ABCB

Structural Robustness

2016

Handbook

NON-MANDATORY DOCUMENT

STRUCTURAL ROBUSTNESS

HANDBOOK

2016

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- guarantee acceptance or accreditation of a design, material or building solution by any entity authorised to do so under any law;
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Preface

The Inter-Government Agreement (IGA) that governs the ABCB places a strong emphasis on reducing reliance on regulation, including consideration of non-regulatory alternatives such as non-mandatory guidelines, handbooks and protocols.

This Handbook is one of a series produced by the ABCB. The series of Handbooks is being developed in response to comments and concerns expressed by government, industry and the community that relate to the built environment. The topics of Handbooks expand on areas of existing regulation or relate to topics which have, for a variety of reasons, been deemed inappropriate for regulation. The aim of the Handbooks is to provide construction industry participants with non-mandatory advice and guidance on specific topics.

Structural Robustness has been identified as an issue that requires consistent uniform guidance.

The Structural Robustness Handbook has been developed to foster an improved understanding of this issue. This Handbook addresses the issues in generic terms. It is expected that this Handbook will be used to develop solutions relevant to specific situations in accordance with the generic principles and criteria contained herein.

Contents

1 Introduction

Reminder:

This Handbook is not mandatory or regulatory in nature and compliance with it will not necessarily discharge a user's legal obligations. The Handbook should only be read and used subject to, and in conjunction with, the general disclaimer at page ii.

The Handbook also needs to be read in conjunction with the relevant legislation of the appropriate State or Territory. It is written in generic terms and it is not intended that the content of the Handbook counteract or conflict with the legislative requirements, any references in legal documents, any handbooks issued by the Administration or any directives by the Building Control Authority.

1.1 Structural Robustness

This Handbook was developed to provide support in understanding the structural robustness requirements of the National Construction Code (NCC), specifically **BP1.1(a)(iii)** of Volume One and **P2.1.1(a)(iii)** of Volume Two, introduced in NCC 2012. *Verification Methods* for these *Performance Requirements*, **BV2** of Volume One and **V2.1.2** of Volume Two, were introduced in NCC 2016.

BP1.1 is supported by a comprehensive list of documents in the *Deemed-to-Satisfy Provisions*, while **P2.1.1 (a)**, **(b)** and **(c)** have supporting *Deemed-to-Satisfy Provisions* through Acceptable Construction Manuals, and Acceptable Construction Practices. These manuals and documents cover most aspects of the Limit State Design Method for most construction materials. However, if designers wish to or have to operate outside *Deemed-to-Satisfy* they must develop a *Performance Solution (Alternative Solution)*. **BV2** and **V2.1.2** are designed to support those who wish to follow the *Performance Solution* path.

This Handbook is focussed on the Australian regulatory aspects of structural robustness. Structural robustness affects different materials in different ways. For further discussion refer to Sections 3 and 4 of this document.

1.2 Limitations

This Handbook is not intended to:

- override or replace any legal rights, responsibilities or requirements; or
- provide users with the specifics of the NCC.

This Handbook is intended to make users aware of provisions that may affect them, not exactly what is required by those provisions. If users determine that a provision may apply, the NCC should be read to determine the specifics of the provision.

1.3 Other Handbooks by the ABCB

The ABCB has produced a range of Handbooks and other educational material relating to topics associated with the NCC. They can be downloaded from the ABCB website: www.abcb.gov.au.

2 Background

2.1 Definition of terms

The following terms are defined within the NCC in Part A1 of Volume One and Part 1.1 of Volume Two. They are used throughout this Handbook. A number of selected defined terms, relevant to the structural robustness, are also included.

Reminder:

Defined terms are amended in the NCC from time to time, so it is important to always refer to the current edition for the correct explanation of these terms. States and Territories may also vary or add to the definitions contained in the NCC. These are detailed in the relevant State or Territory appendix.

2.1.1 NCC Defined Terms

Deemed-to-Satisfy Provisions means provisions which are deemed to satisfy the *Performance Requirements*.

Deemed-to-Satisfy Solution means a method of satisfying the *Deemed-to-Satisfy Provisions.*

Performance Requirement means a requirement which states the level of performance which a *Performance Solution* or *Deemed-to-Satisfy Solution* must meet.

Performance Solution (Alternative Solution) means a method of complying with the Performance Requirements other than by a *Deemed-to-Satisfy Solution*.

Verification Method means a test, inspection, calculation or other method that determines whether a *Performance Solution* complies with the relevant *Performance Requirements*.

2.1.2 Other Terms of Interest

Accidental action means an unspecified action, usually of short duration, which might occur on a building.

Disproportionate Collapse means collapse of a building or structure, which is disproportionate to the initial cause.

Extreme event means an extreme occurrence or change of a particular set of circumstances.

Hazard means potential to cause damage.

Notional removal of element means analytical procedure where supporting structural elements are removed one at a time and the residual building is checked for the extent of resulting damage.

Progressive collapse means sequential spread of damage from an initiating event, from element to element, resulting in the failure of a number of elements.

Risk means the chance of something happening that will have an impact. It is measured in terms of likelihood and consequence.

2.1.3 Acronyms

The following acronyms are commonly used throughout this Handbook and are listed here for ease of reference.

BCA means Building Code of Australia

NCC means the National Construction Code.

2.2 Notation

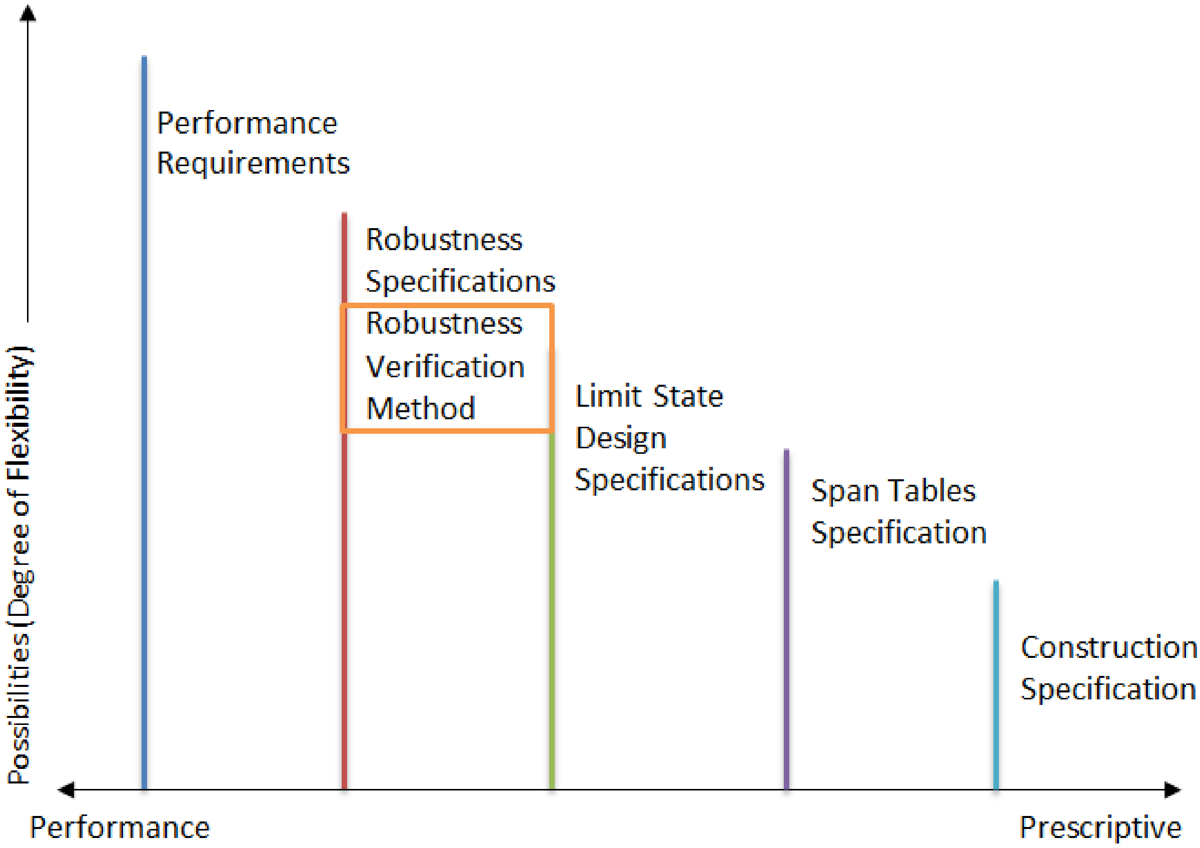
The units and notation used in this Handbook are designed specifically for use with the structural robustness *Verification Methods*. The symbols used are outlined in **Table 2.2.1**.

Table 2.2.1 Symbols

Symbol	***Meaning***
G	Permanent action effect
Q	Live Load action effect
Ψ_c	Live Load Combination Factor

2.3 Hierarchy of Performance

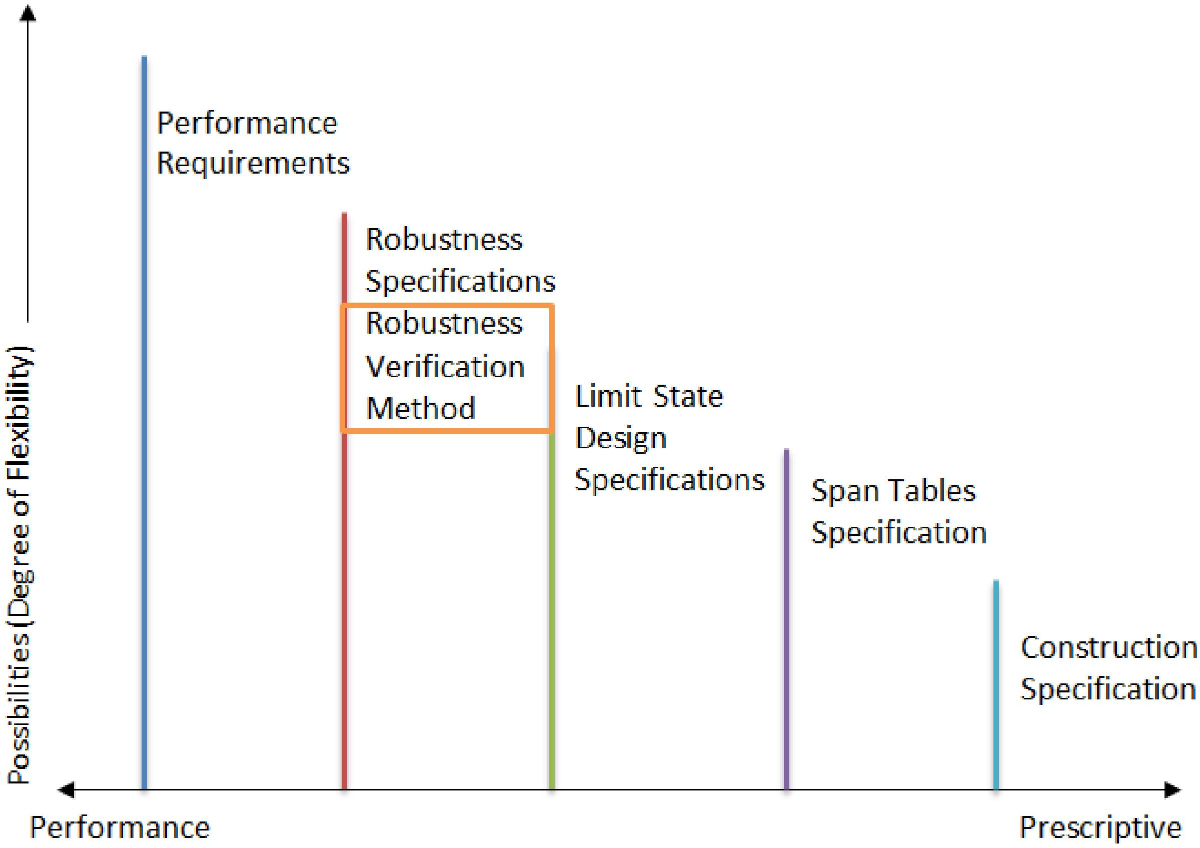
There are various levels of performance specification, from prescriptive, which involves detailed descriptions of how the process should be completed, to pure performance, which allows a greater degree of flexibility in achieving the same requirements or objectives. **Figure 2.3.1** Level of Performance Hierarchy



describes the relationship of prescriptive and performance-based specifications, including where a *Verification Method* sits within this relationship.

The structural robustness *Verification Method* is one way, but not the only way, to demonstrate compliance with the NCC *Performance Requirements*. This *Verification Method* is a performance-based process to assess a structure's robustness.

Figure 2.3.1 Level of Performance Hierarchy



2.4 Structural Performance Requirements

The NCC contains five structural *Performance Requirements*. **BP1.1** and **BP1.2** of Volume One and **P2.1.1(a)**, **(b)** and **(c)** of Volume Two address general structural performance.

The *Performance Requirements* are specifically written to cover strength performance, that is the relationship between the actions and the resistance provided by the structure. The actions are described in **BP1.1** and **P2.1.1(a)** and **(b)** whilst the resistance is described in **BP1.2** and **P2.1.1(c)**.

BP1.1 and **P2.1.1 (a)** and **(b)** consist of two parts:

1. a list of the required performance attributes; and
2. a list of the factors to be considered, namely the actions to which a building 'may reasonably be subjected'.

The list of performance attributes covers the serviceability performance, strength performance and structural robustness. The concept of structural robustness applies to the chosen structural system of the building.

BP1.2 and **P2.1.1(c)** cover general principles in formulating structural resistance.

2.4.1 Verification Methods

In order to meet the structural robustness requirements of the *Performance Requirements* through the *Verification Methods*, **BV2** and **V2.1.2,** a structure is required to demonstrate that it is sufficiently robust against accidental actions.

Reminder:

The *Verification Method* is one way, but not the only way, to demonstrate compliance with the NCC *Performance Requirements*. There are other structural *Performance Requirements* in the NCC that are not covered by these *Verification Methods*.

3 Structural Robustness

Structures are designed to withstand a number of frequently occurring actions and a number of extreme, but expected, events. During construction and over their life, structures are also exposed to a number of unexpected events. While structures are generally not specifically designed for these events, it is expected that they can withstand these accidental actions without being damaged to an extent disproportionate to the original cause. This is generally known as structural robustness or prevention of the progressive and/or disproportionate collapse.

The importance of structural robustness in structural design is universally acknowledged. Almost all structural regulations and codes of practice include structural robustness as one of the fundamental requirements. However, with the exception of United Kingdom (and now Australia), the requirements are generally qualitative and do not provide clear guidance on how to design and demonstrate compliance.

The difficulties in dealing with this issue are:

(i) accidental actions are not quantified; and

(ii) the acceptable extent of damage is not defined.

3.1 Background to Structural Robustness

The public has a general expectation that structures are safe. It is expected that structures should be able to resist high frequency events. However, this expectation is lower for extreme and rarely occurring events. Some events can be easily defined and designed for such as self-weight, imposed actions, wind, snow and earthquake. However, structures can also be subjected to accidental actions (such as explosions, impacts, etc.) that are difficult to define. Structural robustness is the means to protect structures against these unforeseen actions and that, regardless of how they are designed, the damage (if any) should be proportional to the magnitude of the accidental loading.

Most structures have some degree of built-in structural robustness as horizontal resistance is provided for wind and earthquake actions. Older structural codes also have empirical rules to prevent members and connections becoming too fragile, such as limiting slenderness ratios for members and minimum numbers of fasteners for connections. However, these empirical rules have been gradually removed from design standards in the rationalisation process of these documents.

Progressive collapse due to 'unbuttoning' is an example of a lack of structural robustness. This usually occurs at multiple fastener connections or larger supporting

systems where a number of identical components are used to carry a large load. The failure of one component transfers its load to the next component and causes it to also fail. The process repeats itself resulting in the failure of a number of components or total failure of the structure.

3.1.1 Characteristics of structural robustness

The expected characteristics of structural robustness include:

(a) Ability to resist lateral loading at all stages of construction and throughout the life of the structure.

(b) Ability to absorb impacts due to accidental loading.

(c) Ability to tolerate inaccuracies/uncertainties in the design and construction process as well as building movements.

(d) Ability for the structure to redistribute loads safely.

The following structural characteristics have major roles in contributing to structural robustness:

- Ductility: Ability to carry load while undergoing large deformation.
- Stability: Ability to resist whole body movements such as sliding and overturning.
- Buckling: Sudden inability to carry compression loading.
- Load paths: Ways the forces are transferred from one element to another until they reach ground-anchoring points.
- Redundancy: Availability of multiple load paths.
- Impact resistance: Ability to absorb energy released by sudden impacts.
- Joint strength: Ability of the connection to transfer the forces from one structural member to another.

Design Alert:

Fire is an important accidental loading case and its effects on structural robustness should be examined because certain load carrying elements may become ineffective in the event of a fire. The effects of the fire protection system on structural robustness are also worth examining. However, these problems are outside the scope of this Handbook and are specifically covered by *Performance Requirement* CP1.

3.1.2 Identifying structural robustness problems

Problems with structural robustness often occur in relation to:

(a) Partially built structures or unusual situations such as structures within structures (where the need for lateral restraints is often ignored).

(b) Uplift or another form of instability when the restrained forces are finely balanced with the destabilising actions.

(c) Difficulties in connecting different materials such as timber roof trusses on top of concrete walls.

(d) Over reliance on a single element to carry a large portion of a structure, such as transfer beams that support a number of columns and/or other beams.

(e) Long span beams and cantilevers that are prone to instability without adequate lateral restraints.

(f) Flexible structures that are prone to large deformation.

From the above, it is apparent that structural robustness is a performance attribute relating to, but not the same as, strength and resilience. Strength is the ability of a structure to resist a specified action, and is often computable. Resilience is the ability of a structure or a group of structures to resist and recover from damaging extreme events.

3.1.3 Codes and Standards

While structural robustness is a common notion in building codes and standards, its definition does vary.

ISO2394 (1986) and Eurocode 1 (1994) define ‘robustness’ as the ability of a structure ‘*not to be damaged by events like fire, explosions, impact or the consequence of human error, to an extent disproportionate to the original cause*’.

ASCE (2006) refers to ‘structural integrity’ meaning ‘*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*’.

BCA (2006) used the terms *‘prevention of progressive collapse*’ while NCC (2012) adopted a similar form of wording to the ASCE statement. Neither offered any direct *Deemed-to-Satisfy Solutions*, beyond the notional allowances within design standards, or verification procedures.

3.2 Current Relevant International Approaches

This section identifies some general guidance available from two international documents. Neither of these documents are NCC referenced documents.

3.2.1 Eurocode 1

The European Committee of Standardisation's Eurocode 1 (EN1990) focuses on accidental actions and provides guidance on the following:

- avoiding, eliminating or reducing the hazard;
- selecting structural form with low sensitivity to the hazard;
- selecting a design that can survive the accidental removal of an individual element;
- avoiding structural systems which may collapse without warning;
- tying the structure together.

3.2.2 ASCE/SEI 7-05

American Society of Civil Engineers' ASCE/SEI 7-05 focuses on local damage and prevention of progressive collapse by providing:

- continuity;
- redundancy; and
- energy dissipating capacity (ductility).

3.3 Design Guidance

This section discusses some available design techniques for designing robust structures.

3.3.1 Provision for minimum requirements

This technique is often used in traditional design standards. Minimum requirements are introduced to maintain a certain level of structural robustness. For example for members, there are limitations on slenderness and for connections there are a minimum number of fasteners, etc. These requirements are empirical and typically based on experience. However, modern design standards tend to avoid them and use qualitative performance requirements in their place.

3.3.2 Provision of horizontal and vertical ties

Inclusion of ties is an obvious way to prevent structures from “falling” apart. Examples of structural ties are roof tie downs for wind uplift or ring beams on top of unreinforced masonry walls to keep the walls together under earthquake action. Effective anchorage of floors to roofs and walls could also be considered as a form of tie. One important consideration in the provision of ties is to ensure there are sufficient load paths for the actions to be transmitted to the ground. Ties are also useful in allowing catenary and vierendeel actions to develop under extreme situation, therefore preventing total collapse.

3.3.3 Notional horizontal loads

This requires all structures to have some horizontal load capacity regardless of how they are designed. Most structures have this built-in, as they have already been designed for lateral wind and earthquake forces.

3.3.4 Notional removal of structural elements

This is the only method that allows some form of assessment of structural robustness to be made. Members of a structural system are hypothetically removed and the consequential damage assessed. Solutions are then developed to limit the amount of acceptable damage.

It is not always necessary to do complicated structural analysis, as a qualitative application of ‘what if’ scenarios often provides valuable insights into the issues involved.

3.3.5 Provision for critical elements

Critical elements are structural elements whose failure will result in the collapse of the structure. When this situation is unavoidable, the element should either be protected from accidental actions or be designed for a nominated accidental load which is estimated to be strong enough for a range of theoretical accidental actions.

3.3.6 Selection of appropriate structural form

A more sophisticated technique of ensuring structural robustness is the selection of the structural form. Some structural forms provide more redundancy than others and this could help in limiting the damage since alternative loading paths might be able to

contribute to the load carrying capacity once the designed loading path fails. However, this is not always possible due to other design requirements.

4 NCC Structural Robustness Requirements

4.1 Performance Requirements

The NCC *Performance Requirements* relevant to structural robustness are **BP1.1 (a)(iii)** in NCC Volume One and **P2.1.1 (a)(iii)** in NCC Volume Two.

BP1.1(a)(iii) / P2.1.1 (a)(iii)

(a) A building or structure, during construction and use, with appropriate degrees of reliability, must—

…

(iii) 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;

…

4.2 Compliance Solutions

Compliance solutions are the means of satisfying the *Performance Requirements*. The NCC provides different options for compliance being: a *Performance Solution,* a *Deemed-to-Satisfy Solution* or a combination of these. This is shown in the figure below.

Figure 4.1 Performance based compliance framework

There are two possible compliance solutions contained within the NCC. These are described in the following sections.

4.2.1 Performance Solution - Verification Method

The corresponding *Verification Method* to **BP1.1 (a)(iii)** in NCC Volume One and **P2.1.1 (a)(iii)** in NCC Volume Two is **BV2** and **V2.1.2**, respectively. It is identical in both Volumes. The NCC extract below shows this Verification Method.

BV2 Structural robustness

Compliance with **BP1.1(a)(iii)** is verified for structural robustness by—

(a) assessment of the structure such that upon the notional removal in isolation of—

  (i) any supporting column; or

  (ii) any beam supporting one or more columns; or

  (iii) any segment of a load bearing wall of length equal to the height of the wall,

  the building remains stable and the resulting collapse does not extend further than the immediately adjacent *storeys*; and

(b) demonstrating that if a supporting structural component is relied upon to carry more than 25% of the total structure, a systematic risk assessment of the building is undertaken and critical high risk components are identified and designed to cope with the identified hazard or protective measures chosen to minimise the risk.

The first part of the *Verification Method*, **BV2(a)** and **V2.1.2(a),** provides acceptance criterion for the conceptual analysis of notional removal. This is the same as that adopted in UK regulation. **BV2(b)** and **V2.1.2(b)** provides some guidance on the approach which should be undertaken for critical structural elements (those which carry great than 25% of the total structural load).

This risk approach can also be used if compliance with the *Deemed-to-Satisfy Provisions* or *Verification Method* cannot be achieved. It can be used to identify the high risk critical components and appropriate design measures to mitigate the risk (see Section 3.3) or to minimise the risk with protective means.

While the *Verification Method* is generally applicable to all buildings, it is expected that it will be used only for buildings of high importance, when the risk of disproportionate collapse is high or when a *Deemed-to-Satisfy Solution* is not applicable (e.g. for new materials).

Two examples of when the *Verification Method* may be used are provided in Section 5.

Reminder:

The *Verification Method* is one way, but not the only way, to demonstrate compliance with the NCC *Performance Requirements*. Part A0.5 of NCC Volume One and Part 1.0.5 of NCC Volume Two detail all possible Assessment Methods available to develop a compliance solution.

4.2.2 Deemed-to-Satisfy Solution

For design with conventional materials and methods, corresponding NCC referenced documents already have built-in structural robustness provisions. Some examples are listed below.

Structural design actions AS/NZS 1170.0

Section 6 of AS/NZS 1170.0 is about structural robustness. The main requirements are:

- providing load paths to foundation (general);
- vertical and horizontal ties (general); and
- design for notional horizontal forces (specific).

The specific notional horizontal forces specified in AS/NZS 1170.0 are:

- the structure as a whole: 1% -1.5% of long-term gravity loads ($G + \Psi_c Q$).
- connections and ties: 5% of long-term gravity loads ($G + \Psi_c Q$).
- walls: 5% of permanent load (G) acting laterally.

Steel structures AS 4100

Robustness is not specifically mentioned, but the following clauses are relevant:

- Notional horizontal forces are nominated for multistorey structures, which is equal to 0.002 (0.2%) of total design vertical loads at floor level (Clause 3.2.4).
- Minimum design actions on connections are specified (Clause 9.1.4).

Concrete structures AS 3600

Robustness is not specifically mentioned, but the following clauses are relevant:

- Notional horizontal forces are nominated for walls: 2.5% of total vertical load but not less than 2 kN/m length of wall (Clause 11.3).

- Limit on slenderness of columns (Clause 10.5.1).

Timber structures AS 1720

Robustness is not specifically mentioned, but the following clause is relevant:

- Extra strength is required for 'primary structural elements' (i.e. members and joints whose failure could result in the collapse of a structure) (Table 2.5 & 2.6 of Clause 2.3 – capacity factors).

Masonry structures AS 3700

Robustness is specifically mentioned in Clause 4.6, and the following requirements are specified:

- Nominated lateral pressure of 0.5 kPa for walls (Clause 4.6.2).
- Limiting ratio (Height/Thickness) for isolated piers (Clause 4.6.3).
- For members providing lateral support (Clause 2.6.3): the greater of:
    - 2.5% of vertical load on masonry members; or
    - 0.5 kPa lateral pressure on the appropriate tributary area.
- For connections to lateral supports (Clause 2.6.4): 1.25 times the horizontal design load.

All the above documents are NCC referenced documents.

5 Examples

This section provides examples illustrating basic elements of the structural robustness *Verification Methods*, **BV2** and **V2.1.2**.

Robustness issues vary with the materials and methods of construction. For examples of how to design for structural robustness, readers are referred to the documents listed in the Bibliography from which the following two examples are selected to demonstrate the basic elements of the *Verification Method*:

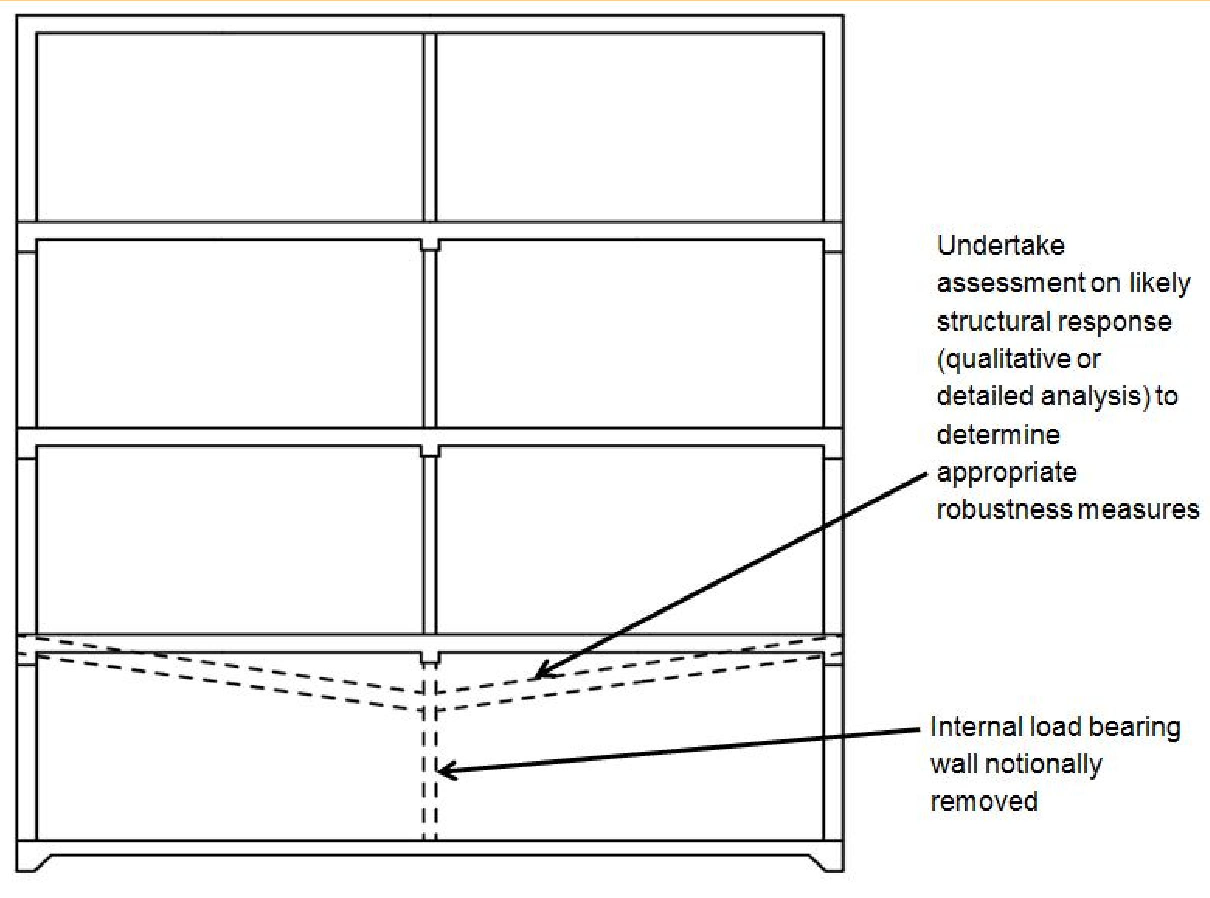
1. notional removal of a load carrying member; and

2. systematic risk assessment.

Example 1: Notional removal of a load bearing wall

Consider the building in Figure 5.1 below. It has external and internal walls supporting continuous concrete slab. The structural robustness of the system is examined by removing the internal wall of the bottom floor.

Figure 5.1 Example 1 Building (section view)



Step 1: Assess the required strength of the slabs with all the walls in place.

The slabs are continuous over the internal supports and should have the capacity to support the gravity loads on the floors. The slabs are not required to support the weights of the internal walls, as they are stacked up the height of the building.

Step 2: Examine the consequences of removing the internal wall at the bottom floor.

Total collapse of all floors is possible since the slabs are not designed to support the weights of the walls and floors above.

Step 3: Find way to limit the extent of damage.

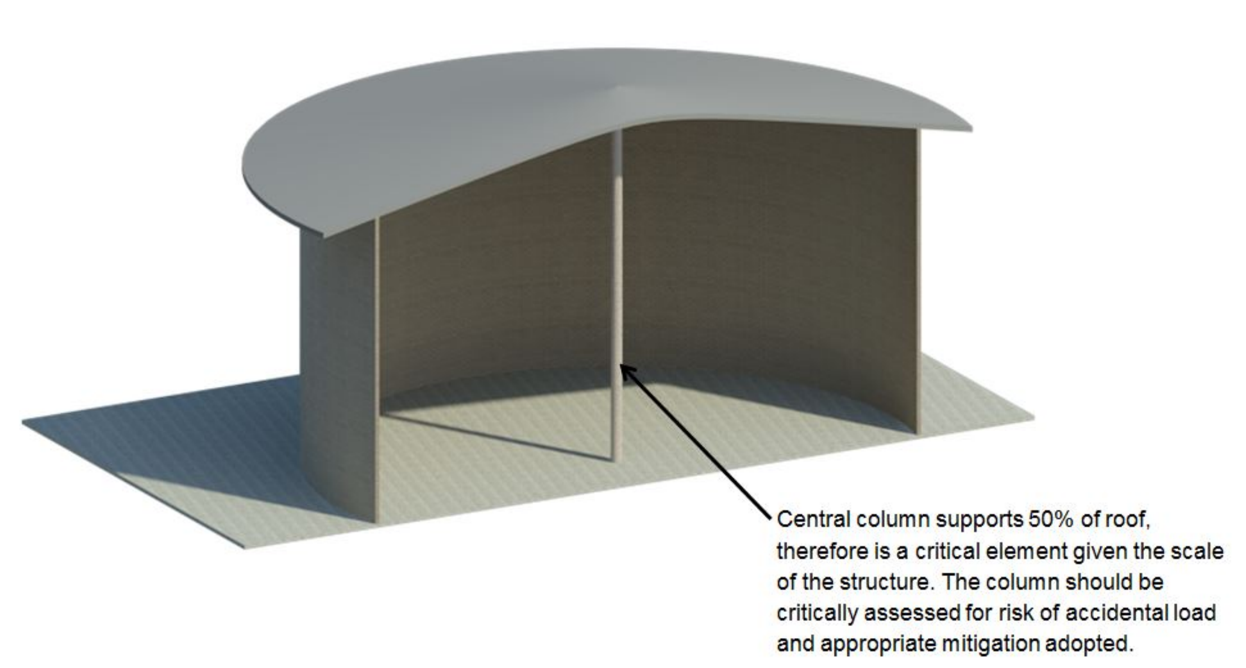
Design all the slabs to carry the weight of a single storey wall, i.e. supported on the external walls only.

Outcome: If Step 3 is followed, there is a good chance that the resulting damage will be limited to the floor above the removed wall. The solution is therefore conformed to the structural robustness requirement.

Example 2: Systematic risk assessment

Consider the roof of a 80m diameter circular building with a central supporting column in **Figure 5.2** below.

Figure 5.2 Circular building with central supporting column



Step 1: Examine the required load carrying capacity of the central column.

The central column will be required to carry 50% of the roof weight.

Step 2: Examine the consequences of removing the central column.

Total collapse of the roof would occur as there is no alternative path for the roof weight.

Step 3: Both of the above steps have shown the structure does not conform to structural robustness requirements part (a) of the V*erification Method* and the only option is to carry out a systematic risk assessment (part (b) of the *Verification Method*) to reduce the risk of any accident that might affect the load capacity of the central column.

Step 4: Examine the likelihood of accidents.

The most likely accident for a building is vehicle impact action at floor level and there are many ways to reduce this likelihood and consequence that will need examination to find the most suitable solutions. For example:

(i) change the design to eliminate the need for a central column (e.g. from flat roof to conical roof)

(ii) provide protective measure against vehicular impact to the central column (e.g. a concrete barrier around the central column that can absorb the impact of a vehicle crashing into it.

Outcome: Either of the solutions in Step 4 can be considered to comply with the structural robustness requirements.

6 Further Reading

The following reference documents are recommended if further information is required on this topic.

- The Institution of Structural Engineers 'Practical guide to structural robustness and disproportionate collapse in buildings' October 2010
- F. Knoll and T. Vogel 'Design for Robustness' IABSE 2009
- Canisius, T.D.G. (Editor) 'COST TU0601 –Structural Robustness Design for Practising Engineers' September 2011
- FPWA 'Design Guide for Robustness in Structures' (to be published in 2016)