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NEW ZEALAND ADVANCES IN PERFORMANCE-BASED SEISMIC DESIGN

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SUMMARY

This paper provides a summary of the objectives and principles which underpin the soon to be published 2004 edition of the New Zealand earthquake design standard, AS/NZS 1170 part 5. As with many modern earthquake design standards, the New Zealand earthquake design standard recognizes that earthquake resistant design that only addresses life safety goals without addressing both operational continuity of essential facilities and damage control, falls short of public expectations. Such standards not longer meet societal expectations.

The paper outlines how these issues have been addressed within New Zealand, and some of the issues addressed by the review committee in preparing appendices to the standard to provide guidance to materials standard writers to ensure consistency with the proposed approach. Recognizing the significance of non-structural components and parts of buildings in both damage control and operational continuity has been an important step forward in attaining the performance levels required.

INTRODUCTION

The Building Act [1] and the associated Building Code of New Zealand (NZBC) that was published within the regulation associated with the Act, provide the regulatory framework within which buildings are approved in New Zealand. The Loading Standard [2] is cited as an acceptable verification method to the NZBC. It has been under review for the past five years and is soon to be republished as part of the joint Australia and New Zealand loading standard, AS/NZS 1170 [3].

While the NZBC is a performance-based code, it lacks clear, quantifiable values against which performance can be verified, relying rather on the examples cited in the accompanying Approved Documents to provide the reference level as to performance acceptability. The review of the loading standard provided the first opportunity to try to clearly prescribe what structural performance is expected from New Zealand building.

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Earthquake resistant design influences all sectors of New Zealand building practice. A unique characteristic of acceptable earthquake performance is that, although collapse is to be avoided, damage is expected to occur. The design challenge therefore is to ensure that cumulative damage is limited to remain within acceptable bounds so that people within and around buildings are able to escape from damaged buildings even after a major earthquake. Setting the design rules to ensure the achievement of this objected was the responsibility of the earthquake standards review committee.

The implications of this revision will have significant and far-reaching consequences in building practice in New Zealand, in part because it places many responsibilities for ensuring adequate post-elastic capacities within structures onto the materials standards and the detailing provisions specified therein. In particular the performance objective which requires significant system capacity to be present within buildings beyond that to which they are designed will be a challenge. It is expected to result in some construction methods finding difficulty in satisfying the stated performance objectives, particularly those associated with the installation of heavy, elevated secondary or non-structural components.

NEW ZEALAND BUILDING REGULATORY FRAMEWORK

Regulations that control building practice within New Zealand accompany the Building Act of 1991. The New Zealand Building Code is published within those regulations. The legislative framework was developed on the premise that the performance objectives and requirements would be prescribed within the NZBC. The Act outlines three available paths by which compliance with the objectives can be demonstrated, namely a verification by design or calculation using approved verification methods, verification by following approved prescriptive or Acceptable Solutions and verification by an alternative solution route wherein expert opinion, testing or other means can be applied to demonstrate equivalent performance. Accepted means of achieving the former two approaches are published in the Approved Documents which accompany the NZBC.

The NZBC identifies a suite of 32 performance attributes that buildings are required to satisfy to meet minimal societal expectations. These attributes include stability (B1) and durability (B2), Fire (C1 to C4), building access (D1), moisture control (E1 to E3), Safety within buildings (F1 to F6), services and hygiene (G1 to G13) and energy efficiency (H1).

Structural Performance Provisions

Clause B1 of the NZBC stipulates that all buildings, including their components & parts are required to:

- be sufficiently rigid that their deflection is small enough to avoid interfering with the amenity value of the building when subjected to more moderate events such as may be expected to occur several times during the life of a building (these being serviceability limit state considerations)

- have the capacity to resist, without rupture, instability or collapse, actions of great intensity which may be expected from very rare, extreme events such as severe earthquakes or extraordinary winds (these being ultimate limit state considerations)

These requirements are required to be satisfied for each action and combination of actions which can reasonably be expected to be applied to the building once or more during its design life. The range of actions required to be considered by Clause B1 is very wide (i.e. Permanent actions (dead loads), Imposed actions (live loads), wind, earthquake, snow and ice, thermal effects, explosion, incremental collapse, the effects of vegetation, subsidence, etc.). Most formal structural designs directly consider only the primary loads (Dead, Live. Wind, Earthquake and snow). Rarely are other actions specifically considered in detailas loading conditions on buildings unless unusual circumstances are present.

The NZBC is frustratingly silent as to quantifying terms 'moderate events' and 'rare, extreme events'. Traditionally this task has fallen to the loading standard. For New Zealand, this continues in with the acceptable annual probability of occurrence for various design actions being prescribed in AS/NZS 1170 Part 0 Section 3. The NZBC Approved Documents currently refers to the existing New Zealand Loading Standard NZS 4203 [2]. That standard is soon to be superceded by a joint Australia and New Zealand loading standard, AS/NZS 1170 (AS/NZS 2004) at which time the Approved Documents are expected to be amended to refer to the new loading standard. This paper will therefore focus on the New Zealand earthquake provisions that will form Part 5 of that Standard.

An important, often overlooked, aspect of building code compliance permitted within the Building Act is the Alternative Solutions route of compliance. This approach requires building consent applications to be submitted with 'justification sufficient to provide reasonable grounds' for the approving agency to accept that the required performance objectives will be met. In practice such 'justification' usually involves reference to aspects of the design and material standards (ie approved Verification Methods) supplemented by special studies and expert opinion on matters which are outside the scope of those standards. Once satisfied, the consenting agency is obliged to issue the building consent, although such consents often include conditions relating to supervision or quality control as this path often is the only option for new materials or new construction techniques.

As the new loading standard was evolving, it became apparent that the role of engineering judgement in the design process had become obscured. Loads and actions imposed on the building are specified in the loading standard. Dependable system capacity and member deformations specified are to be prescribed within structural material design standards. Engineering judgment is, however, essential in both assessing the structural response parameters of specific buildings and in deciding on the member section properties appropriate for in each specific circumstance. For instance, assigning the site sub-surface conditions (for earthquake transmission) of the up-wind terrain roughness characteristics (for wind loads) requires technical judgements to be made. Such judgements are the essence of engineering design. New Zealand regulatory authorities have struggled this reality as if means they have little certainty of design decisions made by practitioners, yet have responsibilities implicit in them accepting design verification methods within the Approved Documents. These issues are currently being addressed with the development of a Certified Professional Engineers register within which ongoing training and technical competency requirements will be required. While this may provide a degree of comfort for the regulators, many more designs are expected to proceed through the Alternative Solution route than has been previously the case. This placed much greater emphasis on ensuring that the performance objectives, previously implicit with in earlier design standards, are clear so that designs which are based on Special Studies or expert opinion (ie departures or extensions beyond the scope of the standard) can be assessed against known criteria within the Standard.

APPLICATION OF PERFORMANCE-BASED DESIGN PRINCIPLES

Joint Australia/New Zealand Loading Standard, AS/NZS 1170

The Australia/New Zealand loading standard, AS/NZS 1170 is to comprise of a suite of six parts namely:

- Part 0 Structural Design Actions - *General Principles*,
- Part 1 Structural Design Actions - *Permanent, Imposed and Other Actions*
- Part 2 Structural Design Actions - *Wind Actions*,
- Part 3 Structural Design Actions - *Snow and ice actions*,

- Part 4 Structural Design Actions - *Earthquake Actions – Australia* and
- Part 5 Structural Design Actions - *Earthquake Actions – New Zealand*

AS/NZS 1170:0 Structural Design Actions - General Principles
The part of the Standard is the umbrella under which other parts operate. The following specific issues are addressed within Part 0:

- Section 1: The linkage between the structural performance objectives of Clause B1 Structure of the NZBC and the Building Code of Australia (BCA)
- Section 2: The procedures required for Ultimate Limit State (ULS) and Serviceability Limit State (SLS) compliance necessary to satisfy the use of the Standard as a Verification Method.
- Section 3: New Zealand building importance categories and acceptable annual probabilities of exceedence for different loading actions and Important Classes (for Australia these are specified in the Building Code of Australia (BCA)).
- Section 4: Basic load combinations and the associated load factors that require consideration.
- Section 5: Methods of Analysis which are acceptable to determine the action effects from the applied loads.
- Section 6: General robustness provision to ensure maintenance of a load path and avoidance of disproportional collapse.
- Section 7: Methods of confirmation that stability and strength (ULS) and serviceability requirements are met.
- Appendix A: Special studies that may be used to justify a departure from code provisions and the expectations of how such studies may be undertaken.

Design Requirements
Section 3 of AS/NZS1170.0 prescribes the design requirements for New Zealand buildings. It states:

"A structure shall be designed and constructed in such a way that it will, during its design working life, with appropriate degrees of reliability, sustain all actions and environmental influences likely to occur."

The clause then elaborates on the necessity for the structure to resist extreme or frequently repeated actions safely, avoid damage that is disproportional to its original cause, and perform adequately under all expected actions.

For earthquake actions for ultimate limit states this means
(i) Avoidance of collapse of the structural system, and;
(ii) Avoidance of collapse or loss of support to parts of the structure that represent a hazard to human life inside or outside the structure, or to parts required for life safety systems; and
(iii) Avoidance of damage that could render inoperative systems (structural and non-structural) necessary for building evacuation.

For earthquake actions for serviceability limit there are different levels of earthquake motion (referred to as SLS1 and SLS2) to be considered depending on the importance category of the structure as follows::
(i) Avoidance of damage to either the structure or its non-structural components to the extent they require repair after the SLS1 earthquake motions, and;
(ii) Avoidance of damage to buildings of Importance Category IV to the extent that they can no longer remain operational after the SLS2 earthquake motions.

Determination of Building Importance Categories & the Design Working Life

The importance category of a building is a function of its use and occupancy class. It is determined according to the consequences of failure of the building or its function and is specified in Table 3.1 of AS/NZS1170.0 (reproduced here as Table 1). Table 3.2 in the standard provides examples of which buildings are likely to be placed into each of the five categories. For example, major medical centres and hospitals are considered as Importance Category 4, whereas buildings design to accommodate more than 5000 people, airport terminals, schools with more than 250 pupils, and public assembly buildings are IC 3. Special structures (IC5), the failure of which will have major societal impact (eg major dams or high hazard facilities) are specifically beyond the scope of the standard and are required to be designed by special study.

From a regulatory viewpoint, the default design life of normal occupancy buildings in New Zealand is nominated to be 50 years. Owners can increase the design life, and often for important buildings this has been extended to 100 years. Shorter design life considerations, while theoretically acceptable, are uncommon.

Table 1 Consequences of Failure for Importance Category

Consequences of failure	Description	Importance category	Comment
Low	Low consequence for loss of human life, or small or moderate economic, social or environmental consequences	1	Minor structures (failure not likely to endanger human life)
Ordinary	Medium consequence for loss of human life, or considerable economic, social or environmental consequences	2	Normal structures and structures not falling into other levels
High	High consequence for loss of human life, or very great economic, social or environmental consequences	3	Major structures (affecting crowds)
		4	Post-disaster structures (post disaster functions or dangerous activities)
Exceptional	Circumstances where reliability must be set on a case by case basis	5	Exceptional structures

Design Event Recurrence

With the design working life and the importance level of any specific building, Table 3.3 of AS/NZS 1170.0 is used to determine the acceptable annual probability of exceedance. Values from this table for earthquake actions have been reproduced here as Table 2. Within this table the risk factor for earthquakes, R, (from AS/NZS 1170.4 as discussed later) has been included. This value is normalised by the 500-year return period motion. It ranges up to 1.8 for the 2500-year return period motion and down to 0.25 for the 25-year return period motion being that assigned to SLS1 considerations. As will be discussed elsewhere in this paper, the return period factor is a direct multiplier, used in combination with the zone factor and the spectral shape factor to develop the earthquake design spectra for different recurrence intervals.

Table 2 Design annual probability of exceedance for earthquake 50 year design working life

Annual Prob. of exceedance	Return Period Factor R	Building Importance Category			
		1 Low hazard structures	2 Normal buildings	3 Important buildings including schools	4 Critical post disaster bldgs
1/2500	**1.8**				ULS
1/1000	**1.3**			ULS	
1/500	**1.0**		ULS		SLS2
1/100	**0.5**	ULS			
1/25	**0.25**		SLS1	SLS1	SLS1

NEW ZEALAND EARTHQUAKE LOADING DESIGN STANDARD, AS/NZS 1170.5

The pre-ballot draft of the earthquake standard [4] comprises 8 Parts with 4 appendices and a commentary. The standard prescribes design procedures that will result in structures, when subjected to earthquake attack, that meet the performance objectives of life-safety and amenity retention established in the NZBC. With the strong interdependence between the earthquake actions on the building and the response characteristic of the building itself, together with the acceptance that damage is both anticipated and accepted during severe earthquake attack, it has been necessary to elaborate on the performance objectives that have been used to underpin the earthquake design standard. These are outlined in Section 2 of the standard and elaborated further in appendix C with provides guidance to structural material standards writers as to measures that the material standards will need to take to match the loading standard expectations.

Several sections of the standard have been impacted by the performance objectives established in Section 2. These are elaborated upon in detail in the remainder of this paper.

PERFORMANCE OBJECTIVES FOR EARTHQUAKE DESIGN

General Requirements.
The principles upon which the New Zealand earthquake design standard was prepared are outlined in Section 2 of AS/NZS 1170.5. The section details the general principles of good earthquake-resistant design, including such fundamentals as ensuring that the building has an adequate structural system to transfer combinations of gravity and earthquake-induced lateral forces from the building to the ground (clause 2.1). The commentary relating to this clause elaborates on the three objectives or principles which underpin this requirement namely:

Objective 1
This objective relates to the serviceability limit states. The objective is that:

- In the event of an SLS1 earthquake, the structure and its parts will not require repair. This can be achieved by keeping the instantaneous and residual interstorey drifts and deflections within appropriate limits to prevent unacceptable damage. The SLS1 earthquake should be expected to occur two or three times during the design life of the building;
- After the SLS2 earthquake the structure can continue to be used for the function for which it was designed without the need for immediate repair

For a building of normal usage and importance, frequent earthquake shaking is assumed to be that which has an annual probability of exceedance of 4 %, that is it might be expected to be exceeded on average perhaps twice during a 50 year design life for a structure. For structures of other usage, importance, or design lifetimes, the annual probability of exceedance is adjusted as indicated in Part 0 of the Standard.

Objective 2

This objective is addressed by the ultimate limit state design procedures. The ultimate limit state requirements, which assess system capacity using dependable material strengths and prescribed detailing procedures that relate member rotational capacities to structural ductility factors, are intended to provide the structure with a high level of protection for life of people in or around the building during an earthquake with a return period specified for the ultimate limit state. The probability of collapse, loss of support for heavy elevated parts or components, or the failure of building evacuation systems is maintained at acceptably low levels. For normal structures the design return period of the earthquake motion used to verify the structure is 500 years or approximately 10% probability of exceedence in 50 years.

Objective 3

This objective is to ensure that the structure has sufficient capacity to sustain the maximum considered earthquake with a small margin against collapse. Specific design for this objective is not required provided the load levels given in the standard are followed and the detailing satisfies the minimum detailing requirements in an appropriate materials standard, that is consistent with this Standard. For normal structures this should give a small margin of safety against collapse in the event of a maximum considered earthquake. The maximum considered earthquake in most instances has a return period of 2,500 years (or 2% probability of exceedence in 50 years). In low seismicity regions, the uniform hazard spectrum has been modified by superimposing the ground motion resulting from a Magnitude 6.5 earthquake 20 km from any site at one standard deviation above the resulting anticipated motion as the level of uncertainty of that motion. In high seismicity regions an upper bound of 0.75 has been assigned to the product RZ to reflect reasonable bounds on already short recurrence, high slip, events which have been assessed with a higher level of reliability than other, less well recognised earthquake sources.

IMPLICATIONS FROM THE PERFORMANCE-BASED DESIGN APPROACH.

General comments

In establishing a rational framework for performance-based earthquake design, it has been necessary to align the regulatory objectives (which are maintained at a high, philosophical level), the general principles of design (from AS/NZS1170.0) and the earthquake performance objectives from section 2 of AS/NZS1170.5. Perhaps the greatest difficulty within the alignment has been the rather unique acceptance of, and design for, post-elastic response and behaviour of buildings which has long been accepted for earthquakes, yet has not gained similar traction for other loading conditions. The effect of this acceptance is that structural systems are specifically detailed to accommodate post-elastic strains and deformations, and that the detailing prescribed to accommodate such behaviour must be sufficiently robust as to ensure that total collapse is avoided even after the modification of the structural forms that occur as damage and degradation become well advanced.

Specific implications of this approach have been identified during the development of the standard. They are as follows:

- The addition of a third objective that requires buildings to maintain a secure vertical load carrying capability beyond ULS is included as a performance requirement. While not expected to be considered specifically during design, it underpins the detailing expectations and member ductility requirements prescribed by the material standards and aims to ensure buildings are detailed in a manner that ensures intrinsic toughness and that they therefore possess the ability to hold together even when the building is moved well beyond the damage state for which its performance can be reasonably predicted during design.

- The inclusion of near-field fault enhancement within the design spectra for buildings of longer period (T>1.5 seconds) led to the requirement to include one earthquake record with forward directivity in the suite of accelerograms selected for time-history analysis. Since motions with forward directivity occurs only for some ruptures, the return period for events with this characteristic will have a return period significantly longer than the target spectra used to scale the suite of accelerograms.
- The overall drift control limits may not be sufficient to avoid weak-storey collapse in some structural forms. Reduced interstorey drift limits will be needed in these cases.
- The ability of parts and non-structural components in buildings to perform either during or immediately following various levels of earthquake-induced ground shaking is an essential aspect of buildings meeting their performance expectations. Heavy elevated parts must remain attached to buildings, and other parts are not to be damaged at low levels of ground shaking. Damage to critical post-earthquake facilities must not be such as to impact on their operational continuity even at high levels of ground shaking intensity.
- Serviceability criteria have been expanded to include both damage control (SLS1) and operational continuity expectations for critical facilities (SLS2). These provisions apply to both the primary structural frame and also the design of the secondary components and parts.

Performance Beyond Ultimate Limit State.

Performance Objective 3 addresses the expectation that buildings have a reserve capacity beyond that considered during design. Many buildings benefit from this phenomenon during earthquake attack. Older, well proportioned buildings, designed to less stringent earthquake design standards, often perform reasonably well, even in relatively high levels of ground excitation. Thus, while the expectation of considerable reserve capacity has been used to set design levels, the new earthquake loading standard will be the first instance in New Zealand that this expectation has been explicitly included in the underpinning philosophy of the standard. The widespread use of capacity design within the New Zealand provides considerable comfort that well engineered buildings will perform satisfactorily under shaking intensities well beyond their design level. However the consequent reduction in design spectral values, particularly in regions of low seismicity, might inadvertently encourage designers to design buildings to remain elastic under ultimate limit state earthquake effects. While this will generally still result in acceptable performance in buildings designed using conventional elastically responding theory, there may be attempts to either use highly brittle materials or detailing that has little or no post-elastic capability at all. Such buildings will still meet the ULS design criteria but the member curvature-ductility demands will be well in excess of those they can sustain without rupture and progressive deterioration.

In addition, Matthews [5] uncovered some rather surprising premature failures in laboratory experiments of prestressed hollow-core long-span flooring systems, similar to those commonly used in New Zealand, identified that such systems may be susceptible to rupture and collapse when fixed directly to the structural frame and the frame subjected to rotations associated with ground motions not greatly in excess of the 500 year recurrence interval earthquake. Details are now being developed to separate the structural frames from the floor systems and provide adequate end-bearing seats to enable the frame to displace well beyond the design deformations while retaining the support of the flooring systems.

The dilemma presented however, is that structural design compliance for the ultimate limit state is based upon the premise that the dependable structural capacities (ie those based on 5%ile characteristic strengths of the structural system) exceed the member demands ascertained by analysis of the structure under rare, extreme loading conditions (ie 10% probability of exceedence over the 50 year building life or approximately 500 year return period). Such an approach has been found to provide sufficient levels of reserve capacity to meet the Objective 3 performance level. This overcapacity cannot be verified by design. This is recognised within the standard in that the design process does not require a specific check of systems for compliance under these conditions. The onus has been placed on the writers of the structural material standards and/or the suppliers of proprietary systems (such as the hollow-core flooring systems mentioned above) to ensure that the detailing and connections of their systems are sufficient to ensure that there is a sufficiently low probability of rupture or loss of load-carrying capacity as the building deforms to the extent determined by very rare actions (ie those which have a 2% probability of exceedence over the life of the building).

Selection of Near-fault Earthquake Records

The design spectra published in the Standard have been derived from hazard analyses that ignore rupture-directivity effects (i.e. neutral directivity ground motions). The long-period component (i.e. that associated with periods greater than 1.5 seconds) are, however enhanced by the near fault factor, N(D,T), which reaches 1.72 at periods equal or greater than 5 seconds. In quantifying N(D,T) it was recognised that the forward-directivity pulse it represents promulgates from the initiation zone outwards and along the fault trace, usually in both directions. To obtain the most severe effect, the site requires to be located at one extremity of the fault trace with the point of initiation being at the opposite end of the fault.

In the development of the factor N(D,T), it was first recognised that most sites are not at a position along the fault length that can experience the maximum possible forward-directivity enhancement. This maximum effect can only occur at sites at either end of a rupture zone where energy from the full rupture length promulgates towards the site. On average the maximum fraction of the fault rupture that can occur towards a given site is 0.75. In addition, near-fault directivity effectors for a given site occur in only some of the faults that occur along a particular fault. It has been assumed that one rupture in three gives forward-directivity enhancement with the other being directivity-neutral. This one-third weighting corresponds to taking the near-fault effect as the maximum value of N(D,T).

When developing rules for the selection of ground motion accelerograms for use with Time-History analyses, a similar approach was considered in that, of the three (minimum) nominal design records, one record is required to have the full forward directivity component present, with the other two records requiring to be directivity neutral. When it comes to ascertaining the interstorey deflections from a forward-directivity record, the designer is offered the opportunity of comparing the computed interstorey drifts with those of the building in a near-collapse (2% in 50 years) condition.

With the basis of design established, it has been possible to constrain the design spectra for each limit state (recurrence interval) to reflect the stated objectives. In the very high seismicity regions, (eg regions of the South Island adjacent to the Alpine Fault where Z=0.6 corresponding to a 500 year rock peak ground acceleration of 0.6g) then a maximum value of 0.7 has been imposed on the product RZ (return period factor by zone factor). This recognises that the high slip rate will result in large (M8+) events at short recurrence intervals (<300 years). Over 2500 years several such events will occur, and although there will be some variation in magnitude, the necessity to amplify the 500 year recurrence event ground motions by R=1.8 is unnecessarily conservative. Conversely in low seismicity regions (eg the northern region of New Zealand) the RZ product for a 500 year return period event is approximately 0.1. However since earthquakes in this region are rare, and historical records of such events non-existant, it was decided to assign Z a minimum value of 0.13. This represents, with 84% confidence, the ground motions resulting from a small (M6.5) earthquake 20 km from the site, which was considered to be the minimum acceptable design load anywhere in New Zealand. On a uniform risk approach it represents an event with a return period of approximately 5000 years in zones of low seismicity.

The inelastic spectra used for design is scaled by the ratio of the structural performance factor over the structural ductility factor (being between 1/1.2 (brittle systems) to 1/9 (fully ductile systems)).For long period structures this results in a lateral acceleration coefficient of between 1.5%g and 2%g. These values, although technically consistent with the derivations discussed above, were below those considered necessary to ensure structures which are robust enough to withstand accidental loads. At the time of writing this paper, a minimum limit of $0.025/R_u$ has therefore been arbitrarily placed upon the base shear coefficient, C_d. This is still subject to review (upwards) before publication.

Interstorey drift limits.
Deformation control criteria are prescribed in Part 5 Section 7 of the standard. These include both the maximum deflected envelope of the building (used to ensure boundary clearance levels between neighbouring buildings) and interstorey deflections (used both to ensure P-delta effects are within acceptable limits and that damage to some Parts and Non-structural components are within acceptable limits).

A common difficulty has been the determination of deformations beyond the elastic limit, particularly if the analysis techniques engaged are based on elastic response (ie equivalent static or combined modal analysis). Studies were undertaken to compare the results derived from inelastic time-history analysis and amplified modal analysis [6, 7]. While it has long been the case that the deformations derived assuming elastically responding structure were amplified by the structural ductility factors only, within the standard there is now an additional multiplier required (being the inverse of the structural ductility factor or $1/S_p$). With deflections so amplified, there was a reasonable match in most cases between the deformation envelopes. However the profile remained markedly different for framed buildings, particularly over their lower storeys where post-elastic hinge rotations demands tended to concentrate. Because of this uncertainty, the maximum permitted interstorey drift differs depending on the method of analysis used to compute these drifts. When inelastic time-history analysis methods are used, the interstorey drift limit is 2.5% but is reduced to 2% when the drifts are calculated by magnifying the deflection profile derived from elastic analysis techniques.

The ability of certain combinations of materials and structural forms to accommodate interstorey drifts of this magnitude without the development of a weak or soft storey has also been recognised. Reductions in the acceptable drift limits for those systems is to be specified within the material standards and will be triggered when the detailing provisions for a specific structural form can only be depended upon under more restrained deflections.

Design of Parts and Non-Structural Components
As with buildings, parts and non-structural components have been assigned importance categories which were derived in accordance with the consequences of their failure. The Parts Importance Categories are reproduced here in Table 3. This table also prescribes the part risk factor, R_p, and limit state under which the behaviour of the part is to be verified. The new earthquake design standard extends ultimate limit state design requirements to include several parts and non-structural systems within buildings where there performance affects the safety of people either within or around the building as required to satisfy objective 2 above.

Parts with categories P1 to P4 are required to be performance without damage as the building responds to earthquakes of ultimate limit state intensity.

Parts that require this somewhat more rigorous design consideration will typically be heavy or hazardous non-structural components such as building facades or glazing system, and systems that are essential to emergency egress of the building. Failure of the supports or connections of elements such as elevated curtain wall glazing facades or heavy suspended ceiling tiles were considered to represent a risk to life close to that created by building collapse. The standard requires that such systems be provided with seating and support fixings that are sufficient to accommodate both the building deformation and resulting imposed earthquake actions, including any dynamic amplification resulting from the building response, without failure when the building is subjected to earthquake motions associated with it ultimate limit state recurrence interval (refer Table 2). The parts themselves must have sufficient strength to resist the resulting earthquake actions without rupture. Clearances between the structure and the parts must be sufficient to avoid pounding between systems, as it is likely that few parts will have the capacity to accept structural loads. It is also undesirable to alter the anticipated structural path by load transfer to parts or non-structural components.

Table 3 Classification of parts and non-structural components

Category	Criteria	Part risk factor R_p	Structure Limit State
P1	Part representing a hazard to life outside the structure. [1]	1.0	ULS
P2	Part representing a hazard to a crowd of greater than 100 people within the structure. [1]	1.0	ULS
P3	Part representing a hazard to individual life within the structure. [2]	0.9	ULS
P4	Part necessary for the continuing function of the evacuation and life safety systems within the structure.	1.0	ULS
P5	Part required for operational continuity of the structure. [3]	1.0	SLS2
P6	Part for which the consequential damage caused by its failure are disproportionately great.	2.0	SLS1
P7	All other parts.	1.0	SLS1

Notes: the criteria used to classify the importance of parts, and assign the risk factor, R_p, were:

1. Parts representing a hazard to crowds, or parts able to fall more than 3 metres onto an accessible area. (For example, an auditorium ceiling or cladding panels over a footpath).
2. Parts representing a hazard to individuals within the building, or those necessary for the continuing function of life safety systems. (Library shelving, or medical gas lines)
3. Parts required for operational continuity, or whose failure would have disproportionate consequences. (For example, a cool store chiller, or a leaking water pipe) In these cases the risk factor may be a commercial decision requiring input by the owner.

Parts of category P5 are those required for buildings to maintain their operational capability and discussed in the next section. The standard requires this level of performance for essential components of critical facilities and imposes an annual probability of exceedence of 1/500.

Ordinary non-structural components and parts of buildings, being those with classification P7, are required to be capable of withstanding shaking and deformations associated with earthquakes which have a annual probability of exceedence of 1/25 (or 4% probability of exceedence in any year). When the failure of the part or component is expected to have an effect which is disproportionately greater that the part itself (e.g. water damage as a result of ruptured sprinkler heads, rupture of fire rated wall systems) then the part is classified as P6 and is required to sustain forces and deformations imposed by an earthquake with an annual probability of exceedence of 1/100 (or a 40% probability of occurrence within a 50 year design life of the building).

Serviceability Limit State Criteria

Serviceability limit states are defined in Part 0 of the standard as 'States that correspond to conditions beyond which specified service criteria are no longer met'. Within the gambit of earthquake design, the applicable service criteria are damage control and continued operational capability. Sensory concerns about feeling that the earthquake is happening and the anxiety that results from that experience are not dealt with. Damage control measure apply to both the primary structure and the parts and non-structural components therein. While the onset of damage to the structural components usually results from strains within those elements beyond their elastic limits, it is usually the damage to parts and non-structural components that provide realistic control criteria. Parts are typically damaged either because their fixings or restraints are insufficient to hold them in place as the building sways, or the clearances between the part and either other parts, or the primary structure, are insufficient to avoid the pounding effect as they clash.

The standard recognises two serviceability limits. The SLS1 earthquake motions are the event required to avoid damage in buildings and is applicable to all buildings. The SLS2 earthquake motions are those associated with maintaining operational continuity and for regulatory purposes is applicable only to critical facilities. The SLS1 earthquake motions have an annual probability of exceedence of 1/25 years (or a 20% probability of occurrence over 20 years (being the period most can remember)). By reference to Table 2 it can be seen that $R_{25} = 0.25$ indicating that the design event for this limit state will be 25% of that for ultimate limit state strength assessment. The SLS2 earthquake has an annual probability of exceedence of 1/500 years (or a 10% probability of occurrence over 50 years (the design life of ordinary buildings))

The introduction of SLS2 is recognition that the life-safety expectations of performance objective 2 requires that critical post-disaster facilities must be able to maintain their core operational capability after a major earthquake. Thus ambulance stations need operational garage doors and communications facilities and operating theatres require services to be maintained immediately after an earthquake, even if the building façade or internal linings have experienced damage. As normal buildings approach their ultimate limit state during shaking resulting from an earthquake with a recurrence interval of around 500 years, so parts with importance category P5 are required to remain undamaged and operational under such an event. SLS2 was introduced to represent the design earthquake for such consideration, with designers of these P5 parts being required to demonstrate they are able to continue operating to demonstrate compliance.

CONCLUSIONS

The inclusion of clear performance objectives into the New Zealand loading standard has created a platform for consistency in design approach. It identifies several areas of control that have not been previously engaged and provides a valuable reference line which can be used to ensure consistency between various life-safety and damage control constraints. Of particular relevance were the following:

- The requirement for buildings to maintain load-carrying capacity beyond ULS design levels is a reasonable expectation that is usually achieved by inherent reserves within the real system. It is the X factor that explains why older buildings often survive levels of earthquake shaking well beyond that to which they were designed. The challenge is to quantify the converse, namely what are the aspects of well designed buildings that either collapse or are severely damaged while nearby counterparts are largely unscathed.

- The inclusion of near-field fault considerations complicate the selection of earthquake ground motions for time-history analysis and can confuse limit state compliance verification.

- The overall drift control limits may not be sufficient to avoid weak-storey collapse in some structural forms. Reduced interstorey drift limits will be needed in such cases.

- The ability of parts and non-structural components in buildings to perform either during or immediately following various levels of earthquake induced ground shaking is an essential aspect of buildings meeting their performance expectations. Heavy elevated parts must remain attached to buildings, and other parts are not to be damaged at low levels of ground shaking. Damage to critical post-earthquake facilities must not be such as to impact on operational continuity even at high levels of ground shaking intensity.

- Serviceability criteria are expanded to include both damage control (SLS1) and operational continuity expectations for critical facilities (SLS2). These provisions are applied to both the primary structural frame and also the design of the secondary components and parts.

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