidence of any *compliance*.
iii. The stated regulatory controls (may include building and *WHS* regulations) to which any design specification must comply and *certification* that what has been specified does comply.
iv. The stated specification documents to which the construction must comply and *certification* that by inspection of works the construction does comply with the design intent.

It is noted that in some countries it is mandated by regulation to have design peer review and periodic construction inspections for buildings over a specified height/ occupancy.

N

Chapter

Disassembly, Reuse & Recyclability

N Disassembly, Reuse and Recyclability

N0.0.0.1

This topic relates to the end of a module's functional *design life* where it is decommissioned from its intended function, removed from service and its constituent parts salvaged. It also relates to the case where modules are dismantled and relocated for further service elsewhere, perhaps several times (see **Chapter Q**). In both cases the *Designer* should make provision for the required disassembly and, most importantly, for at least one repetition of transport and handling dynamics of modules after some period of service exposure. This should be documented in the Build Manual (see **Chapter M**).

N0.0.0.2

Traditional on-site demolition typically uses large machinery that disassociates workers from the large quantities of waste that is generated, essentially "bulldozing" large developments. This demolition method results in a mixed, damaged and even contaminated waste stream that immediately downgrades the material to a lower rung in the waste hierarchy. Furthermore, most waste facilities receiving construction and demolition waste do not sort the incoming waste stream, meaning that economically valuable and highly re-usable or recyclable materials, such as metals, may be lost as residual waste to landfill, the least preferred option in the waste hierarchy.

N0.0.0.3

Modular Construction presents an opportunity to achieve a greater degree of reuse and recycling. The capacity of modules for disassembly removes the need for demolition and enables potential reuse. Furthermore, disassembly accommodates a much more orderly, systematic and thorough segregation of preassemblies, products and materials. This alleviates certain environmental and human health concerns related to demolition, such as dust production, noise and contamination from the uncontrolled transportation of materials, thus resulting in a cleaner and less environmentally impactful decommissioning phase with benefits to the local and wider community. However, it is important that preparations are made for disassembly as this process requires much more planning and co-ordination. Without a simple demolition strategy, the *risk* is that traditional demolition techniques are used and the cross contamination of waste streams is even greater than that of traditional construction.

Case study: Tools to Ensure the Integrity of Waste Disposal

The **Better Buildings Partnership** is a collaboration between the City of Sydney and a consortium of commercial property owners/managers operating within the City of Sydney council area. The Partnership has developed a series of tools to combat the complexity of roles, responsibilities and the lack of transparency inherent to waste disposal activities. These tools highlight the need for a strong consideration of waste disposal methods, management and auditing for the disposal of components comprising a modular structure.

The tools available include:

i. Model contract clauses, to ensure requirements extend to sub-contractors and the contracts are aligned with other non-waste contracts, such as cleaning services;
ii. A template for reporting material streams and densities, to ensure consistency in waste classification and the corresponding metrics used;
iii. Roles and responsibilities KPIs, to ensure that there are no 'gaps' in the processes required to fully carry out waste disposal activities;
iv. A waste data integrity rating protocol, to provide credibility to waste data and improve the accuracy of overall waste data. This enables benchmarking activities that are more meaningful and to ultimately achieve better resource efficiency.

For more information and to access the tools, please visit the Building Better Partnerships website: http://www.betterbuildingspartnership.com.au/

N0.0.0.4

The requirement for the *Designer* to nominate a *design life* implies a foreseeable phase at the end of service life where the modules are to be removed or improved to extend *design life*. Just as modular structures require assembly and interconnection on site to create the complete building, it follows that their removal by controlled disassembly is a foreseeable, if not probable, activity in the future.

N0.0.0.5

Work Health and Safety (*WHS*) law [2.3] requires that the *Designer* ensures, *so far as is reasonably practicable*, that a structure is designed to be without *risks* to the health and safety of persons who carry out any reasonably foreseeable activity at a workplace in relation to the manufacture, assembly, use, proper demolition or disposal of the structure. This is expanded upon in "Safe Design of Structures" [4.1]. It is worth noting that even a residential building becomes a workplace in any areas where organised or proper decommissioning, demolition, dismantling, disposal or recycling works can be foreseen or are carried out.

N0.0.0.6

The duty of the *Designer* in relation to dismantling, demolition or disposal activities may extend to carrying out any required analysis to ensure the structure is without *risks* to health and safety. This may further require the *Designer* to make provision of adequate information to others concerning conditions necessary for safety.

N0.0.0.7

The duty of the *Designer* applies not just to the structural engineer but extends to those who specify architectural systems (e.g. cladding, glazing), mechanical/hydraulic/electrical systems and the like.

N0.0.0.8

Further from [4.1], a structure should be designed to enable dismantling using existing techniques. The *Designer* should provide information so that potential "demolishers" can understand the structure, load paths and any features incorporated to assist dismantling/demolition, as well as any features that require unusual techniques or sequencing. For example, consideration at the time of design may be given to:

i. Protection of lifting lugs/inserts used during erection on modules for later use in dismantling
ii. Durability of lifting points and connections (see **Chapter F**)
iii. Provision of extra lifting points in modules for dismantling
iv. Provision of information to assist demolition of post-tensioned or pre-tensioned concrete elements in the specific structure
v. Protocols for decommissioning of building services
vi. Not specifying products, materials or systems with poor, unknown or inefficient removal characteristics

Case study: Deconstruction Social Enterprises in the Not-for-Profit Sector

Social enterprises are a growing segment in the not-for-profit sector, delivering traditional welfare services in a more holistic and empowering manner and operating on financially sustainable business models. These enterprises often build a business model that promotes environmental and social benefits to its clients. Deconstruction social enterprises enable disadvantaged groups to gain employment, break cycles of abuse and escape neglect, whilst also providing environmental benefits through deconstruction.

As outlined in **Sections N0.0.0.5–N0.0.0.8** in the main text, deconstruction can be a hazardous and time-consuming activity without proper planning and management. Social enterprises have capitalised on this barrier to implementation by designing programs for disadvantaged groups. These incorporate elements of a social program, such as casework support, housing and work-ready or rehabilitation programs along with employment, training and certification in deconstruction and other construction-related skills. Social enterprises can thus carry out the deconstruction activity while also enabling their 'workforce'.

Many examples of deconstruction social enterprises exist in the United States of America. For example, *Better Futures Minnesota* is a social enterprise that engages men with histories of incarceration and homelessness by providing housing, health and wellness support, workforce deployment and certification. The care provided to the men is funded through the deconstruction services that Better Futures Minnesota offers as a business service, and that the men carry out, as well as collaborations with other social services.

For more information on Better Futures Minnesota, please see their website: http://betterfuturesminnesota.com/

N0.0.0.9

Where structural adequacy is not assured for aged framing and other building fabric to safely withstand the disassembly operations, the *Designer* should establish a process for assessment or testing of existing material and connections to validate design capacities. This may follow similar processes to the establishment of design values for new materials by testing.

N0.0.0.10

The site erection process of *Modular Construction* should directly lend itself to efficient disassembly in the future – i.e. removal of complete modules and transportation to an off-site location for detailed dismantling or, ideally, appropriate modification to enable reuse at another location.

N0.0.0.11

Modular structures lend themselves to reuse. Depending on the type of structure and its intended use, it is often desirable and necessary to design the structure for service at multiple locations (and function during relocation between each). Provision for such activities should ideally be made in line with **Chapter Q**, which would typically be designed to be relocated several times within their *design life*.

N0.0.0.12

Reuse of structures may be suited to the same operational purpose, that of lower economic value, or for use with a different function (of any value). Modular design can allow for flexibility to be designed into buildings, utilising a 'plug and play' approach; allowing for minor or major modifications to be made to existing assets as user requirements change for a particular location. This can provide significant value to the owner, operator and user. Similarly, reuse of such modular structures can be conducted to offer the same function of the same value (which may require re-fitout), or transform for a different use (often of lower value as the asset ages).

Unfortunately, it is usually undesirable to include upfront assurance for relocation of modular structures fulfilling a permanent purpose at the design stage. This is because most projects in today's market will not warrant that level of commitment and do not have sufficient confidence of what future requirements may be. However, whilst designing for disassembly and removal, an opportunity remains to incorporate reuse considerations for the end of the *service life*, without significant cost. One should note here the distinction between *design life* and *service life*; the latter relates to the intended period of use of the structure in service, whereas the former relates to the period of time during which the structure is expected to maintain its stability. This relates to durability; for more details see **Chapter F**.

Case study: Adaptive Reuse Practices for Preserving Heritage Buildings

Heritage buildings can tend towards disuse and fit-out work is often necessary in order to preserve a building and convert it to a new use. These preservation strategies and their associated social, environmental and economic benefits present a valuable rationale for modifying modules in order to maintain their current level of service or to convert modules to a new use.

Adaptive reuse is a term that encapsulates the adaptation of a disused or ineffective product in order for it to be re-used for a different purpose. The preservation of heritage buildings is now recognised as best practice in offering the best value in terms of environmental, social and economic outcomes. For example, adaptive reuse retains much of the embodied energy of a building and the energy savings from reuse, compared to construction, creates economic savings. However, it is the social benefits of adaptive reuse that are considered to be of the most value. Adaptive reuse practices preserve the heritage of a building for future generations, often making them more open and accessible to the public, and thus promote inter-generational equity. Furthermore, reuse ensures the quality and design of the built environment is maintained. This can be consequential to the quality of life and liveability of a community.

Examples of adaptive reuse exist throughout Australia, with the conversion of infrastructure from the latter half of the 19th century into contemporary buildings in the early 2000s. For example, the old Launceston Railway Workshops of Tasmania, in use from 1868, were modified for a new use as The Queen Victoria Museum and Art Gallery in 2001 (see figure below). In Victoria, the Beechworth Lunatic Asylum, built by 1867, ran into disuse as the methods of treating the mentally ill came to be rethought around the world. It was purchased in 1996 by La Trobe University and converted into an International Hotel School, an intuition for tertiary education (see figure below right). Furthermore, from 2011 the building has undergone its 3rd use with tenants ranging from commercial businesses to community groups and artists.

These case studies highlight the many advantages of the adaptive reuse of buildings, and the potential of various building types, from railway workshops to hospitals, to be converted to new uses.

Figure N1: Entrance to the Queen Victoria Museum and Art Gallery, retrieved from Department of Environment and Heritage, (2004). Adaptive Reuse: Preserving our past, building our future. [online] Canberra. Available at: https://www.environment.gov.au/system/files/resources/3845f27a-ad2c-4d40-8827-18c643c7adcd/files/adaptive-reuse.pdf [Accessed 27 Oct. 2016].

Figure N2: Exterior and interior of International Hotel School, La Trobe University Campus, retrieved from Department of Environment and Heritage, (2004). Adaptive Reuse: Preserving our past, building our future. [online] Canberra. Available at: https://www.environment.gov.au/system/files/resources/3845f27a-ad2c-4d40-8827-18c643c7adcd/files/adaptive-reuse.pdf [Accessed 27 Oct. 2016].

N0.0.0.13

Whilst most structures have a specific *design life*, the majority of structures can usually perform for much longer periods. The *Designer* is therefore encouraged to consider how such modular assets may be inspected, verified and repurposed (as necessary) at the end of its intended operational period. This will include similar provision to disassembly considerations (without inflicting significant damage), as well as aspects such as accessibility to services, fixtures/fittings and options for re-fitout.

N0.0.0.14

Demolition of any kind requires that the nature of demolition materials and debris be considered for safe handling and disposal. Especially *hazardous* materials (such as asbestos) may have regulations applicable and warrant specific *risk* assessment.

In Australia it is unlikely that structures constructed after 1990 will include any asbestos-containing materials. However, when sourcing materials from other jurisdictions with potentially lower material quality standards, it is important to make a thorough verification that the materials are as specified. The *Designer* has a duty of care to minimise the use of *hazardous* materials (or potentially *hazardous* materials after service) where possible and to plan for their safe disposal (when unavoidably used).

N0.0.0.15

Building materials account for about half of all materials used and also for about half the solid waste generated worldwide [6.15]. In Australia, management of construction and demolition waste generally is regulated via State and Territory legislation. Direct landfill costs and regulated levies for waste disposal both exert significant incentives to rationalise construction material use and re-use, and to minimise material waste. This trend is reflected internationally.

N0.0.0.16

More advanced forms of re-use, still largely in the research phase, include the re-use of structural elements (e.g. beams, columns, slabs, walls) joined by embedded steel connectors. These elements must have a unique identifier and information, such as their location and design capacities, must be available for storage and reallocation of the elements to a new building. The storage of this information can be facilitated by computer databases and the overall design, assembly, disassembly and reallocation of elements can be co-ordinated using tools such as Building Information Modelling. Consequently, this form of re-use introduces data and computational analysis, management, storage and inventory into a building's end of life stage, which would traditionally be a demolition only process.

N0.0.0.17

Recycling incentives are only likely to increase, whilst legislation will further prevent the disreputable mass disposal of waste to landfill. Moreover, as finite materials become scarcer, the value of materials at the end of the design life may amount to a considerable monetary return from recycling companies willing to pay for the material. The *Designer* should therefore consider the recyclability of the module during the design phase. For example, it should be possible to disassemble into strict recycling categories (e.g. by material) to ensure the purest recycling streams and thus maximising resource recovery, recyclability and economic value.

Case Study: Advanced Re-use of Individual Structural Elements

A study published in 2014 and conducted by researchers from The University of New South Wales and the National University of Singapore investigated the use of Building Information Model (BIM) software for the selection of end-of-life disposal options for buildings, based on economic and environmental considerations. The study considered an advanced form of re-use, where individual structural components were considered uniquely for re-use; see the figure below. The technique developed in the study was applied to a 14-storey residential building in Singapore.

The form of re-use applied in this study required the collection and computation of large data sets. As such, the study introduced new functions within Tekla Structures BIM software to characterise the deconstruction-related attributes of individual structural elements. For example, a property window for a steel column in the study's BIM software would display a 'deconstruction' tab, where information on recyclability, reusability, original design capacities, disassembly, condition and geographic location could be stored. The deconstruction data, available for each individual structural component in the building and stored within the BIM model, was then able to be transferred to a secondary processor which performed a computational analysis for the most sustainable end-of-life option.

Modification to the BIM software provided the opportunity for more end-of-life options to be considered, beyond traditional demolition and disposal options. The study found that reuse of building components for use in a second building and the ultimate recycling of those components after their second use cycle is positive. These are more cost effective, with lower embodied energy and less embodied carbon, than other combinations of reuse and demolition using traditional disposal and recycling.

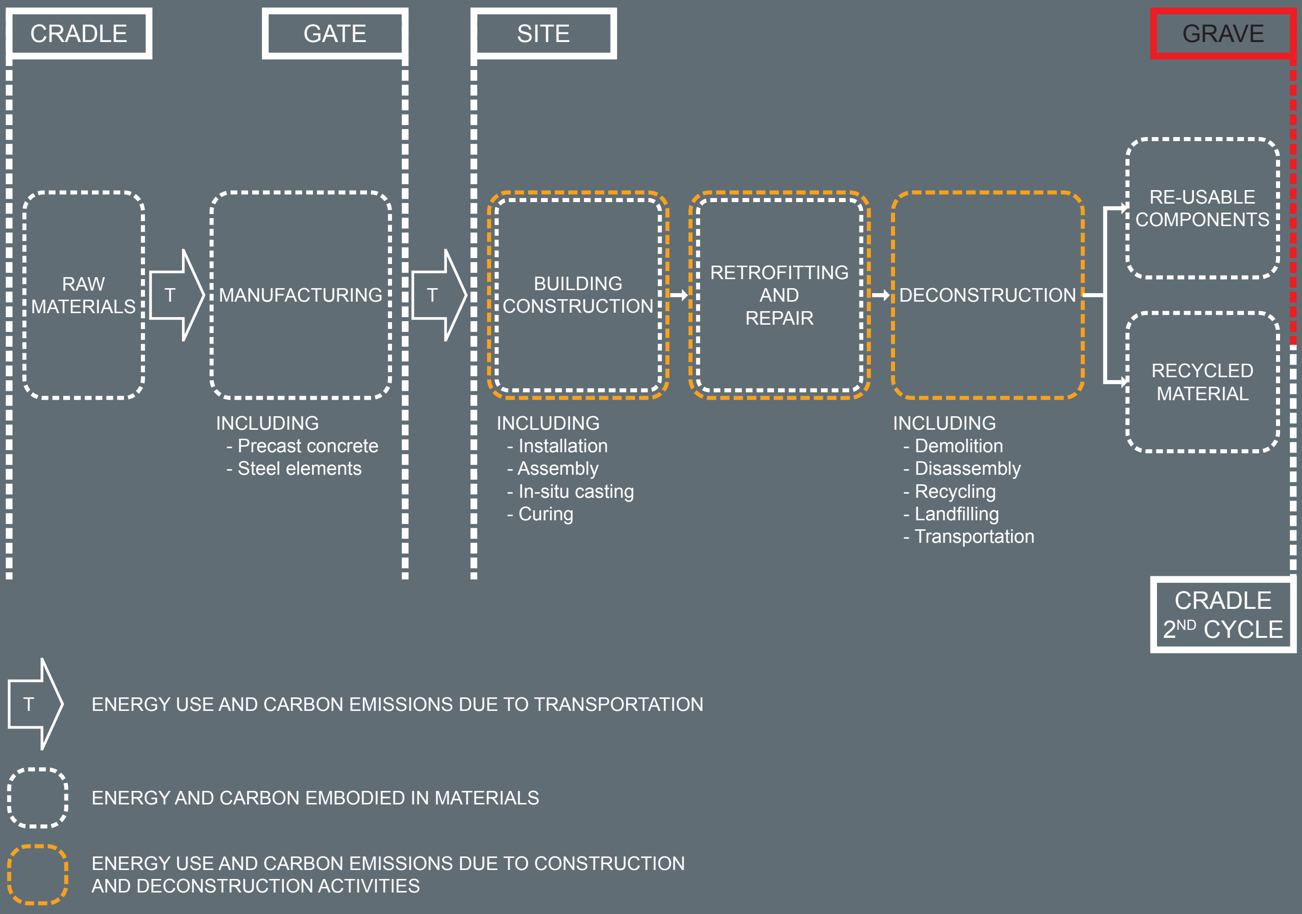
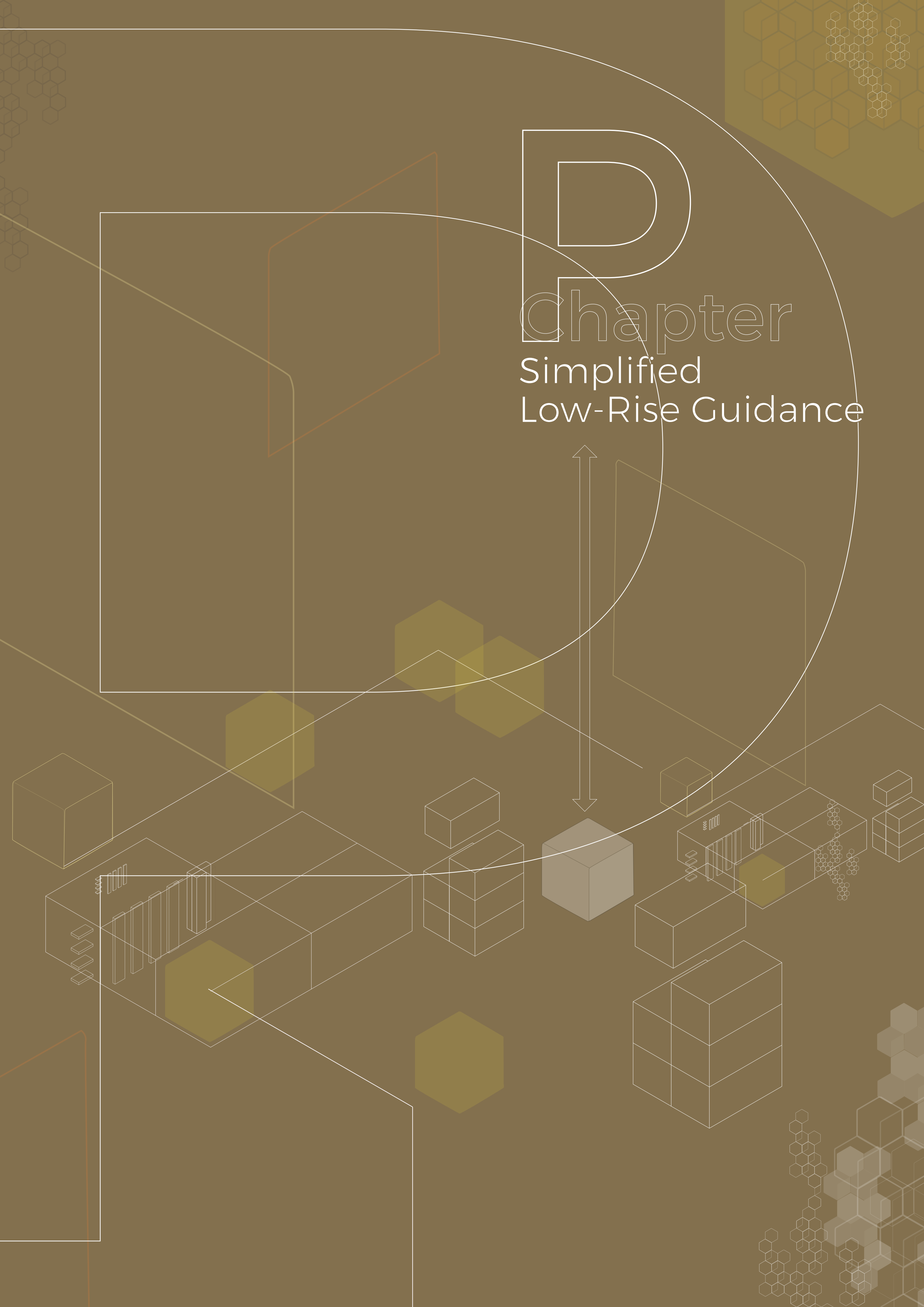


Figure N3 – Contribution of various construction and deconstruction activities in the overall embodied energy and embodied carbon of building components - retrieved from “Economic and environmental assessment of deconstruction strategies using building information modeling” by A. Akbarnezhad, K.C.G. Ong, L.R. Chandra, 2014, Automation in Construction, Volume 37, Pages 131-144, ISSN 0926-5805

P

Chapter

Simplified Low-Rise Guidance



P Simplified Low-Rise Guidance

P0.0.0.1

The definition of what constitutes a “Low-Rise Building” (or Medium-Rise) relates mainly to licencing of *Builders* and their required competency for categories of project scope and complexity. In turn, licencing requirements are prescribed by State-based Regulation and they are not uniform across Australia. Some Regulations (e.g. as in Victoria) differentiate Low or Medium-Rise based upon the number of building storeys with exclusions for so-called “special buildings”. Other jurisdictions (e.g. as in Queensland) draw upon distinctions of Building Class and Type of Construction as defined in the *NCC* [6.2], and gross floor area. So called “High-Rise” is not defined but is taken to refer to what exceeds the limits for Medium-Rise.

The *NCC* is not concerned with restriction on permitted heights of buildings (this is prescribed directly by the Regulations and approved Planning Schemes) but with the safe performance of buildings.

P0.0.0.2

The *Builder* should clarify any regulatory definition of the modular project in terms of Low-rise, Medium-rise or High-rise (or the like) for the jurisdiction where the project is located. This may have implications for licencing limits.

Technically there is no distinction between the structural physics applied to the various arbitrary descriptions of structure types as Low, Medium or High Rise. However, these points should be noted:

i. Prior to the erection on-site of modules and incorporation into the completed structure, each independent module may be considered a type of small Low-Rise structure for the duration of its life in the handling and transportation phases.

ii. Regarding the Regulated provisions for *Robustness* (see *NCC* [6.2]) the requirements for buildings of less than three storeys, as is typical of Low-Rise, are confined to overall building stability.

iii. *Designers* are reminded that *Modular Construction* is just a form of construction. It need not inherently involve any novel applied engineering or new material for which existing guidance is inappropriate. Given the historic popularity of including prefabricated elements for general in-situ Low-Rise construction the choice to use prefabricated modules is merely one of scale, sequencing and completing necessary connections on site (including structural, cladding, services, etc.).

P0.0.0.3

Guidance may be found in the approach of the *NCC* [6.2]. Whereas the *NCC* sets no limits on building height, it offers Prescriptive Solutions (Deemed-to-Satisfy) in relation to fire resistance and defined Types of Construction for various combinations of building Class and the Rise in Storeys. From *NCC* [6.2] Table C1.1 is reproduced as **Table P1**:

Table P1 – Type of construction required via NCC [6.2] Refer to NCC Vol 1, Part A3 for Classification of Buildings[1]

Rise in Storeys	Class of Building	
	2, 3, 9	**5, 6, 7, 8**
4 or more	A	A
3	A	B
2	B	C
1	C	C

The Types of Construction specify minimum *FRL* (*Fire Resistance Level*) values required for various building elements. Type A construction is usually more substantial than Type B, which is usually more substantial than Type C. Type C, for its combinations of building Class and Rise in Storeys, might be considered Low-Rise and the simplest. Details of the FRL values nominated for Type C construction are found in *NCC* Specification C1.1 Table 5. Note that for some building Classes there may be no difference in required *FRL* between the different Types of Construction.

P0.0.0.4

Further to what may constitute Low-Rise & referring to **Table P1**, in the State of Victoria for example, except where varied by Planning Schemes, the regulated height of buildings is limited generally to 9 m. In this case, and with appropriate detailing, it is unlikely that buildings from Class 1 or 10 (typical freestanding single dwellings and associated domestic structures) could exceed 3 storeys above ground. Note that Class 4 is a special case wherein the subject dwelling is contained within a Class 5, 6, 7, 8 or 9 building.

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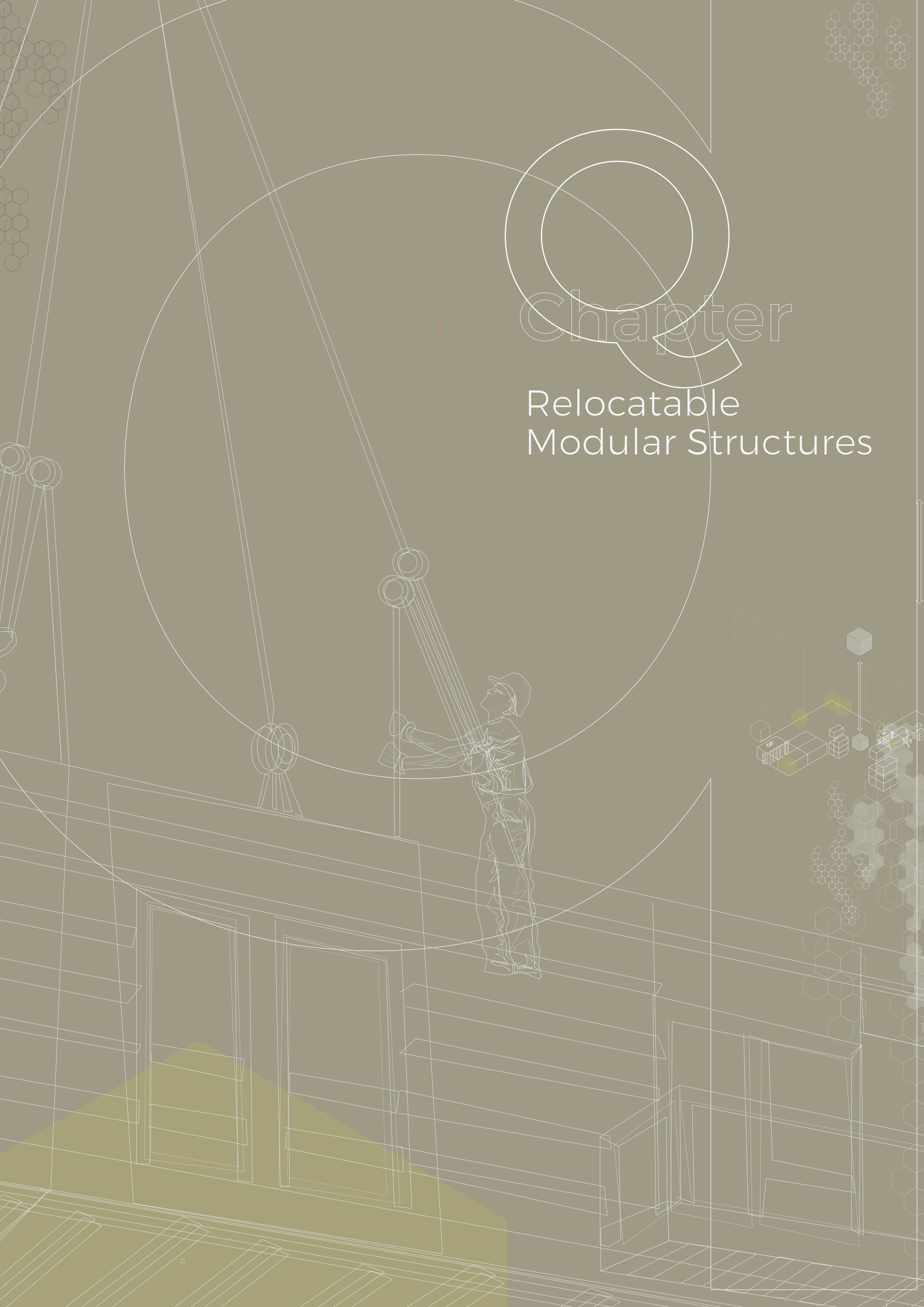
[1] Information sourced from the Australian Building Codes Board (ABCB) www.abcb.gov.au

P0.0.0.5

In relation to structural framing, if Low-Rise is associated with structures for typical small dwellings, as described by building Classes 1 and 10, then the *Designer* may consider the corresponding Prescriptive Solutions guidance for:

i. Light steel framing – **NASH Standard** [5.25]
ii. Timber framing – **AS 1684** [5.26]

The *Designer* is also referred to the NASH Technical Note 4 [6.1] which provides guidance for developing Performance Solutions and testing-based design.



Chapter Q

Relocatable Modular Structures

Q Relocatable Modular Structures

Q0.0.0.1

A "relocatable building" is a common description for buildings intended for lifting, transportation and re-siting during their *design life*. Temporary sheds at a building site are frequently cited as examples. In some cases, in-situ constructed houses, not originally intended for relocation, are moved to a different site.

All *Modular Construction* may be covered by this description even if the building modules are intended for siting once only within a larger project building. They need to be detailed for and capable of dismantling/relocation one day, even if just to be scrapped (see **Chapter N**).

In all cases the laws of physics and engineering behaviour still apply as do the overall duties on the building personnel involved to carry out their functions in a way to safeguard people and prevent property damage from reasonable and foreseeable conditions.

Q0.0.0.2

The *Designer* should apply all necessary design skill and judgment in relation to the design and construction of so-called "relocatable" modular structures, as for all modular structures generally.

The requirements relating to Building Regulation for "relocatable buildings" are not so straightforward and may vary with legal jurisdiction. In the State of Victoria, for example, certain types of buildings are exempt from some provisions of Building Regulations [1.2]. With structures of a movable nature in mind (for relocation to a different site and different footings), these exemptions include:

i. Any building that cannot be classified as per the *National Construction Code (NCC)* provisions.
ii. A building used only temporarily for the duration of building work.
iii. "Temporary structures" except for those prescribed (see **Section Q0.0.0.3**).
iv. A relocatable building (defined as a "movable unit" in the Victorian Housing Act 1983) constructed for a community service as temporary accommodation on a non-profit basis. Conditions apply.
v. A relocatable building used in a State School, other school or TAFE Institution (as defined in various legislation). Conditions apply.

Such exempted structures are outside the normal controls of building regulation so building permits and occupancy permits may not apply.

Q0.0.0.3

The prescribed "temporary structures" in Victoria (which may not require building permits but still may require occupancy permits) include:

i. Tents, marquees, booths with floor area greater than 100m^2
ii. Seating stands for greater than 20 persons
iii. Stages or platforms of floor area greater than 150m^2
iv. Prefabricated buildings exceeding 100m^2 except where placed directly on the ground (no separate footing system)

The above details relate to the State of Victoria which may or may not be similar to other jurisdictions. In Victoria further guidance may be found in the VBA Practice Note 2014-55, Section 11 [6.3].

Further guidance concerning the regulation and *compliance* of temporary structures can be found in the Temporary Structures Standard [6.13]. It states that

> "*the fact that a structure is designed for temporary use does not change the overall expectation for safety*".

See **Section A1.2** concerning the case of temporary loads on modules.

Q0.0.0.4

With regard to regulated (i.e. not exempt) buildings, generally their classification and consequent applicable *Performance Requirements* are determined by their:

i. Intended purpose and function
ii. The details of the building proposed
iii. The location of the subject site

Where any of these are proposed to vary in the future (e.g. building purpose, building alterations, building location) this may trigger a review of regulatory assessment for Building Class and permits etc. under the regulations that apply at that time. For example, it could be that a compliant building at one point in time may not be compliant under revised regulations which apply at a later date when seeking even a minor re-siting. There have been significant amendments in recent years to *NCC* provisions including those concerning:

iv. Structural reliability and robustness
v. Bush fire resistance
vi. Access and facilities for disabled users
vii. Damp and weatherproofing
viii. Energy efficiency

In the case of modular structures intended or allowing for multiple phases of siting and use or occupancy, the concept of these processes are likely to be applied.

Q0.0.0.5

Where a modular building is not designed to withstand any and all environmental conditions, its limitations should be permanently marked in an area where they would be seen during relocation. For example, a short relocation of less than 100km could result in a structure in a Category C cyclone region, that was only designed to resist Category A wind loads.

Q0.0.0.6

The *Designer* of a module should obtain an appropriate assessment for applicability of regulations where a service life of multiple relocations is proposed or allowed for. With the knowledge that the module may be intended for multiple cycles of relocation and use, the *Designer* should make clear the *NCC* assessment applicable at the time of the design being undertaken (as applicable when permits are issued).

Where a modular structure is intended to be "relocatable" (an item of hired plant for example) this should be specified in the scope of the design brief. Design issues to be considered include:

i. Durability implications for the service life of lifting points on the module.
ii. The effects of multiple handling on the module structure itself (e.g. stresses and deflections for aged materials and connections).
iii. Accessibility to connection points (e.g. with adjoining modules or footings) for removal.
iv. Accessibility to areas/materials key to verifying *compliance* to *Performance Requirements* for subsequent reassessment (e.g. structure, services).
v. The range of conditions (e.g. geographic, climatic, fire *hazard*) the modules may be exposed to beyond the initial use so as not to be disqualified from subsequent use.
vi. Details to minimise the *risk* of retaining and transporting contaminants from one site to another.

There is some overlap of considerations required with **Chapter N** regarding Disassembly.

As with all modular construction, the effects of transport loading need to be assessed against the critical in-service structural loads. Where a structure may have an indefinite number and distance of relocations such as relocatable mining type housing, fatigue will likely become the governing factor in the durability of the structure and services. If the structure is compromised by fatigue, structural failures may occur at far less than the design loads. To compensate for this, it may be prudent to identify the fatigue failures that will eventually occur and mandate a testing and inspection regime at certain intervals or after each transportation, to ensure the module is structurally safe.

Q0.0.0.7

In relation to provision of building services in modular buildings there are various regulatory controls in jurisdictions concerning energy safety. Considering space heating via gas combustion in particular the *Designer* should note any safety requirements including:

i. Acceptable gas source
ii. Ventilation of gas source
iii. Ventilation of combustion products
iv. *Risks* to occupants from oxygen depletion
v. *Risks* from confinement of potential gas leaks

The vibration due to transportation of some services will be quite different to the in-service loads.

It would be prudent to treat hard lines such as propane, natural gas and air conditioning similar to the requirements of Automotive LPG hard lines. There are many more connections required to fasten automotive LPG lines to a motor vehicle than in a typical building. The self-weight of a service line will cause it to vibrate under transportation accelerations, significantly increasing the risk of fatigue failure resulting in leaking gas/water, electrical short circuits etc.

Experience from the mining industry has shown that failures of items such as air conditioning units are common during relocations. It should be noted that while air conditioners are often supplied with rubber vibration isolators, these are designed specifically to isolate the building from the vibration of the air conditioner in operation, not vice versa. Correctly isolating susceptible items such as air conditioner units will save significant resources in service.

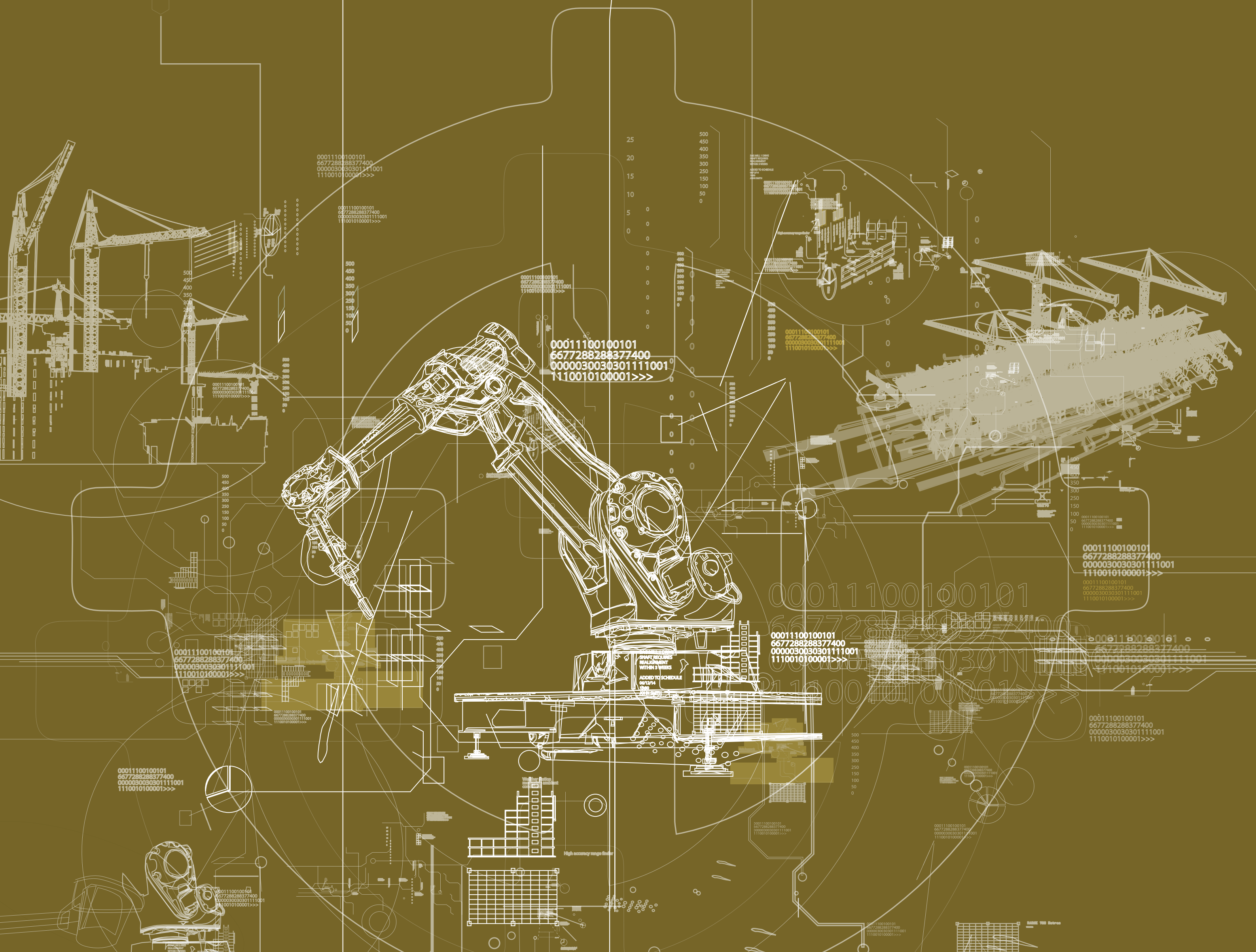
Q0.0.0.8

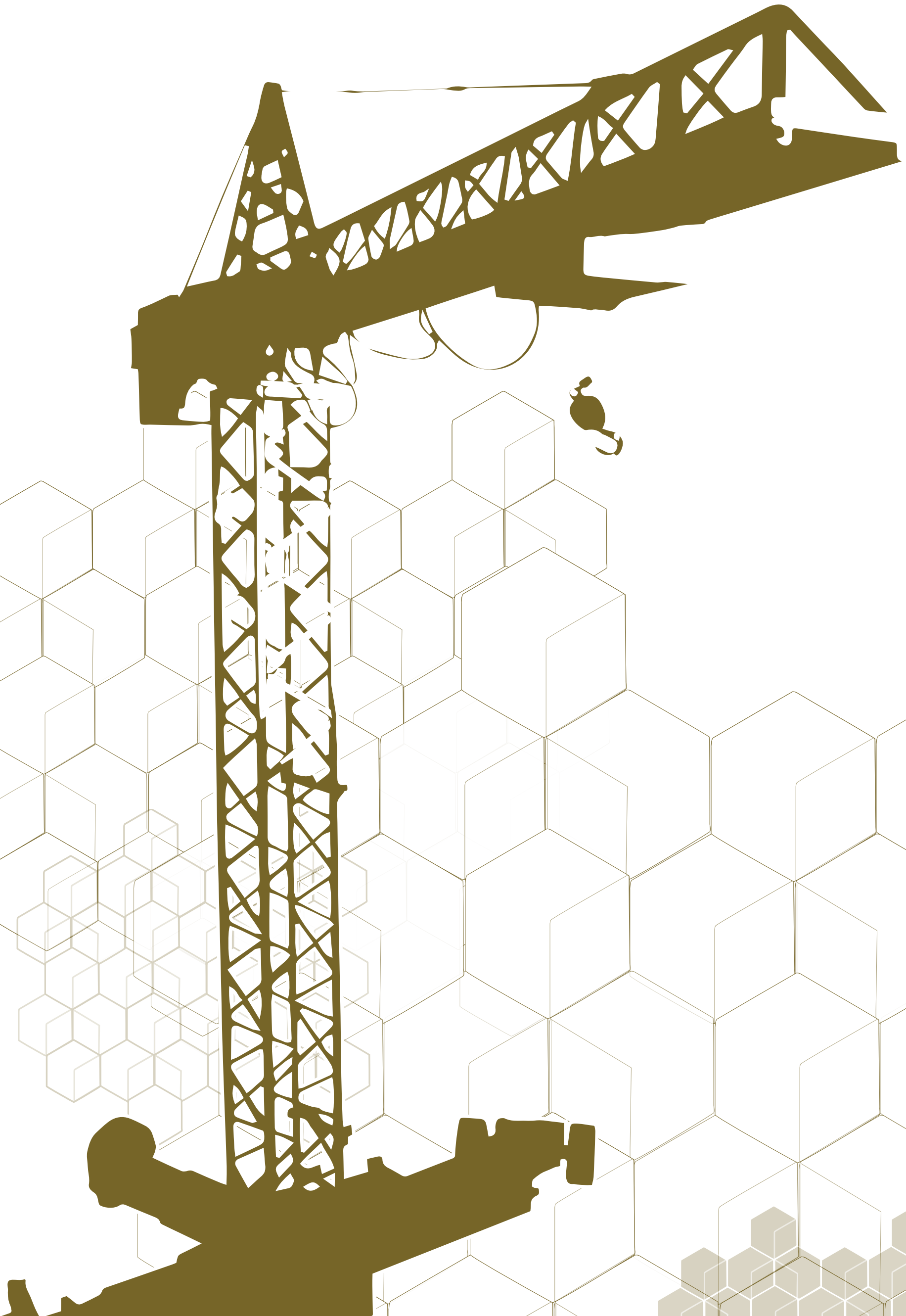
Structures may be designed for part reuse and part temporary application. This comes from consideration of the whole of life use and how this is best addressed. Various Life Cycle Assessment (LCA) methods can be utilised to assess the solutions with the lowest energy, carbon and cost implications.

Good examples of such relocatable structures that are adaptive come from Olympic venues, such as the London Olympic Park. This project had a significant sustainability focus as Olympic Games generate large crowds and specific requirements for a very short, high capacity event, after which venues are often only used to a fraction of their initial design capacity. The main London Olympic Stadium was therefore designed with removable upper seating and a structure that could be adapted for other activities, such as for use by football teams.

Chapter R

DfMA, Digital Engineering & Lean Manufacturing





R DfMA, Digital Engineering and Lean Manufacturing

R0.0.0.1

Design for Manufacture and Assembly (DfMA), Digital Engineering and Lean Manufacturing are fundamental principles and tools that can form the basis for successful *Modular Construction* projects. This chapter explores these areas to help promote best practice and maximise the value that can be obtained by constructing buildings offsite.

R0.0.0.2

A brief description of each of these areas follows:

DfMA (Section R1)
A Design for Manufacture and Assembly (DfMA) approach to *Modular Construction* is important for success. This requires consideration and understanding of each step of the supply chain and construction process. DfMA means much more than simply building modules away from their final location, which is often a simplistic perception of modular construction. The “DfMA Envelope” is presented in **Section R1.1**: this is a definition of components encompassed by DfMA, including geometry, production and metadata.

Digital Engineering (Section R2)
It is important to close the gap that traditional construction contracts generally place between different parties and to develop a holistic mindset that thoroughly considers the knock on effects of every design decision. In *Modular Construction* such interfacing issues are much more difficult to ‘firefight’ and resolve on site. It is therefore essential that all disciplines’ designs are well coordinated and any potential clashes resolved before manufacture and construction. Digital design and delivery tools and processes, here referred to as ‘Digital Engineering’, should therefore be embedded in order to avoid issues and encourage collaboration.

Lean Manufacturing (Section R3)
In order to maximise the value that *Modular Construction* offers to any particular project, it is important that the manufacturing processes are well considered, right from the design outset. It is well proven that lean principles enable successful results with DfMA processes. Lean thinking should therefore not only be deployed to the manufacturing and assembly phase, but towards design of the entire project construction period.

R1 Design for Manufacture and Assembly (DfMA)

R1.0.0.1

DfMA is the design and manufacture of discrete sections of a product (or structure) which are then assembled at one location, typically a factory for mass-production. The individual sections can be manufactured at geographically dispersed locations from the factory. However, when applied to the construction industry, DfMA involves the manufacture of discrete sections of the final construction in a factory (or multiple factories) which are then transported to site for final assembly.

R1.0.0.2

DfMA-based construction is not a new concept; the Romans developed sophisticated prefabricated building techniques approximately 2000 years ago, for both temporary army fortifications and permanent structures such as hospitals, aqueducts and major iconic buildings [9.1].

In the modern context, DfMA applies techniques to the construction process that have been used in the automotive, aerospace and shipbuilding industries for many years.

R1.0.0.3

The uptake of DfMA in the construction industry has been slow and sporadic, or only as a partial solution, e.g., precast concrete elements, structural steelwork components etc. However, computing hardware and software-enabled holistic DfMA approaches are gaining momentum; allowing project stakeholders to analyse modular solutions and plan the construction more carefully.

R1.0.0.4

The basis of DfMA is virtual reality modelling of the project, which should include the following elements:

i. Discretisation of the construction;
ii. 3D design collaboration;
iii. 4D construction planning;
iv. 5D quantification and costing.

DfMA allows all elements of the project to be interrogated by the construction team until the optimum solution is achieved.

R1.1 The DfMA Envelope

R1.1.0.1

There is no universal definition for DfMA when applied to the construction industry. The terms DfMA and *Modular Construction* are often used interchangeably. However, a more explicit definition is that *Modular Construction* (or off-site manufacture) is actually a part of the DfMA process. The key components of the DfMA envelope [9.2] are described in further detail as follows and are illustrated in **Figure R1**.

Geometry

The Geometric Model is the virtual 3D model, as represented in a software package such as Building Information Modelling (BIM). It allows technical and non-technical team members to visually understand and interrogate the design intent. Its main components should include engineers' finite element models, geometrical components and computer numerical control (CNC) models, which enable automated production of the relevant elements of the project.

The 3D model may also be used to produce 2D drawings, which may be required for non-automated processes such as approvals by statutory authorities, third party manufacture of small-scale items, etc. However, this should be minimised with preference for 3D approvals directly from the full model.

Production

DfMA production covers off-site manufacture in a factory environment. Modules produced can include: small-scale items, such as electrical fittings; large scale items, such as precast concrete floors and panelised systems in steelwork, precast concrete or timber; and fully enclosed volumetric spaces, such as individual rooms or complete buildings [9.3]. The entire fit-out process, i.e., structural, electrical, mechanical and decorative work, is ideally carried out in a factory. A higher level of quality control and improved overall quality assurance is generally achieved through factory production.

A significant proportion of the work can be automated and performed by robots. Input for the robots should be via computer numerical control software derived from the Geometry Model.

Metadata

The Metadata Model is a multi-dimensional database, containing all relevant project

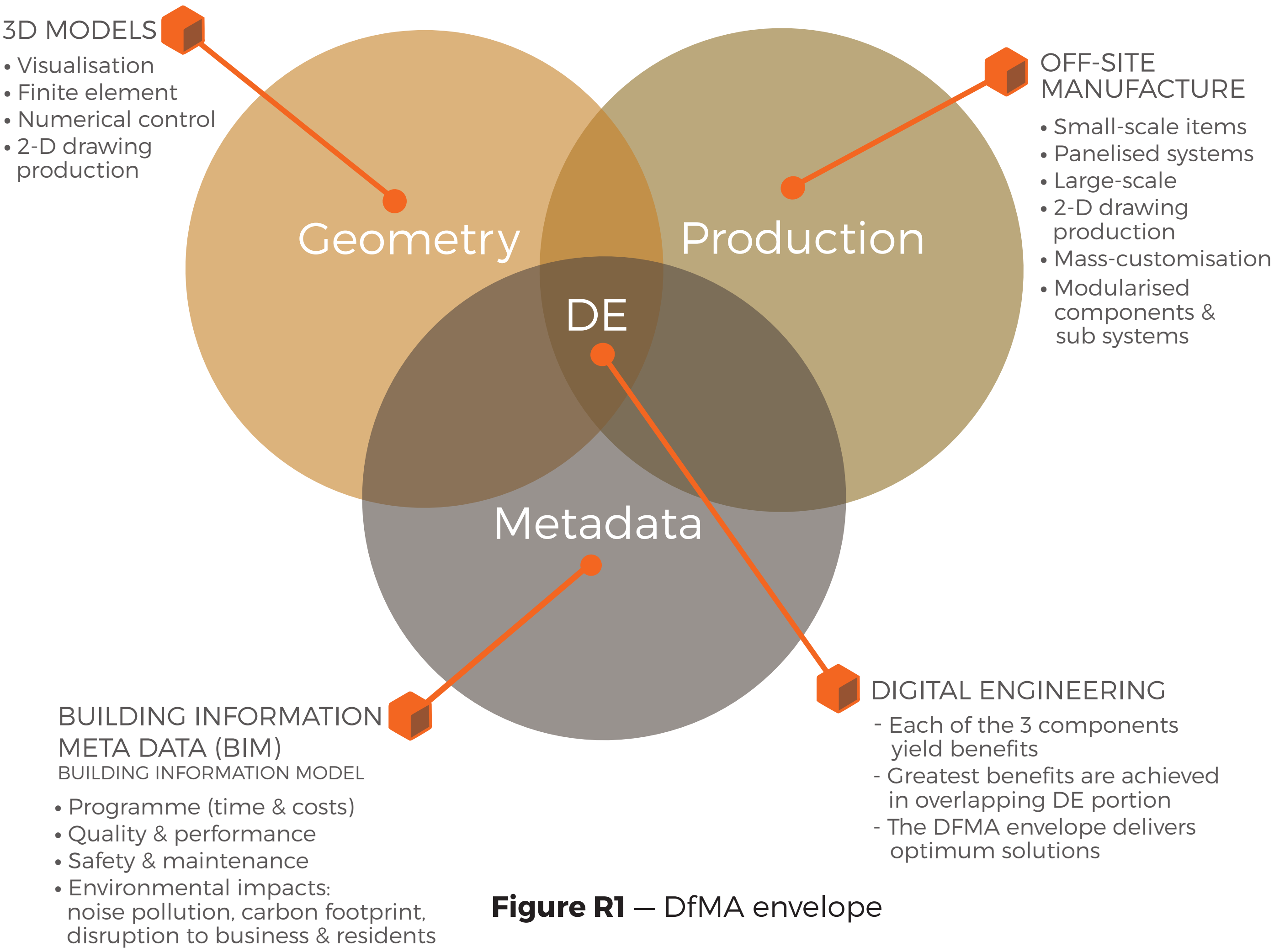


Figure R1 — DfMA envelope

parameters. Not only can this be used to calculate impacts of time, sequencing, scheduling and costs but it can also be used to analyse environmental impacts, such as carbon footprint, sustainability, noise pollution, air quality and other effects on the environment. Additional benefits include waste reduction, error avoidance and lowering of cost. When combined with the 3D Geometry Model, the Metadata Model can therefore allow all stakeholders to analyse the impacts of different design options. This is further discussed in **Section R2.3**.

R1.2 Advantages of DfMA

R1.2.0.1

Some advantages of DfMA when compared with traditional construction are summarised as follows:

i. Interactive participation in the design and planning process by all stakeholders (technical and non-technical), leading to optimal solutions, including rapid implementation of design changes or variances and improvements in overall design integration.
ii. Increased efficiency and reduced costs.
iii. Higher quality construction with guaranteed quality assurance levels achieved on site.
iv. Improved health and safety performance and a safer operational asset over the whole-life cycle.
v. Reduced construction time, enabling an earlier return on investment.
vi. Improved sustainability and environmental performance.
vii. Reduced wastage: factory wastage is reduced to near-zero and on-site wastage is significantly reduced.

R1.2.0.2

A typical construction programme for traditional construction and DfMA methodology is compared in **Figure R2**.

This shows that a significant reduction in construction program can be achieved by utilising DfMA – time savings of 30% are normally achieved but savings approaching 50% have been reported in some case studies.

R1.2.0.3

In order to achieve such programme savings, it is essential that DfMA is implemented early in the design process. In order to optimise the design and construction of the project, the following key elements of DfMA need to be implemented [9.4]:

i. Developing flexible processes and techniques that encourage the efficient off-site prefabrication of modular and portable elements for easy transportation and rapid on-site assembly.
ii. Organising the construction site work innovatively so that adverse environmental and societal impacts are minimised.
iii. Achieving sustainable solutions at multiple levels, namely: project-based, location-based and country-wide levels.

R1.2.0.4

Adverse impacts of traditional construction and maintenance practices in the urban context include:

i. Noise pollution
ii. Dust and air pollution
iii. Service disruptions
iv. Access problems
v. Delays and traffic jams
vi. High proportion of material waste
vii. Obstacles to safety and security

R1.2.0.5

Attempts have been made to realise a change from the craftsmanship-based and labour-intensive process of traditional construction, towards sustainable construction practices but these have tended to be piecemeal and ad-hoc.

R1.2.0.6

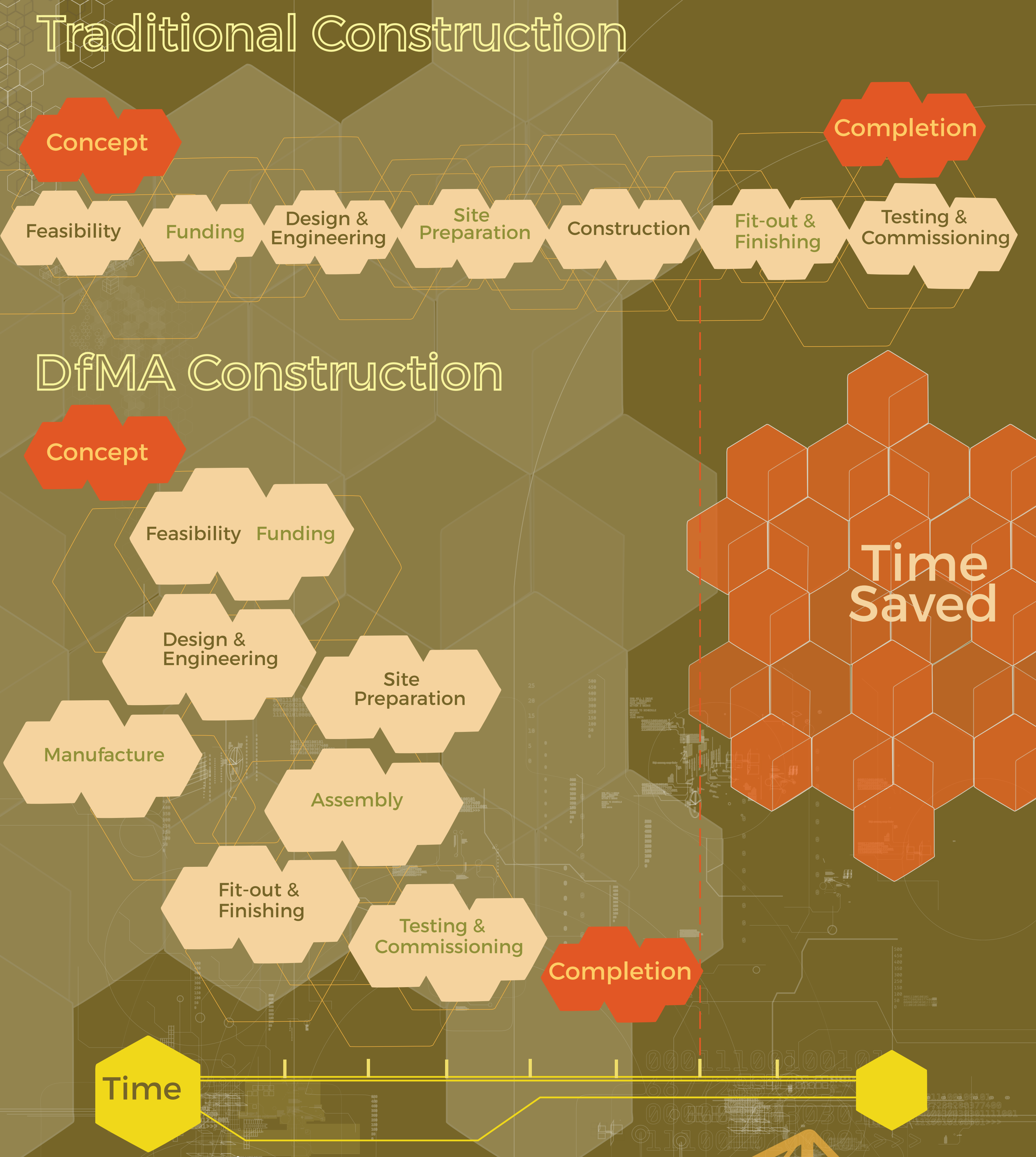
It is only by using DfMA that a holistic, efficient, time-saving and low-disturbance assembly process can be achieved on the construction site. Additionally, DfMA results in high added value to the economic viability and environmental sustainability of the construction project.

R1.3 Obstacles to DfMA

R1.3.0.1

There are various obstacles to widespread implementation of DfMA in construction. These include the following:

i. Negative associations amongst the general public with “pre-fabricated” structures.
ii. Reluctance of the wider industry to adopt DfMA and off-site manufacturing.
iii. Risk averse financial and investment institutions.
iv. Traditional procurement processes that discourages DfMA.
v. Time lag for new technologies gaining acceptance in the marketplace.
vi. Design standards and statutory approval processes that do not keep pace with or fully integrate with new construction methodology.



Traditional Construction

Concept

Feasibility

Funding

Design & Engineering

Site Preparation

Construction

Fit-out & Finishing

Testing & Commissioning

Completion

DfMA Construction

Concept

Feasibility

Funding

Design & Engineering

Site Preparation

Manufacture

Assembly

Fit-out & Finishing

Testing & Commissioning

Completion

Time Saved

Time

Figure R2 — Typical reduction in construction programme using DfMA

This Handbook aims to help alleviate some of these obstacles by providing guidance and promotion of *Modular Construction*, but it is the construction community's collective responsibility to address these obstacles.

R1.3.1 Procurement Process

R1.3.1.1

DfMA requires a collaborative design team, with direct input from constructors, fabricators and suppliers. The procurement methods associated with traditional construction present a major barrier to *Modular Construction* as DfMA principles cannot usually be incorporated until it is too late.

R1.3.1.2

In a traditional procurement process the client nominates a *Designer* (usually a design team comprising an architect and engineers). After the detailed design and technical specifications are prepared, the client organises a construct only tender to select a contractor.

The traditional tender process is designed to produce direct price competition for a specified product and the project will be awarded to the lowest price bidder. Traditional procurement methodology therefore becomes an obstacle to integrated project development methodologies such as DfMA. The organisation of the work to minimise costs and environmental impact, through optimal coordination between design and construction, is constrained by the predefined client's specification and design, as well as by the contractual separation of design and construction responsibilities.

R1.3.1.3

Integrated procurement using DfMA, in contrast to traditional methodology, encourages innovation in design and construction. The basic principle of the integrated procurement method is that the client establishes a contract with a single party (ideally a *Designer*/contractor consortium) which assumes the full responsibility for both design and construction. Through early contractor involvement, the client gives the freedom to the winning contractor (or consortium) to propose and realise an innovative design, including the use of new materials, production and assembly techniques. The main requirement is that the design meets the client's functional requirements. Since the same contractor (or consortium) is usually responsible for the design and build processes, with significant buy in from the client, an optimal design that is efficient to construct, maintain and operate can be achieved.

R1.3.1.4

Integrated procurement processes that encourage DfMA are becoming more popular in the construction industry due to the benefits (time, cost and environmental) that they bring to all stakeholders in the construction project. This must be further promoted by industry, for example, clients encouraged to approach projects in a more collaborative manner, and should be a key consideration when establishing a *Modular Construction* or DfMA project.

R1.4 Implementing DfMA

R1.4.0.1

In order to support *Modular Construction* and lean manufacturing, a disciplined product development process is required with a DfMA methodology at the core of the process. This process guides the implementation of a product from conception through to production.

R1.4.0.2

Implementation of DfMA will be made more effective by taking the following into account:

i. Throughout the design phase, the product *Designer* should consider the full lifecycle process, including the manufacturing and assembly processes.
ii. Stakeholders should conduct collaborative DfMA, Failure Mode and Effects Analysis (FMEA) and Lean Manufacturing workshops throughout the design phase to maximise production efficiency, reduce program risk and minimise costs.
iii. The involved parties should seek to maximise and quantify the 'value add' in the off-site manufacturing process by creating preassembled elements; for example, façades, finished internal walls and services rough-in.
iv. A continuous improvement process should be embedded in the development process to ensure issues are reported, recorded and resolved.

R2 Digital Engineering

R2.0.0.1

All effective modular projects should adopt a rich digital communication strategy at their core. Building Information Modelling (BIM) software can significantly help collaboration and transparency, but not when used in isolation. In order to build a central source of truth, all data must be structured effectively, appropriately managed and updated throughout all design and construction stages.

This requires full buy-in from all project members. Digital tools can be extremely valuable at all stages of the project lifecycle, ultimately helping to reduce project duration and cost.

R2.0.0.2

A digital model can be used to facilitate design coordination, simulation and visualisation of all project details. Furthermore, various digital tools can be utilised to facilitate an effective customer-centric design process.

R2.0.0.3

It is essential that a detailed, well-coordinated model is used to ensure design compatibility, simulate construction processes and eliminate clashes. Since *Modular Construction* components are usually only assembled at the final construction stage (once the majority of other components are fabricated and site works completed), this is even more important than for traditional construction projects.

R2.0.0.4

Traditional design that is led from 2D drawings should be avoided, instead embracing a digital design environment. This minimises task repetition, avoids interpretive mistakes and allows clear coordination. BIM models better enable inter-discipline and organisational interfacing, provided that the base coordination model is established on a common platform that all sub-models can feed into.

R2.0.0.5

An accurate, data-rich model with metadata can be integrated with facilities management software to significantly assist owners and service providers in improving building and infrastructure management. This therefore presents a valuable asset that can be developed and provided at handover. However, this will often require education to clients and a thorough understanding of their requirements. The earlier that these are understood, the more effectively client needs can be catered for.

R2.1 Digital Design Process

R2.1.0.1

The use of specialised BIM software programs expedites the design and drafting process, decreases document errors, delivers more information to team members, increases client certainty and improves the speed and accuracy of the build process.

R2.1.0.2

One of the greatest advantages of BIM software is the way in which it facilitates collaboration between various internal and external disciplines (e.g. engineering, architectural, construction, planning, commercial, fabrication, etc.). Collaboration is facilitated through generating a model coordination file, the setup of the software interface and functions allowing real-time collaboration between all stakeholders. The emergence of various BIM formats has led to coordination challenges, and therefore a thorough management strategy is essential.

R2.1.0.3

It is important for consultants to be familiar with *Modular Construction*. In particular structural and mechanical, electrical and plumbing (MEP) engineering for *Modular Construction* requires specialised knowledge. Although clients and architects can work with any consultant of their choosing, it is important to choose consultants who are familiar with *Modular Construction*.

R2.1.0.4

Collaboration during the design phase is essential for *Modular Construction* to be effective. It is therefore important to enable and empower the full supply chain to access and input the digital information that they need. *Designers*, suppliers and other parties should provide sufficiently detailed information to assist others, which is often best managed by contractual requirements for BIM information of a particular level of detail. It is important that appropriate suppliers and fabricators with the right products and capabilities are selected at an early stage. This often requires alternative procurement strategies.

R2.1.0.5

Collaboration on construction design and documentation is a significant benefit of working with modular systems. Benefits include:

i. Design integration of all building components into the module.
ii. A natural breakdown of work packages, facilitating clearer project management and communication between parties.
iii. Greater collaboration in the specification process.
iv. Higher level of scrutiny and design coordination offered by using BIM.
v. Highly detailed shop and construction drawings (preferably digital), reducing ambiguity during manufacture and on-site assembly.

R2.1.0.6

The BIM design process allows for the generation of detailed and precise shop drawings. These packages include the details for each part being produced and generation of a bill of materials. However, this requires more detailed modelling than consultants would typically conduct, provided in the appropriate format. This level of detail may therefore be conducted by the fabricator and fed back into the parent coordination model during design checking and approval.

R2.1.0.7

More complex projects may require that a digital model simulation be generated which animates the setting process. This dynamic modelling tool can help predict and plan for the movement of modules and other prefabricated elements to prevent any conflicts.

R2.1.0.8

With 21st century digital BIM platforms, there should be no surprises as to what will be delivered and clients should be able access digital models to visualise exactly what they are going to receive in advance of project handover. For example, interrogation of BIM models of increasing levels of complexity can allow fast iterative feedback from the client or potential customers during design development. Application of digital tools, such as the use of Augmented Reality (AR) and Virtual Reality (VR), is rapidly developing and can enable a much more engaging and rewarding experience.

R2.2 Digital Manufacture

R2.2.0.1

For projects involving computer aided fabrication, design software programs provide parametric design capabilities that integrate the BIM model with seamless integration of CNC operations.

R2.2.0.2

In lean production practice, the Bill of Materials generated by the BIM model replaces the much more time-consuming, inaccurate, and often wasteful method of performing take-offs.

R2.2.0.3

A digitally integrated manufacturing process creates the opportunity for material to be ordered using the Kanban Method of lean production (see **R3.1.1.8**) which results in the elimination of inefficiencies related to material stockpiling through just-in-time delivery. The material for each workstation is delivered directly to the station by the supplier. The material is scheduled to arrive only at the moment that it is needed and it is delivered directly to strategically located points to maximise worker efficiency. This practice reduces unnecessary human motion and material movement.

R2.3 Digital Construction

R2.3.0.1

The active use of digital models greatly improves the effectiveness of on-site delivery, particularly for *Modular Construction* where prefabricated elements are clearly defined and require logistical coordination. A digital model allows constructors to run through the construction process in a virtual environment and refine all coordination, logistical and programme steps well in advance of reaching site. Rehearsing the installation in advance can create significant value by avoiding site interfacing issues, geometrical clashes and physical limitations.

R2.3.0.2

Construction Visual Method Statements can be created from the BIM model to help accurately communicate specific tasks and operations to Workers. The repetitive nature of *Modular Construction* offers a great opportunity to use the model to help explain detailed steps, highlighting any associated risks and creating a safer fabrication yard and construction site.

R2.3.0.3

A Metadata Model is a multi-dimensional database, which contains all relevant project parameters. This can be used to calculate impacts of time, sequencing, scheduling and costs but can also be used to analyse environmental impacts, such as, carbon footprint, sustainability, noise pollution, air quality and other effects on the environment; many of which will need to be ensured and reported on during the construction stage.

R2.3.0.4

The use of on-site handheld tablet computers should be considered. These can be set up to interface with the model and have two advantages. Firstly, they facilitate a paperless workplace with all required information available at the fingertips of site personnel. Secondly, they can allow Augmented Reality, where future proposed construction (such as building services or cladding) is superimposed on the actual construction to date. This expedites on-site error checking and detection of conflicts.

R2.4 Operation and Facilities Management

R2.4.0.1

Metadata Models (fed by the geometrical BIM model) can be used by asset managers for facilities management purposes. This can be built from the same model developed by the project team and supplemented with additional product data information maintenance regimes and service records.

R2.4.0.2

Such Metadata Models can be used to simplify maintenance processes, collate information that may otherwise be lost and even produce virtual training of specific required operations.

R2.4.0.3

An Internet of Things (IoT) approach to building management can be developed for the asset manager. For example, various factors (such as specific power load, temperature, humidity, occupancy, time of day etc.) are recorded, collated and analysed to understand the actual performance of a building. This can inform optimisation of MEP services to significantly reduce running costs, even using machine learning algorithms to automatically change the response of different interconnected system components.

R2.4.0.4

By understanding the client's ultimate whole of life drivers, rather than a construction brief alone, components can be embedded into the initial system. *Modular Construction* provides an excellent opportunity to incorporate high-tech products, systems and sensors as they are constructed in a much more controlled way, but this benefit is lost if it is not embedded into the upfront design.

R3 Lean Manufacturing

R3.0.0.1

Modular Construction is based around the idea of optimising construction through off-site manufacture of various components, transport to site and assembly. This permits manufacture in controlled factory conditions, leading to efficiency and safety gains, through the implementation of lean manufacturing techniques and principles.

R3.0.0.2

Many definitions and concepts have been developed that underpin lean manufacturing. At its simplest form, 'lean' refers to a mindset of eliminating waste in order to increase efficiency.

R3.0.0.3

Lean thinking has been used for centuries and can be applied to any set of activities that need not be constrained to a manufacturing environment. Lean manufacturing methods for designing and performing manufacturing processes in a more efficient way, should therefore be a fundamental basis of every step of *Modular Construction* and can even be applied to traditional on-site construction [9.5].

R3.0.0.4

The lean paradigm was developed in automobile manufacturing with the Toyota Production System (TPS) and has now spread across a wide range of industries. The TPS focused on minimising waste (to be taken in its most general sense), which occurs through excessive production resources, overproduction, excessive inventory and unnecessary capital investment.

Henry Ford
Henry Ford introduced an attention to waste to the automotive industry whilst developing his mass assembly system. This was hugely successful in the early 20th century with a steady-state production line which also embraced a Design for Manufacture approach (now evolved into DfMA). However, Ford suffered when they needed to diversify and was proved to not be a robust lean solution.

Toyota Production System
The Toyota Production System (TPS) was a revolution in production management which occurred after World War II. The emphasis in manufacturing was shifted away from mass production and towards lean production; promoting each step that adds value and reducing everything else. Amongst other lean concepts, TPS is famous for "just-in-time (JIT)", its identification of the "7 wastes" and striving for "continuous improvement".

Toyota Motor Corporation's founder, Kiichiro Toyoda, developed TPS ideas from his father, Sakichi Toyoda, a weaving machine inventor who ran a successful textile factory, Toyota Industries. This included; the principle of 'Jidoka', whereby automated machines stop themselves when a problem occurs, and the "5 why's" to find root causes.

The Toyota development of lean manufacturing was driven by the lack of capital and the small scale market in Japan, which made it difficult for the Japanese automotive industry to compete with the dominant American and European industries. Toyota is now the largest automotive manufacturer in the world and provides the basis for lean principles applied to many industries.

R3.1 Lean Techniques

R3.1.0.1

This section explores several general lean techniques. Since these techniques can be applied to any repetitive process, especially in manufacturing environments, they are naturally applicable tools for establishment and improvement of *Modular Construction* practices.

R3.1.1 Reduction of Waste

R3.1.1.1

As waste is reduced or eliminated, quality improves whilst time and cost are reduced. The more types of waste that can be identified, quantified, and reduced, the greater the improvement that is possible. Since the core focus of construction projects is typically cost, programme and quality, it is worthwhile considering all wasteful areas.

R3.1.1.2

The TPS defined three broad types of waste: "muda", "muri" and "mura". These are defined in the following three sections.

R3.1.1.3

The original seven wastes or "muda" (Japanese for "futility; uselessness; wastefulness") are defined as the following:

i. **Transport** (moving products that are not actually required to perform the processing)
ii. **Inventory** (all components, work in process and finished product not being processed)
iii. **Motion** (people or equipment moving or walking more than is required to perform the processing)
iv. **Waiting** (waiting for the next production step, interruptions of production during shift change)
v. **Overproduction** (production ahead of demand)
vi. **Over Processing** (resulting from poor tool or product design creating activity)
vii. **Defects** (the effort involved in inspecting for and fixing defects)

R3.1.1.4

An eighth form of waste is now also commonly referred to:

viii. **Latent skill** (capitalising on employee's other skills and creativity that may be beyond the specific skills that they were originally employed for)

R3.1.1.5

"Mura" is Japanese for "unevenness; irregularity; lack of uniformity; non-uniformity; inequality". This type of waste is avoided through Just-In-Time (JIT) systems, which are designed to improve flow, maximising productivity and minimising storage overhead.

R3.1.1.6

JIT is an inventory strategy used to decrease waste and increase resource efficiency during production. This is based on a 'pull system' whereby goods are only received as they are needed in the production process. This is facilitated by sub-processes withdrawing items from preceding sub-processes and only making parts when a request is received.

R3.1.1.7

The JIT method requires that producers are able to accurately forecast demand and that suppliers can reliably deliver quality products in a strict timeframe. Small buffers accommodate minor fluctuations and allow continuous flow. JIT requires problems to be identified and corrected quickly.

R3.1.1.8

A key element of JIT is the use of a "Kanban" system, which uses simple tools (traditionally physical cards) to "pull" products and components through the process. This is used to simplify planning and fine tune day to day flexibility.

R3.1.1.9

Production levelling, smoothing, or "heijunka" in Japanese, is a technique to reduce unevenness. Production levelling is vital to production efficiency, but is difficult when customer demand fluctuates. There are two approaches to deal with this:

i. **Demand levelling** (deliberate influencing of the demand itself)
ii. **Flexible production** (production levelling by volume, product type and production mix)

R3.1.1.10

JIT is further facilitated by a flexible workforce. In a flexible workforce, workers are trained to be multi-skilled and capable of moving between different workstations. In this way, the improvement of production efficiency is guaranteed, where workers being able to work with different machines can be relocated to different workstations when necessary.

R3.1.1.11

Single-Minute Exchange of Die (SMED) is a lean production method aimed to reduce "mura" waste (a "die" here refers to a particular type of tool used in manufacturing to cut or shape material). This is achieved through a rapid process of converting an assembly line from running the current to next product. This is key to successfully reducing production lot sizes and facilitating flexible production levelling.

R3.1.1.12

JIT strategy is applicable to each phase of *Modular Construction*, during: component, product, prefabrication and module manufacture; and, most importantly, at the on-site assembly phase.

R3.1.1.13

"Muri" is Japanese for "unreasonableness; impossible; beyond one's power; too difficult; by force; perforce; forcibly; compulsorily; excessiveness; immoderation". It can be thought of as the situation where workers are overburdened. This type of waste is avoided through standardised work.

R3.1.1.14

Standard conditions are defined to allow simple quality assessment of basic elements and processes. Work elements are then combined to create:

i. Work flows,
ii. Repeatable process steps,
iii. Standardised "takt time" (Japanese for "measure time"). This is the average time to produce one unit.

R3.1.1.15

"Poka-yoke" (Japanese for "avoiding mistakes") is a mechanism in a lean manufacturing process that helps an equipment operator to avoid mistakes by preventing, correcting or drawing attention to human errors as they occur. The term is used more broadly for any constraint built into a process to prevent incorrect operation by the user.

R3.1.1.16

Zero-defect production can be achieved through "autonomation" (smart automation designed to assist human activity, or "Jidoka" in Japanese). This enables rapid identification, address and correction of mistakes that occur in a process which would otherwise cause compound delays.

R3.1.2 The 5S Approach

R3.1.3.1

The 5S approach refers to daily practices that were developed in the TPS to encourage positive worker habits:

i. **Sort**: materials and equipment must disposed after their use in the designed areas, close to workstations in order to minimize movements.
ii. **Straighten**: materials must be stored in a certain order, in appropriate boxes or shelves. In this way the workplace is kept tidy and workers know where they can find materials to avoid wasting time for searching.
iii. **Shine**: workers must clean the work area (sweeping, putting trash in the bins, etc.) when the job is done.
iv. **Standardise**: a pattern for helping workers to locate material has to be established in order to reduce worker movements.
v. **Sustain**: set in place ways to continue and improve upon good habits. Perform audits, training of Workers through goals, encourage feedback and a "do without being told" mentality.

R3.1.3 Continuous Improvement

R3.1.3.1

"Kaizen" (Japanese for "improvement") aims to eliminate waste through continually improving standardised activities and processes.

R3.1.3.2

Embracement of lean concepts by all workers is essential for successful implementation. Workers should therefore be constantly striving to improve the way that tasks are conducted.

R3.2 Application of lean manufacturing in construction

R3.2.0.1

At first glance, construction and manufacturing seem to be a bad match, since construction has traditionally been a matter of processing and assembling raw materials on-site, in an environment far removed from a factory. Indeed, the construction industry has been slow to innovate in this area.

However, efforts have been made to research and apply the methodologies first developed in lean manufacturing to construction. For example, existing lean manufacturing techniques were modified for adaptation to construction, such as the utilisation of the “poka-yoke” device (see **Section 3.1**) for promptly detecting the occurrence of production defects or the application of the kanban method for managing material supply. Other efforts have been focussed on designing new methodologies specifically for the construction industry, such as the Last Planner System, which is an organisational system devised for managing construction activities, and the Building Information Modelling (BIM) approach that has become increasingly used.

R3.2.0.2

Subsequently, implementation of *“lean construction”* has become entwined with the *Modular Construction* industry. Enhancement of module manufacturing facility layout designs in the industry have been developed using a qualitative approach considering the mutual distance and area dimension requirements of factory stations. Now, hundreds of construction projects have exhibited the effectiveness of the implementation of lean techniques in construction production.

R3.2.0.3

The emergence of modular and prefabricated buildings is being facilitated by computer-aided design (CAD). Like the modern automobile, created and engineered as a virtual object before it is produced, modular buildings benefit greatly from integrated computerised design, wherein the entire design and assembly process is represented in some digital form.

The factory setting allows the optimisation of this technique, as fabrication and assembly are optimised through studies of how the process proceeds as a function of time. There is no doubt that the use of computer numerical control (CNC) fabrication and robotic assembly will create ever greater advantages as modular buildings continue to evolve with the application of mass customisation techniques by architects.

R3.2.0.4

Prototypes (or mock-ups) allow the client, architect and contractor to predict the outcome of the project with a high degree of certainty. The ability to create prototypes can be a significant benefit for repetitive projects such as hotels, accommodation blocks, wet areas (e.g. kitchen risers and bathroom pods), plant rooms etc. Modular prototypes are generally built using the proposed methods of construction and validate the design prior to volume production. Where lean, flexible and automated manufacturing processes are used, modular prototypes can generally be produced at a much lower cost for modular than for in-situ construction. More likely to resemble the final product than an in-situ prototype, they offer much clearer certainty of delivery. In most cases the prototype can be used to bolster sales and/or be reused on site, thus reclaiming further value.

R3.2.0.5

Modular Construction, particularly with respect to lean manufacturing, allows for the ability to more closely monitor work and improve quality. This is the case because in *Modular Construction*, quality control is a very methodical and consistent process performed at each assembly station, eliminating error and reducing the time needed to perform the quality checks.

Improved build quality in modular buildings is the result of:

i. Increased skill level and cooperation
ii. Repetition of work
iii. Ability to create specialist tools and jigs
iv. Improved physical access to the work
v. Improved working environment
vi. Access to technology in the factory environment
vii. Monitoring and quality control
viii. Tolerances
ix. Consistent and controlled work environment

R3.2.0.6

The organisation and layout of work on an in-situ construction site is temporary and therefore generally perceived to not be worth the time investment required in order to optimise as a work environment. Time-motion studies and value mapping of the production process could be used to find ways of optimise the work flow and eliminate non-value-added working.

R3.2.1 Advantages of lean modular construction

R3.2.1.1

The modular building construction process provides increased opportunities for jigging. A jig is any type of apparatus for holding work and for guiding a machine tool to the work. The increased use of jigs is the result of the repetition of factory work, even on customized projects. As well, the increased ability for storage and easy access of items in a factory setting improves the viability of using jigs and fixtures.

R3.2.1.2

Increased proximity of the location of the work to the requisite tools and materials is an important benefit. The placement of the work and the arrangement of workstations can allow assembly work to be conducted without impediment or strain.

R3.2.1.3

One-Piece Flow Manufacturing is a method which makes use of a production line with multiple stations where the work is performed. Each one of these stations performs specific tasks so that when the module has passed through all stations it is complete and ready to ship.

R3.2.1.4

A factory environment allows for the monitoring and control of air quality and ventilation. Hazardous or noxious construction activities can have their own zones equipped with specialized mitigation and safety equipment, such as spray booths, welding shields, vent hoods, etc. leading to a safer working environment.

R3.2.1.5

The factory environment has improved worker services such as bathrooms, a locker-room, and break-room with lunch facilities.

R3.2.1.6

A secure environment and the elimination of job-site theft allows for greater investment in equipment and tools.

R3.2.1.7

The high volume of buildings produced provides a greater economic incentive to invest in technology. This allows high first costs to be offset by lower life-cycle costs.

R3.2.1.8

Improved physical access to the work allows for the inspection of any component at any time during the construction process. This is a benefit for owners, architects, building inspectors, quality control staff and others.

R3.2.1.9

The primary factors in determining tolerances are the inherent characteristics of the material or assembly and craft. Since factory methods segregate activities and improve the craft of construction, tighter tolerance can typically be achieved in *Modular Construction* relative to in-situ construction.

In *Modular Construction*, *tolerances* fall into two categories: inner-module *tolerances* and assembly *tolerances*. Inner-module *tolerance* refers to the *tolerance* of the walls and finishes within a modular frame. Assembly *tolerance* refers to the *tolerance* of the module frame itself and the process of placing modules on site.

Case Study: Kullman Building Corporation Pilot Project

A pilot project has been developed by Kullman Building Corporate (KBC), contemplating the application of different lean production techniques in the production line [8.20]. KBC is one of the leading companies in the modular building sector in the U.S. However, the company proved to not be competitive in the construction market, sustaining production costs 10–20% higher compared with other companies using on-site construction rather than off-site. The production line used as a pilot project was a communication shelter line, responsible of the production of two similar building modules. The line was chosen for its simplicity and facility of control. The pilot project ran for 6 months.

The first lean technique introduced into the production line was the 5S approach. The decision to introduce first the 5S method was based on the evaluation of two different aspects, one technical and another psychological. Various experts had suggested to introduce the 5S first, to train workers in good conduct and discipline. Moreover, the resistance of people to radical changes has been observed. 5S is a tool that can give tangible results in a short time. If improvements are immediate and visible, workers tend to be more inclined to the introduction of other changes. The modification of mentality at all levels, from labour force to managers, is a preliminary requirement to implement lean techniques with effectiveness. Training was provided to the workers to show them the procedures to follow systematically, in order to ensure the best working conditions. Tools had their own positions and were always placed close to the workstation, and the workspace was kept organised to ensure a safe and pleasant environment.

The next step involved the standardization of work. First, the time to complete each module for each station, termed the “takt” time, was established. The target takt time was calculated based on the forecast of customer demand. Once this time had been fixed, worksheets were drawn up to give to workers precise guidelines for daily work practices. In particular, an overall organizational sheet, comprising all the tasks related to various workforce teams, and a one-of-a-kind task specifications sheet were provided and put in a visible position for all the workers. Nominated people supervised the work, assuring the quality of workflow and intervening when any problem could undermine it. Moreover, a mobile work crew was established, in order to deal with unexpected events, such as defects or delays in the production line or worker absenteeism. At the end of the test period (6 months) the company registered an improvement in productivity from 1.1 modules per workday (8 hr takt time) to 1.73 modules per workday (5 hr takt time).

The KBC case study shows how the application of lean techniques in traditional construction can produce visible and tangible benefits when applied in modular construction. Moreover, the author asserts that the approach developed in the pilot project can be used as a universal approach for implementing lean construction in production lines with different features. However, there is still a need to provide more empirical evidence to better understand the effectiveness and improvements related to the implementation of lean construction.

Conclusion

Modular Construction places an emphasis on maximising off-site manufacture of components and minimising on-site assembly and rework time, aiming to thereby reduce the required resources, avoid environmental impact, encourage affordable housing, introduce efficiency and improve productivity. The viability of this emerging industry is contingent upon confidence across the range of stakeholders that this innovative form of construction, and indeed this paradigm shift in the underlying philosophy, can be successful, with managed risk and thorough compliance with relevant regulations. In Australia, this form of construction has not yet gained traction. This can be attributed in part to the reluctance of the construction industry (and other involved sectors such as financiers) to move away from established practice and towards what may be perceived as risky and untested construction methodologies.

Expressed in another way, there is insufficient stakeholder confidence that *Modular Construction* can achieve the desired outcomes. Confidence in traditional construction stems partly from a long history of established practice, but also from the large body of available codes and standards which provide guidance for the industry. The novelties, subtleties and caveats of *Modular Construction* are not addressed by these codes and standards; consequently, embarking upon a modular construction project is uncharted territory for the involved parties. Having a well-rounded, thorough body of work addressing this area would serve as a map of the various aspects to consider along the way.

This Handbook for the Design of Modular Structures endeavours to provide a consistent body of guidance for a varied audience; from architects and engineers through to financial institutions. The emphasis is on Design for Manufacture and Assembly (DfMA), which embodies a holistic approach to design. In this detailed design philosophy, the complete process of construction is considered, from concept to manufacture, through to assembly of a completed structure. To the knowledge of those involved in the preparation of this Handbook, there is no comparable document in the world.

Any building, no matter how it was constructed, must ultimately comply with the relevant local building codes. These codes do not specify the construction method, but rather state the *Performance Requirements* of a completed structure. The codes may in turn reference relevant local or international standards. This Handbook makes some specific references to the Australian *National Construction Code (NCC)* as well as to standards referenced therein, but generally seeks to present general guidance on what considerations are pertinent to *Modular Construction*. The present document tries to avoid making design prescriptions, but rather encourages a detailed consideration of the relevant issues associated with any particular area.

It is anticipated that this document will significantly aid in promoting *Modular Construction* in Australia and beyond, by providing a document that brings together in one place a broad range of guidance and considerations for this emerging form of construction.

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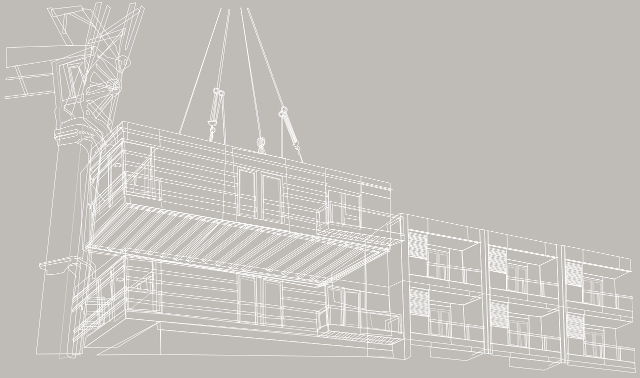

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