Design for Extreme Events, Coping with Conflicting Demands; Limit States, Legislation and Black Swans

Doug Jenkins
Interactive Design Services, Hornsby, NSW 2077.
Email: dougjenkins@interactiveds.com.au

Abstract

Building design codes are largely based on the statistical analysis of expected variation in materials and loads, to arrive at procedures that will ensure a very low risk of failure under the greatest expected loads and most severe expected conditions. This approach is applied to design for earthquake loads, but in Australia the standard return period is comparatively short, whereas it is recognised that design loads for longer return period events would be substantially greater. Recent ‘Safety in Design’ legislation requires that **all** risks must be removed or minimised ‘so far as is reasonably practicable’, creating an apparent inconsistency with the standard design approach.

This paper provides an overview of current code requirements, both in Australian and the main international codes, including inconsistencies between the standard limit state design approach and legal requirements. It discusses ways in which structures can be designed and detailed to cope with rare extreme events without collapse, recommends a change to a limit state approach specifically recognising a third ‘collapse’ limit state, and providing better definition of measures appropriate to ensure compliance with legal requirements to reduce hazards ‘so far as is reasonably practicable’.

Keywords: limit state design, code requirements, legal requirements, collapse limit state, black swans, risk, uncertainty, consequences of failure, robustness

1. INTRODUCTION

The limit state design method identifies events or conditions that may have an adverse effect on the performance of a structure and seeks to reduce the risk of these outcomes as far as reasonably practicable, having regard to their expected frequency and the consequences of their occurrence. A number of ‘limit states’ are specified, together with load magnification factors, material strength reduction factors, and any other design parameters appropriate to the particular limit state. The potential benefits of this approach, compared with methods relying on limiting material stresses with a single ‘factor of safety’, are:

- The design may be optimised to minimise the overall risk, allowing improved reliability at no additional cost, equal reliability at reduced cost, or some combination of the two.
- The focus on limit states and modes of failure encourages the use of design features appropriate to the particular mode of failure.
- In particular, where a structure requires additional ductility, energy absorption, or stability under extreme conditions, the limit state method is more likely to identify and provide these requirements than methods that focus on limiting stresses in isolated sections under expected loads.

The limit state method also has a number of potential disadvantages:

- Analysis and design procedures are likely to be significantly more complex than those required by traditional ‘allowable stress’ methods.
- Where limit state factors are closely calibrated against the results of earlier design methods there may be no significant improvement in the cost or safety of completed structures.
- Conversely, if design factors are optimised based on recognised risks there may be an overall reduction in safety due to risks not considered in the calibration process.
- Differing approaches to risk minimisation between technical documents and legal requirements may increase the possibility of engineers being considered legally liable for structural failures, even if they have followed specified design procedures with due diligence.

2. PRACTICAL SIGNIFICANCE

This paper examines the application of the limit state method as specified in loading and structural codes in Australia, New Zealand, Europe, and the USA, focussing on earthquake design requirements for concrete structures. The intent of the review is to:

- Identify significant differences in the application of limit state design principles.
- Identify areas where changes to the application of limit state principles could be significantly improved.
- Identify inconsistencies within codes or between code and legal requirements.
- Make recommendations for changes to Australian structural codes to enhance the benefits of the limit state method.

3. LIMIT STATE TERMINOLOGY AND DEFINITIONS

The terms and definitions given in this section are based on Australian usage, in the structural loading and concrete codes. Significant differences in other codes are discussed in later sections.

In AS/NZS 1170.0 (2002) the following definitions are given:

Limit states: States beyond which the structure no longer satisfies the design criteria.

Limit states, serviceability: States that correspond to conditions beyond which specified service criteria for a structure or structural element are no longer met.

Limit states, ultimate: States associated with collapse, or with other similar forms of structural failure. NOTE: This generally corresponds to the maximum load-carrying resistance of a structure or structural element but, in some cases, to the maximum applicable strain or deformation.

Structural robustness: Ability of a structure to withstand events like fire, explosion, impact or consequences of human errors, without being damaged to an extent disproportionate to the original cause.

Section 6 of AS/NZS 1170.0 provides general requirements for design and detailing of the ‘force-resisting system’:

- Structures shall be detailed such that all parts of the structure shall be tied together both in the horizontal and the vertical planes so that the structure can withstand an event without being damaged to an extent disproportionate to that event.
- The design of the structure shall provide load paths to the foundations for forces generated by all types of actions from all parts of the structure, including structural and non-structural components.

Other standards use the term ‘progressive collapse’ and require (under some circumstances) provision of ‘alternative load paths’.

There is broad agreement between the international standards regarding the basic concept of limit states, and the specification of two limit states that must be satisfied; that is the serviceability and ultimate limit states. Detailed provisions for the serviceability limit state vary widely between different codes, but these detail differences are outside the scope of this paper. There are also significant differences in the wording of requirements for the ultimate limit state, which are examined in detail in the next section.

4. CODE PROVISIONS FOR LIMIT STATE DESIGN

This section provides an overview of provisions for limit state design in Australian and international codes, focusing on inconsistencies between the stated intentions of the code and how these are implemented. For a more detailed review including specific code provisions see Jenkins (2015).

4.1 AS-NZS 1170.0 and 1170.0 Supplement

Section 7 of AS-NZS 1170.0 provides requirements for two classes of Ultimate limit states:

- 7.2.1 Stability: When considering a limit state of static equilibrium or of gross displacements or deformations of the structure, it shall be confirmed that …

- 7.2.2 Strength: When considering a limit state of collapse, rupture or excessive deformation of a structure, section, member or connection it shall be confirmed that …

The Supplement to AS-NZS 1170.0 (2002) provides further background information to the requirements of the standard. It states:

‘The Standard incorporates the fundamentals of the limit states method and enables the designer to confirm the design of a structure. The intention is that confirmation establishes the ability of the proposed structure to resist known or foreseeable types of action appropriate to the intended use and design working life of the structure.’
It quotes ISO 2394 (2015) as follows:

‘In particular, they shall fulfil, with appropriate degrees of reliability, the following objectives:
(a) They shall perform adequately under all expected actions.
(b) They shall withstand both extreme actions and frequently repeated actions occurring during their construction and anticipated use.
(c) They shall have structural robustness.

These three objectives enunciate the serviceability, ultimate and fatigue, and progressive collapse (structural robustness) aspects of design.’

Section 7 divides ‘Strength ultimate limit states’ into 3 sub-classes:

‘(a) Attainment of the maximum resistance capacity of sections, members or connections by rupture (in some cases affected by fatigue, corrosion, and similar) or excessive deformations.
(b) Transformation of the structure or part of it into a mechanism.
(c) Sudden change of the assumed structural system to a new system (e.g., snap through).’

Appendix CA (Special Studies) states:

‘Accidental actions include explosions, collisions, fire, unexpected subsidence of subgrade, extreme erosion, unexpected abnormal environmental loads (flood, hail, etc.), consequences of human error and wilful misuse. It is impractical to design for all accidental actions as they are very low probability events. However, precautions should be taken to limit the effects of local collapses caused by such actions, that is, to prevent progressive collapse (see Section 6 and its commentary).’

In summary, the code recognises different types of failure, with different levels of consequences, but includes all these under a single “ultimate” limit state.

4.2 AS 3600

The Australian Standard Concrete Structures Code, AS 3600 (2009), refers to the Loading Code, AS-NZS 1170.0 for definitions and principles of the limit state method. Most provisions for the ultimate limit state relate to strength of members at a single section (or with limited load redistribution), however there are requirements to consider the potential for total collapse, such as:

Clause 2.2.5 require consideration of the behaviour prior to collapse of the structure as a whole, including the margin between first yielding and peak load.

Clause 6.5, Non-Linear Frame Analysis, requires analysis of the structural behaviour at three separate levels: ‘This Clause applies to the non-linear analysis of framed structures at service load, at overload, and at collapse.’

The supplement to AS 3600 (2014) contains a requirement that the removal of one member from a framed structure should not result in a progressive collapse:

4.3 AS 5100

The Australian Standard Bridge Design Code, AS 5100 (2017) includes detailed provisions for general design principles, loading, and the design of concrete structures, which whilst they generally follow the requirements of other Australian Standards include significant variations where considered appropriate for the differing load conditions and longer design life of bridge structures:

4.3.1 Part 1: Scope and general principles

Clause 8.1 General:
All structures shall be designed and detailed to fail in a ductile manner after they reach the ultimate limit state, so far as is reasonably practicable, such that when any element reaches an ultimate limit state alternative load paths shall ensure the continued stability of the structure. Where it is not practicable to ensure overall stability of the structure, consideration shall be given to segmentation of the structure to limit the consequences of any structural failure

Clause 8.3.2 Ultimate limit states (ULSs):
‘The ULSs include the following:
(a) Stability limit state, which is the loss of static equilibrium by sliding, overturning or uplift of a part, or the whole of the structure.

(b) Strength limit state, which is an elastic, inelastic or buckling state in which the collapse condition is reached at one or more sections of the structure. Plastic or buckling redistribution of actions and resistance shall only be considered if data on the associated deformation characteristics of the structure from theory and tests is available.

4.3.2 Part 2 Design Loads

Clause 15.16.1: Structural detailing requirements for earthquake effects; General:
‘Particular attention shall be given to the provision of viable, continuous and direct load paths from the level of the bridge deck to the foundation system.

4.3.3 Part 5 Concrete, Clause 2.6

Requirements, such as progressive collapse and any special performance requirements, shall be considered where relevant and, if significant, shall be taken into account in the design of the structure in accordance with the principles of this Standard and appropriate engineering principles.’

4.4 NZS Codes

The New Zealand loading codes are jointly published with Australian Standards (1, 2), but earthquake loading requirements are in two separate sections for Australia and

New Zealand (Parts 4 and 5 respectively), and the New Zealand Concrete Structures Standard, NZS 3101 (2006) is totally separate from the Australian Standard, other than referring to the same loading codes.

The code defines an ‘ultimate limit state’, rather than ‘limit states’ as used in AS/NZS 1170.0. The definition relates to the structure as a whole, rather than individual members or sections:
‘ULTIMATE LIMIT STATE. The state at which the design strength or ductility capacity of the structure is exceeded, when it cannot maintain equilibrium and becomes unstable.’

Clause 2.6 lists additional requirements for earthquake effects:
‘2.6.1.1 Deformation capacity: In addition to the requirements of 2.3.2 for strength, the structure and its component parts shall be designed to have adequate ductility at the ultimate limit state for load combinations including earthquake actions.’

4.5 Eurocodes

The Structural Eurocode series consists of ten documents covering the basis of structural design and application to different materials and load conditions. This paper examines the contents of EN 1990, Basis of Structural Design (2002), and EN 1992, Design of Concrete Structures (2004).

EN 1990 defines ultimate limit states as follows:
‘1.5.2.13 ultimate limit states: states associated with collapse or with other similar forms of structural failure. NOTE They generally correspond to the maximum load-carrying resistance of a structure or structural member.’

Section 2 lists basic requirements, including: ‘A structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact, and the consequences of human errors to an extent disproportionate to the original cause’.

Section 3 lists ultimate limit states as the limit states that concern ‘ - the safety of people, and/or - the safety of the structure’

‘In some circumstances, the limit states that concern the protection of the contents should be classified as ultimate limit states. …States prior to structural collapse, which, for simplicity, are considered in place of the collapse itself, may be treated as ultimate limit states.’

EN 1992, Eurocode 2-1 (2004) has the following requirement for prevention of progressive collapse: ‘Structures which are not designed to withstand accidental actions shall have a suitable tying system, to prevent progressive collapse by providing alternative load paths after local damage. …’

EN 1998, Eurocode 8-3, Earthquake Design (2005) lists three limit states: ‘Near Collapse’, ‘Significant Damage’, and ‘Damage Limitation’

4.6 ACI 318

The ACI building code, ACI 318 (2008) does not define design limit states; nonetheless its requirements for provision of adequate strength and resistance to collapse correspond to the ultimate limit state requirements in the other codes examined in this paper.

Requirements for strength design are stated in terms of the strength of individual members (Cl. 8.1.1)

Chapter 21 covers design of earthquake resistant structures, including provisions to prevent progressive collapse (Cl. 21.1.1.1)

4.7 AASHTO

The AASHTO Bridge Code (2007) generally follows similar principles and procedures to ACI 318, however it is the only one of the codes examined that explicitly defines a separate limit state for extreme events:
1.3.2.5 The extreme event limit state shall be taken to ensure the structural survival of a bridge during a major earthquake or flood, or when collided by a vessel, vehicle, or ice flow, possibly under scoured conditions.

5. LIMIT STATE PROVISIONS IN OTHER CODES AND DOCUMENTS

Whilst the great majority of structural design codes follow the practice of dividing limit states into the ‘serviceability’ and ‘ultimate’ categories, there are a number of documents that define a ‘collapse limit state’, either in addition to, or in place of the ultimate limit state. This usage is generally limited to those codes where design actions are much higher than can be accommodated by a strength design approach (such as earthquake loading in high seismic regions), or where the probability and/or consequences of failure are particularly high (such as off-shore drilling structures). Documents related to seismic design of concrete structures, that include reference to a specific collapse limit state include:

- Procedures developed by The Engineering Advisory Group set up following the Christchurch earthquakes require consideration of building performance at the ultimate limit and collapse limit states (see Oliver et al. (2012)).
- The commentary to Part 5 of the AS-NZS Loading Code, NZS 1170-5 (S1), (2004) states that ‘it is not currently considered practical to either analyse a building to determine the probability of collapse or base a code verification method around a collapse limit state … it is possible to consider a limit state at a lower level of structural response, … and then rely on margins inherent within the design procedures to provide confidence that acceptable collapse and fatality risks are achieved.’
- Clause 2.1 of NZS 1170-5 (S1) states: ‘It is inherent within this Standard that, in order to ensure an acceptable risk of collapse, there should be a reasonable margin between the performance of material and structural form combinations at the ULS and at the collapse limit state.

The concept of separate ‘ultimate’ and ‘collapse’ limit states is further discussed in the Interim Report of The Canterbury Earthquakes Royal Commission (2013).

Outside of earthquake design requirements, a number of codes and technical papers deal with requirements for an ‘accidental collapse limit state’ and for prevention of ‘progressive’ and/or ‘disproportionate’ collapse, for example references Moan (2007) and Talaat and Mosalam (2007).

6. RISK MANAGEMENT

6.1 Approaches to Risk Management

In ‘Safety of Structures, and a New Approach to Robustness’ Beeby (1999) writes: ‘It is proposed that the provision of adequate safety in structures depends on the satisfaction of three independent requirements: adequate safety factors, adequate control of the design and construction process, and adequate robustness.... The risks from failure may not be greatly changed by changes in safety factor’. This statement highlights the two main areas in which structural design codes may fail to minimise the risk of building collapse:

- Statistical analyses used to calibrate code load and resistance factors do not include significant sources of risk, such as failures in the design and construction process, or unforeseen events after completion.
- Increasing design strength may have little effect on the risk of collapse where extreme conditions require ductility, energy absorption, and load distribution.

Analyses of risk in other areas arrive at similar conclusions. In ‘The Black Swan’ Taleb (2007) examines risk in global financial management, and finds (immediately before the start of the Global Financial Crisis) that focus on expected risks leaves institutions with increased susceptibility to collapse from the unexpected. He writes ‘the idea is not to correct mistakes and eliminate randomness … *The idea is simply to let human mistakes and miscalculations remain confined, and to prevent their spreading through the system*, …’ (author’s emphasis).

6.2 Legal Requirements

Legal requirements to minimise risk have developed largely independently of structural design codes, and may have requirements that are inconsistent with the approach of the national codes. In some cases specific legal frameworks have developed over time as the result of a single incident. The most influential such incident is the Ronan Point Collapse of 1968, leading to widespread research into disproportionate and progressive collapse mechanisms, and specific requirements in the UK National Building Regulations, contained in ‘Approved Document A’ (2013).

In the Australian context requirements for prevention of collapse are much less well defined, however national safety in design legislation requires that all risks be eliminated or minimised ‘so far as is reasonably practicable’, and this requirement applies to the design of structures, both for the construction stage and after completion (Work Health and Safety Act 2010).

The phrases ‘so far as reasonably practicable’ (SFARP, or SFAIRP) and ‘as low as reasonably practicable’ (ALARP) have a long history of use in the UK, which is documented in a publication by the Centre for the Protection of National Infrastructure (2011). This document, and other reviews of the UK and Australian legislation suggest that the two phrases have effectively the same meaning (Institution of Civil Engineers (2010), Safe Work Australia (2012)). A paper by Robinson (2014) however suggests that the two phrases reflect fundamentally different approaches to the design process, and that in the event of a structural failure, the hazard focussed ALARP approach is unlikely to be found (in hindsight) to have satisfied the statutory requirements of the precaution focussed SFAIRP approach. This paper prompted further discussion related to earthquake design in the March 2014 AEES Newsletter (Somerville, 2014).

These issues remain to be resolved, but to minimise the risk of legal action against design engineers who have performed their duties with all due diligence (SFAIRP) it is highly desirable that design code provisions should be consistent in their requirements and terminology, and that where different levels of precaution are required for different classes of structure, these differences should be explicitly stated.

7. SUMMARY AND CONCLUSIONS

It is found that although the basis of the limit state method is stated in similar terms in most of the codes, there are significant differences in the method of application. In particular, most of the ultimate limit state provisions in all codes consist of simplified procedures requiring the calculation of maximum design actions and design capacity at isolated sections, rather than a consideration of the collapse behaviour of the whole structure. Different approaches are often required for earthquake and other extreme loads, but these loads are generally still classified as coming under the ultimate limit state.

Other than the AASHTO Bridge Design Code, the design codes examined in this paper all shared an inconsistent approach towards design for the ultimate limit state in that:

- The Ultimate limit state is characterised as a requirement to avoid structural collapse, but the great majority of the detailed code provisions relate to strength at a single cross-section, or in a single member (after limited allowance for load distribution).
- Code provisions for earthquakes and impact loads allow significant damage to the structure, provided that partial or total collapse is avoided, but these requirements are treated as being the same limit state as those that require the design strength of every section to be greater than the maximum design actions.

In the UK detailed provisions for prevention of collapse are given in the Building Regulations Approved Document A (2013). In Australia and New Zealand the joint loading codes require structures to be robust, and to provide ‘alternate load paths’, but do not provide any specific guidance on how this should be achieved, or on the levels of robustness appropriate to different classes of building. In the Australian Concrete Structures Code and Commentary the code contains only general requirements for robustness, but the recently published commentary requires that ‘should one member be removed, the remainder of the structure would hang together and not precipitate a progressive collapse.’

Recent Australian legislation relating to ‘Safety in Design’ requires that all known risks should be removed or minimised ‘so far as is reasonably practicable’. Only very general guidance is given on how the limit of practicability should be determined and applied, and it has been argued that the design approach given in current standards and codes of practice is inherently incompatible with the legislated requirements (Robinson, 2014).

In order to make design code procedures more internally consistent, and more consistent with legal requirements, it is recommended that three separate levels of limit state should be specified:

- Serviceability: the level at which unscheduled maintenance or repair is required, or specified performance requirements are no longer met.

- Strength: the level at which any member fails or suffers excessive deformation.
- Collapse: the level at which a structure is on the point of substantial or total collapse.

The following changes to the Australian loading and structural design codes are also recommended:

- Consideration of the collapse limit state should include all potential causes of collapse, including loss of support, deterioration of material properties, improper construction procedures, effects of fire, as well as seismic loads.
- Where the degree of collapse resistance is considered to be related to the classification of the structure and the consequences of failure, specific guidance should be provided in the code regarding the type of analysis and the level of robustness required for different types of structure.

The advantages provided by these changes include:

- The limit state principles would be consistent with the actual requirements of the structures design codes, including a more logical framework for provisions that already exist for earthquake loads.
- The code requirements would also be more consistent with the Safety in Design legislation.
- The risk of design engineers being held legally liable for failures due to unexpected causes would be reduced.
- A general increase in structural robustness would allow a review of load and reduction factors for the strength limit state, potentially allowing a significant improvement in design efficiency.

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