A Review of Limit State Design Principles and Practice

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Abstract: The intent of the limit state design method is to provide adequate performance for the worst combinations of load and environmental conditions and material behaviour, having regard to the expected frequency of conditions and consequences of failure. The advantage of this approach is that design may be optimised to suit the worst combination of conditions, rather than providing a single arbitrary "factor of safety". To achieve the greatest benefit of this approach design procedures should be appropriate to the type of loading, and load and reduction factors should take account of all sources of uncertainty.

In this paper the provisions of Australian and international concrete design codes are reviewed, in particular with regard to their provisions for dealing with unpredictable load conditions, and uncertainties in materials properties. It is concluded that whilst provisions are made for specific extreme load conditions, these are not handled in a consistent way within the principles of limit state design, and codes do not take adequate account of unknown sources of variability in structural resistance.

Recommendations are made to allow the full benefit of the limit state design approach to be achieved, including: 1) Design for expected maximum loads, and for extreme unpredictable loads should be recognised as two separate limit states, the former requiring adequate strength in all structural members, and the latter requiring adequate robustness to prevent collapse in the overall structure. 2) Load and reduction factors should take account of unknown sources of variation, as well as known statistical variations.

Keywords: limit state design, 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 the strength of 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 for risk minimisation 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 Australian concrete codes, and in concrete and other structural codes in New Zealand, Europe, and the USA, with the intent 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.
- Make recommendations for changes to Australian structural codes to enhance the benefits of the limit state method, and reduce the likelihood of adverse outcomes.

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, the Ultimate Limit State provisions in all codes largely 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.

It will be argued that the Ultimate Limit State should be divided into two separate limit states, with different load factors and acceptance criteria:

- The Strength Limit State: considering maximum expected loads and minimum design strength of isolated sections.
- The Collapse Limit State: considering the behaviour of the whole structure under collapse conditions.

This recognition will provide a more logical framework for provisions that already exist; for instance for seismic and impact loads. It will also provide a better basis for ensuring that all structures are designed and detailed with an appropriate level of resistance to unexpected events, including gross overload, ductility demand, or deviations from specified construction or maintenance procedures.

3. Limit State Terminology and Definitions

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

In AS/NZS 1170.0:2002 (1) 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

4.1 AS-NZS 1170.0 and 1170.0 Supplement

Section 7 of AS-NZS 1170.0 (1) 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 …

Note that the overall stability of the structure, total collapse of the structure, and failure or excessive deformation of a single member or connection are all treated as examples of failure of the same limit state.

The Supplement to AS-NZS 1170.0 (2) 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 (3) 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 6 of the Supplement provides more specific advice on design for structural robustness:

"... The potential damage may be avoided or limited by use of the following: …

(c) Selecting a structural form and design that can survive adequately the accidental removal of an individual element or a limited part of the structure or the occurrence of acceptable localized damage.
(d) Avoiding as far as possible structural systems that may collapse without warning.

The design should provide alternate load paths so that the damage is absorbed and sufficient local strength to resist failure of critical members so that major collapse is averted. …

Connections for example should be designed to be ductile and have a capacity for large deformation and energy absorption under the effect of abnormal conditions."

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)."

4.2 AS 3600

The Australian Standard Concrete Structures Code, AS 3600 (4) refers to the Loading Code, AS-NZS 1170.0 (1), for definitions and principles of the limit state method. Code clauses where the general provisions of the Loading Code are significantly amplified or varied are noted below:

Clause 2.2, Design for Strength, requires that:

"2.2.1 General: Strength checks for concrete structures and their component members shall be carried out ..., as appropriate to the strength check procedures being used."

"2.2.5 The strength check procedure for use with non-linear analysis of framed structures at collapse shall be carried out as follows: …"

The provisions of 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 (5) contains the only specific requirement that the removal of one member from a framed structure should not result in a progressive collapse:

"C2.1.3 Design for robustness: A structure is to be designed such that … , should one member be removed, the remainder of the structure would hang together and not precipitate a progressive collapse."

4.3 AS 5100

The Australian Standard Bridge Design Code, AS 5100 (6) 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 (1,2,4,5), include significant variations where considered appropriate for the differing load conditions and longer design life of bridge structures. The extracts below relate to the major differences in wording and requirements for the ultimate limit state, and design for robustness:

4.3.1 Part 1: Scope and general principles

Clause 6.3.2 Ultimate limit states:
"The ultimate limit states 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.

Clause 11.3 Collision from railway traffic:
(b) … supports adjacent to railway tracks may be permitted subject to …
(i) Alternative load paths are available through the structure to ensure that the superstructure does not collapse in the event of removal of the supporting piers or columns as a result of collision…

4.3.2 Part 2 Design Loads

Clause 14.7.5: Structural detailing requirements for earthquake effects; Ductile behaviour: "For bridge structures in BEDC-2, BEDC-3 and BEDC-4, a clearly defined collapse mechanism shall be established. The structural members shall be ductile at the potential plastic hinge locations defined in the mechanism."

4.3.3 Part 5 Concrete

Clause 2.11: Design Requirements and Procedures; Other Design Requirements:
"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."

Clause 7.7: Seismic Analysis Methods:
"For a bridge structure in earthquake design category BEDC-4, the collapse mechanism shall be defined using a post-elastic analysis and it shall be ensured that there is a unique and enforceable strength hierarchy within the structural system."

4.4 NZS Codes

The New Zealand loading codes are jointly published with Australian Standards (1, 2), but the New Zealand Concrete Structures Standard, NZS 3101 (7) is totally separate from the Australian Standard, other than referring to the same loading codes. NZS 3101 contains extensive requirements for design and detailing of structures under different levels of earthquake loading, but for the purposes of this paper only general requirements relating to the specification of limit states have been reviewed.

The code defines an "ultimate limit state", rather than "limit states" as used in AS/NZS 1170.0 (1). 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."

Clause 2.5 lists fatigue requirements as a serviceability limit state:
"2.5 Other design requirements: …
2.5.2 Fatigue (serviceability limit state) "

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 (8), and EN 1992, Design of Concrete Structures (9).

Code clause numbers followed by (P) in the quoted extracts below indicate clauses that are defined as "Principles" comprising:

- general statements and definitions for which there is no alternative, as well as ;
- requirements and analytical models for which no alternative is permitted unless specifically stated.

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:

2.1 Basic requirements …

"(4)P 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.

(5)P Potential damage shall be avoided or limited by appropriate choice of one or more of the following:
avoiding, eliminating or reducing the hazards to which the structure can be subjected;
selecting a structural form which has low sensitivity to the hazards considered;
selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localised damage;

avoiding as far as possible structural systems that can collapse without warning;
tying the structural members together."

Section 3 lists ultimate limit states as follows:

"3.3 Ultimate limit states

(l)P The limit states that concern:
- the safety of people, and/or
- the safety of the structure

shall be classified as ultimate limit states.

(2) In some circumstances, the limit states that concern the protection of the contents should be classified as ultimate limit states.

…

(3) States prior to structural collapse, which, for simplicity, are considered in place of the collapse itself, may be treated as ultimate limit states.

(4)P The following ultimate limit states shall be verified where they are relevant:
- loss of equilibrium of the structure or any part of it, considered as a rigid body;
- failure by excessive deformation, transformation of the structure or any part of it into a mechanism, rupture, loss of stability of the structure or any part of it, including supports and foundations;

failure caused by fatigue or other time-dependent effects."

EN 1992, Eurocode 2-1 (9) has the following requirement for prevention of progressive collapse:

"9.10.1 General
(1)P 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. The following simple rules are deemed to satisfy this requirement …"

4.6 ACI 318

The ACI building code, ACI 318 (10) 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:

"8.1.1 — In design of structural concrete, members shall be proportioned for adequate strength in accordance with provisions of this Code, using load factors and strength reduction factors φ specified in Chapter 9."

Chapter 21 covers design of earthquake resistant structures, including provisions to prevent progressive collapse:

"21.1.1.1 — Chapter 21 contains requirements for design and construction of reinforced concrete members of a structure for which the design forces, related to earthquake motions, have been determined on the basis of energy dissipation in the nonlinear range of response."

"R21.8.4 … The design procedure should identify the load path or mechanism by which the frame resists gravity and earthquake effects."

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:

- EN 1998-3, Eurocode 8: Design of structures for earthquake resistance – Part 3 (11) lists three limit states: “Near Collapse”, “Significant Damage”, and “Damage Limitation”. It states that “The definition of the Limit State of Collapse given in this Part 3 of Eurocode * is closer to the actual collapse of the building than the one given in EN 1998-1: 2004 and corresponds to the fullest exploitation of the deformation capacity of the structural elements.”
- 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. (12)).
- A paper presented to the Australian Earthquake Engineering Society 2011 Conference (Fardipour et al. (13)) deals with the “Collapse Limit State Assessment of Lightly Reinforced Concrete Columns”.
- The commentary to Part 5 of the AS-NZS Loading Code, NZS 1170-5 (S1), (13) 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. In this Standard this limit state is referred to as the ultimate limit state (ULS).”
- 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. For most ductile materials and structure configurations it has been assumed that a margin of at least 1.5 to 1.8 will be available. This is intended to apply to both strength and displacement.”

The concept of separate “ultimate” and “collapse” limit states is further discussed in the Interim Report of The Canterbury Earthquakes Royal Commission (14).

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 15 – 19.

6. Risk Management

6.1 Approaches to Risk Management

In “Safety of Structures, and a New Approach to Robustness” (20) Beeby 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 unforseen events after completion.
- Increasing design loads, or reducing design strength capacity may have little effect on the risk of collapse where extreme conditions require ductility and energy absorption, or the ability to distribute loads to alternative load paths.

Analyses of risk in other areas arrive at similar conclusions. In “The Black Swan” (21) Taleb 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” (22).

In the Australian context requirements for prevention of collapse are much less well defined, however recent national safety in design legislation (23) 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.

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 (24). This document, and other reviews of the UK and Australian legislation (25, 26) suggest that the two phrases have effectively the same meaning. A recent paper by Robinson (27) 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.

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

The design codes examined in this paper have a similar approach to the statement of the limit state method (other than ACI 318 (10), which does not use this terminology). They also have a similar approach in the application of design procedures to different classes of structure. They 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.

Of the codes examined in this paper only Eurocode 2 (9) contains specific general provisions (outside seismic or impact load requirements) intended to ensure resistance to disproportionate collapse after localised failure. In the UK further detailed provisions are given in the Building Regulations Approved Document A (22).

In Australia and New Zealand the joint loading codes (1,2) 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 (4, 5) 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” (23) 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 (27).

In order to make design code procedures more internally consistent, to improve consistency with legal requirements, and to provide specific guidance on what measures should be considered practicable, the following changes to the Australian loading and structural design codes are recommended:

- 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.
- Consideration of the Collapse Limit State should not be limited to seismic and impact loading, but should include all potential causes of collapse, including loss of support, deterioration of material properties, improper construction procedures, effects of fire, and extreme loads due to any cause.
- 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.
- 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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