Performance-based Seismic Assessment: Myths and Fallacies

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ABSTRACT: Performance-based seismic engineering has been the thrust of research in earthquake engineering internationally in the past 10-20 years. Despite significant effort within the research community to improve the quantitative tools to characterise seismic hazard, nonlinear responses, elemental behaviours, uncertainties, damages and losses – the reality is an accurate prediction of building performance in earthquakes is still very challenging and maybe impractical for real buildings.

In the authors' opinion, the ability to predict seismic performance for a particular earthquake is a myth and that the focus of a performance-based seismic assessment should be on ascertaining the likely building behaviour and the governing inelastic mechanism such that informed decision can be made of the implied seismic risk and required seismic strengthening.

This paper explores some of the fundamental concepts in performance-based seismic assessments in both international and New Zealand context. Some common "myths" are discussed in the context of seismic assessment of existing buildings. We put forward some thoughts on how performance-based seismic assessment can be carried out in the New Zealand context.

1 MOTIVATION

Performance-based seismic engineering has been the thrust of research in earthquake engineering internationally in the past 10-20 years. Despite significant effort within the research community to improve the quantitative tools to characterise seismic hazard, nonlinear responses, elemental behaviours, uncertainties, damages and losses – the reality is an accurate prediction of building performance in earthquakes is still very challenging and maybe impractical for real buildings.

In the authors' opinion, the ability to predict seismic performance for a particular building in a particular earthquake is a myth and that the focus of a performance-based seismic assessment should be on ascertaining the likely building response and the governing inelastic mechanism such that an informed decision can be made of the implied seismic risk and possible seismic strengthening.

As late Prof Allin Cornell and late Prof Helmut Krawinkler wisely stated on the ultimate goal of performance-based seismic engineering (Cornell and Krawinkler, 2000):

> *"The final challenge for PEER researchers is not in predicting performance or estimating losses; it is in contributing effectively to the reduction of losses and the improvement of safety. We must never forget this. It is easy to get infatuated with numbers and analytical procedures, but neither one of them is useful unless it contributes to this final challenge."*

This paper explores some fundamental concepts in performance-based seismic assessment in both international and New Zealand context. Some common "myths" are discussed in the context of seismic assessment of existing buildings. We have taken some liberty in our choice of the word "myth" –to provoke a wider debate and discussion within the industry. We have put forward some thoughts on how performance-based seismic assessment can be carried out in the New Zealand.

2 PERFORMANCE-BASED SEISMIC ASSESSMENT

2.1 From prescriptive design to performance-based assessment

Traditionally, seismic design codes provide prescriptive “deemed to comply” criteria that specify minimum levels of strength, stiffness and ductility, and outline the acceptable materials, detailing and configuration in order to achieve the minimum levels of safety and performance of buildings in earthquake. Our experience is that past earthquakes shape these prescriptive criteria.

The expected performance of a building in earthquake is not generally assessed in new building design but a minimum level of performance is implied by the rules that are prescribed. These rules include the use of capacity design and minimum requirements for element detailing e.g. minimum tie spacing in concrete columns. The minimum levels of performance required extend beyond the design levels of shaking even though they may not be explicitly accounted for.

Existing buildings, which were generally designed prior to the introduction of modern seismic codes, are expected to be non-conforming to at least some of these prescriptive rules. First principle understanding of how the structural components behave and respond under earthquake shaking becomes more important than necessarily meeting specific code clauses but a high level of understanding of a building’s seismic behaviour is required to ensure that contravening a rule does not unduly jeopardise the minimum levels of resilience that are inherently provided for in a new building.

Performance-based seismic assessment offers a consistent framework for engineers to evaluate how a building may behave in an earthquake, in particular when a building that does not meet a number conventional prescriptive requirements and responds in a highly non-linear manner with potentially mixed-ductility response (NZSEE,2006 ; ASCE-41, 2006).

The framework also provides the means for engineers to both communicate and relate the diverse structural performance of buildings with the diverse objectives of building owners / society.

One key step in performance-based assessment is to assess the likely behaviour of the structure and the performance consequences for a range of earthquake ground shaking. This leads to a more explicit description of the relationship between performance objectives, type of facilities, earthquake hazards/frequency and engineer response parameters. SEAOC Vision 2000 document (1995), for example, illustrates this in a performance matrix as shown in Figure 1.

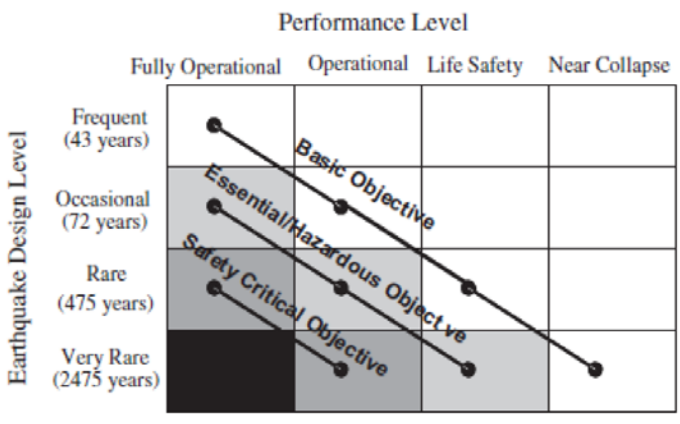

Figure 1: SEAOC Vision 2000 performance matrix (1995)

However, it may not be practical to assess building behaviour at numerous level of shaking particularly once the building moves to the non-linear range (FEMA P-58, 2012). Determining the relationship between building performance, as a whole(i.e. damage, collapse, loss of functionality etc), and the behaviour of individual structural components/elements (concrete cracking, beam hinging etc) is equally challenging.

Instead of a ‘pass / fail’ approach, performance-based seismic assessment requires the engineer to consider whether the failure of a particular structural component is likely to compromise the integrity of the gravity and lateral load resisting systems leading to structural behaviour exceeding the acceptable performance levels e.g. collapse or life safety risk?

A whole new set of rules, procedures and a mind-set change is needed as part of this framework in order to provide a consistent framework to assess buildings falling outside the prescriptive code requirements and that could potentially have a range of performance outcomes.

2.2 Overseas performance-based seismic assessment guidelines

Recognising the need outlined above, and made possible by the advances of non-linear analysis procedures, FEMA-273 (1997) pioneered performance-based seismic assessment of existing buildings. FEMA-273 and its subsequent revisions (FEMA-356, 2000 and ASCE-41, 2006) compiled and introduced a number of new concepts and tools for a performance-based seismic assessment. These included definition of various performance levels and associated structural and non-structural 'performance', ways to use non-linear analysis techniques and definitions of "acceptance criteria" i.e. plastic capacity deformation and strength limits for various structural components.

A building's seismic performance (e.g. damage state of structural and non-structural components) is associated with various engineering demand parameters (inter-storey drift or floor acceleration), which are quantified using non-linear analyses and experimentally-calibrated local structural component capacities. Figure 2 illustrates both the discrete performance levels of these first-generation performance-based assessment methods; and the 'performance continuum' introduced in the second-generation guidelines (Heintz et al, 2014)

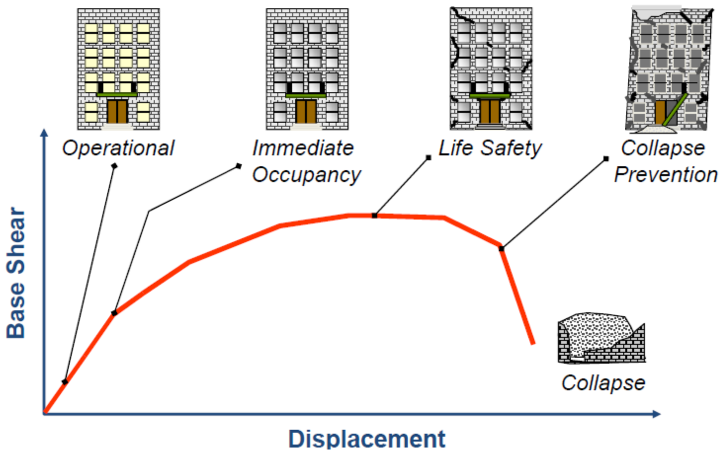

Figure 2: Relationship of building response/damage to member response (Heintz et al, 2014)

The second generation of performance-based seismic assessment suggests that the improved understanding of building behaviour would allow either a qualitative or quantitative estimate of seismic performance including risks of casualties, building damage and downtime, and resulting economic loss that may occur as a result of earthquakes (Krawinkler, 1999; Deierlein et al, 2003; FEMA 445, 2006 ; FEMA-P58, 2012).

The proposed procedure (FEMA P-58) is probabilistic with uncertainties explicitly considered, as it is recognized exact performance prediction is not possible with the many inherent uncertainties that exist (Heintz et al, 2014). Seismic performance is expressed, in terms of the probable consequences i.e. human losses (deaths and serious injuries), direct economic losses (building repair or replacement costs), and indirect losses (repair time and unsafe placarding) resulting from building damage due to earthquake shaking.

Structural engineers and non-engineers alike may be excited by the prospect of being able to discuss seismic risk and its mitigation in terms risk, damage, reparability, cost – terminologies that may have more meanings than structural ductility, flexural hinging and base shear; but need to recognize that past deterministic thinking needs to change if the concepts are to be adequately conveyed.

3 MYTHS IN PERFORMANCE-BASED SEISMIC ASSESSMENT

While significant improvements in this field have been made in the past decade, a number of myths about performance-based seismic assessment have crept into practice. In our view, these can divert practitioners away from forming a better understanding of the seismic behaviour of buildings and can inhibit the objective of understanding and reducing the seismic risk.

3.1 Myth No 1 – Building performance including collapse can be reliably predicted

The premise of first-generation performance-based earthquake engineering in the North-American guidelines (FEMA-273, ASCE-41 and FEMA-P58) is that building seismic performance can be predicted and evaluated with quantifiable confidence. The ASCE-41 standard for example, makes reference to performance levels and structural component acceptance criteria related to loss of intermediate occupancy and building near-collapse. Recent research has also promulgated in several guidelines on collapse prediction and assessment (FEMA P-695; NIST, 2013)

However, evidence from analytical-experimental and post-earthquake reconnaissance studies (e.g. Maison et al, 2009; Kam et al, 2011) has shown that structures generally perform better than what the sophisticated non-linear assessment procedure may suggest. The fact is they need to otherwise the Building Code objective of an acceptable risk of collapse, considered holistically, will not be met.

This is also evident from a comparison of the "code-level" design spectra and the response spectrum of the recorded ground motions from the Christchurch February 2011 earthquake as shown in Figure 3. The recorded ground shaking demand greatly exceeded the "design level shaking in all CBD recording stations, but only a small number of buildings, mostly earthquake-prone unreinforced masonry construction (plus, of course, the CTV and PGC buildings), collapsed.

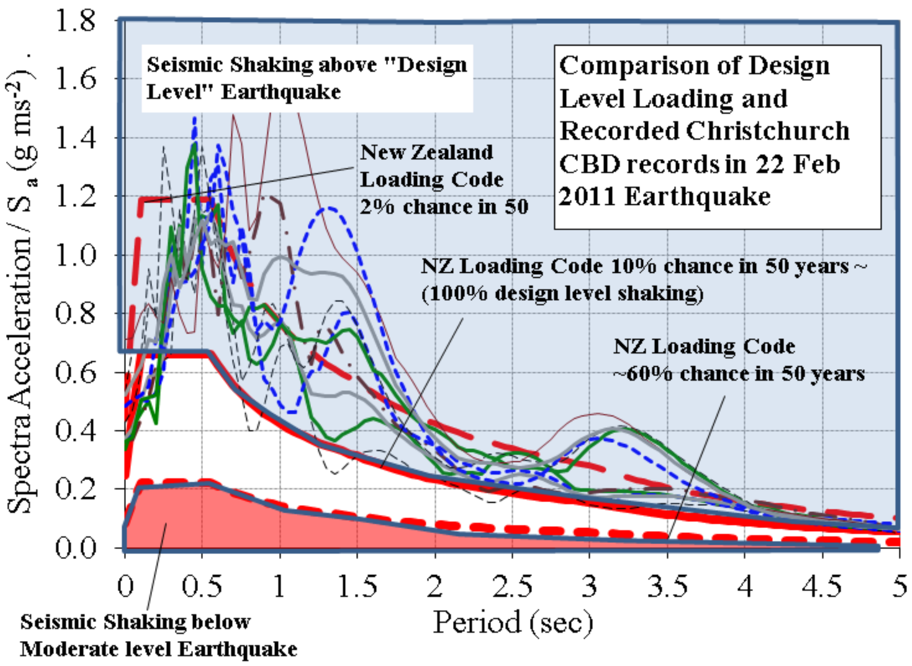

Figure 3: Comparison of "Design Level" and Moderate Level Shaking (33%) with the recorded horizontal acceleration response spectra in Christchurch CBD from the 22 February 2011 earthquake.

An assessment using force-based linear analysis would suggest a large number of the buildings in Christchurch should have collapsed under the recorded seismic loads, which were 2 to 6 times the calculated 'design' capacity. Explanations are offered regarding, for example the relatively short duration of shaking in this particular earthquake, but the fact remains that similar observations have been made after every earthquake affecting a region that has had some historical earthquake resistant design requirements.

The next generation performance assessment guidelines, FEMA P-58, recognises the inability to precisely assess the seismic performance of a building due to the cumulative results of uncertainties in the various components of the performance assessment (hazard, modelling, damage and losses) (FEMA P58, 2012). It advocates the use of performance functions that incorporate probability and uncertainties; but relies on the use of Monte Carlo simulation of specific analytical model with calibrated probability functions. However initial benchmarking studies of the FEMA P-58 suggest losses and damage using these techniques were over-predicted when compared to past earthquake data (Heintz et al, 2014.)

When the performance-based seismic assessment is extended for a large group of buildings to predict probabilistic hazard, damage, loss, fatality, and downtime etc., the validity of the predictive models is even more questionable due to the numerous uncertainties and sensitivity of the input parameters (Li et al, 2012; Liel and Deierlein, 2012). This type of analysis may provide some insights into the general trend of the building population seismic performance to inform code development, but in our opinion, it is not necessarily very meaningful for assessment of individual buildings.

Bradley (2013) rightly pointed out that the little to none emphasis in the research for performance-based earthquake engineering in terms of the "high level" uncertainties in the constitutive model and modelling methodology. The problem being a rigorous consideration of modelling uncertainties is simply impractical as it requires a good understanding of likely building inelastic behaviour prior to the refined and sophisticated analysis – and this is only practically achievable with simpler analysis tempered with engineering judgment; though it is acknowledged this may be a low variance high bias outcome noted by Bradley (2013).

3.2 Myth No 2 – Sophisticated analyses must improve accuracy and reliability

While the response of buildings to earthquake is a complex, three-dimensional, non-linear and dynamic problem –a similarly complex non-linear dynamic analysis may not necessarily provide the silver bullet towards aiding our understanding of a building's seismic behaviour.

Advanced and sophisticated analyses such as non-linear time-history are useful in understanding the non-linear and dynamic behaviour of the building. However, it is important to recognise that any output of a non-linear time history analysis is only a snapshot representation of the building response to one particular earthquake record and then highly dependent on the ability to adequately model the non-linear element behaviour. The actual performance in an actual earthquake is contingent on a number of other variables that may or may not be modelled (NIST, 2013).

Post-earthquake forensic investigation of collapsed buildings, including those presented at the Canterbury Earthquake Royal Commission for the collapsed CTV and PGC buildings (CERC, 2012) have also shown further challenges in predicting the exact performance of a single building even with the very sophisticated non-linear time-history analysis techniques that are now available.

There is a tendency to think that more sophisticated analyses "should "always provide a more accurate answer, resulting in a more efficient and less conservative design" (Chambers and Kelly, 2004; Searer, 2008) and a better assessment for an existing building. However, this is not always the case as a more complex analysis needs more input parameters, each subject to judgement, probabilistic outcome and potential errors. There is a fine balance between accuracy, reliability (or precision), cost and complexity in structural analysis, as illustrated in Figure 4. It would be erroneous to conclude that the need for judgement decreases as the sophistication of the analysis increases. The more sophisticated the analysis, the greater the probability that something unintended has been modelled, and the greater the reliance on judgement that this will be recognised.

Contrary to complex analysis of individual buildings undertaken for research projects, there is often a higher cost and limited time for similar rigor for commercial projects. Thus, there is limited opportunity for sensitivity and parametric analyses, and limited opportunity for "testing" different input ground motions etc. This results in a limited number of results / runs for a particular building, which limits the usefulness of nonlinear time-history analysis to anything other than another tool in the engineer's toolkit to aid in the understanding of how a building might perform.

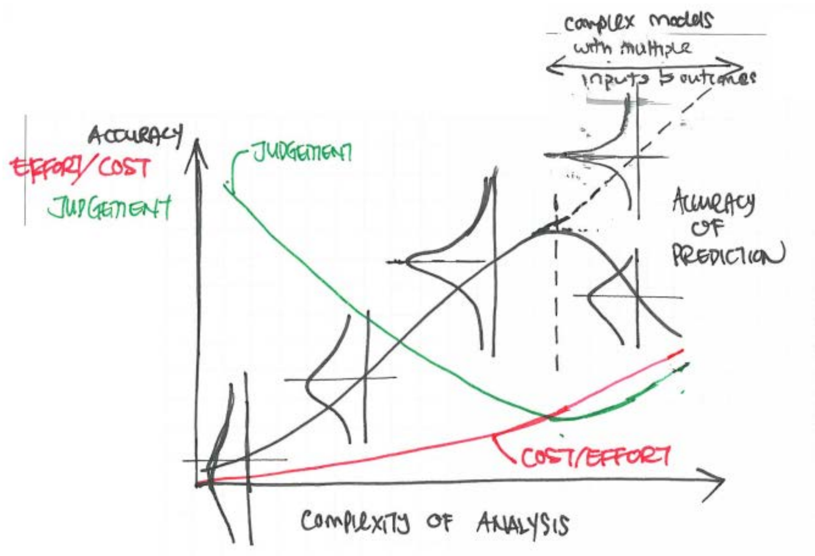

Figure 4: Trade-off between accuracy, engineering judgement, cost and complexity of structural analysis

A blind prediction contest sponsored by UCSD, the Portland Cement Association and the Network for Earthquake Engineering Simulation (NEESinc) in 2006 (Panagiotou and Restrepo, 2007) illustrates the challenges and uncertainty in relation to prediction of structural behaviour, let alone performance (i.e. damage, losses etc.). It involved a large scale shaking table test of cantilevered reinforced concrete walls, and researchers and professionals were invited to predict the response of the test wall to the four input earthquake motions.

The 'best estimate' results itself showed a significant scatter, as shown in Figure 5, despite the structure being 'capacity-designed' to ensure a specific inelastic flexural mechanism formed at the base of the walls. The overall system lateral capacity and stiffness was typically underestimated. The explanation was that this was likely due to the inadequate modelling of the interaction between the walls, the slab and the gravity columns, something not intended in the original test design (Panagiotou and Restrepo, 2007; Kelly, 2007).

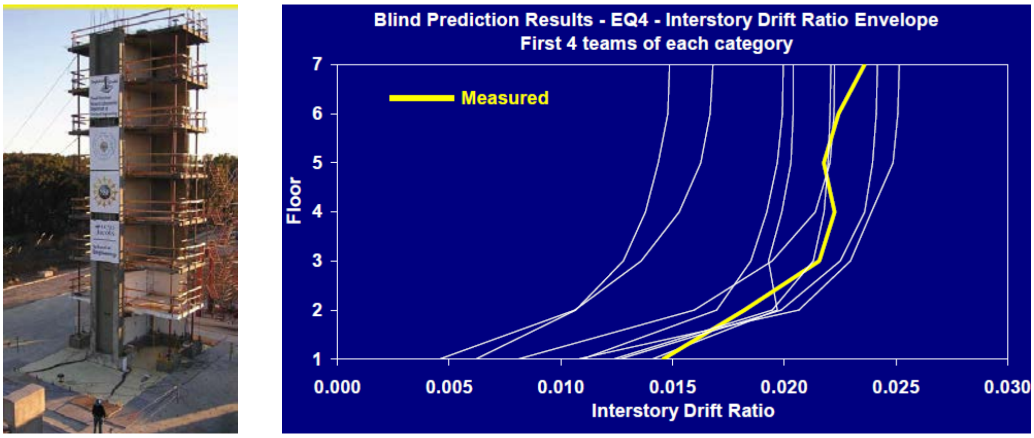

Figure 5: UCSD, PCA & NEES blind prediction contest for a shaking table test of a full-scale reinforced concrete wall test building (image from Panagiotou and Restrepo, 2007)

A few years later, UCSD organised another blind prediction contest, and this time of a simpler reinforced concrete cantilevered column sub-structure (PEER, 2010). The organisers concluded, "the results individually and collectively show a very high level of analytical capability, but also suggest we have a ways to go to be able to predict both the global and local responses of even simple structures." Figure 6 shows a sample experimental – prediction comparison of the maximum horizontal displacement of the single-degree-of-freedom system – where there is a large scatter of prediction, despite deploying some of the most sophisticated analysis available to practitioners and researchers.

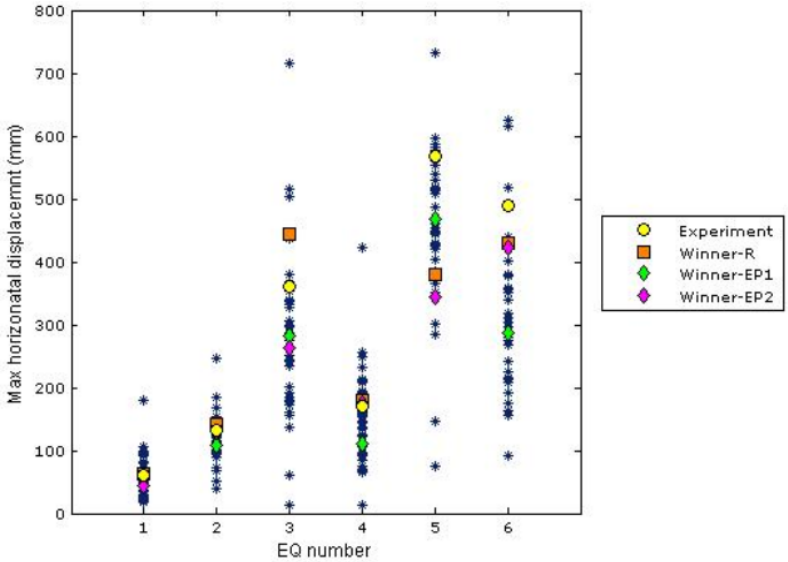

Figure 6: PEER blind prediction experimental-prediction for shaking table test of a full-scale reinforced concrete column sub-assembly (PEER, 2010).

In our view, while there is a place for sophisticated analysis such as non-linear time history in performance-based seismic assessment, this ought to be tempered with simpler analyses that provide some indication of the likely building behaviour and the governing inelastic mechanism. We believe that a black box non-linear time history analysis presents significant risks of complacency and a potential focus on localised element rather than a holistic view of building behaviour.

Any advanced analysis requires significant effort and engineering judgement to ensure the validity of the outputs. Fundamentally, such an analysis should be treated as another tool to approximate behaviour and probable outcome, rather than a predictive tool with an exact output. While the accuracy may have increased with the use of complex and sophisticated analysis, the uncertainties, precision and reliability remain a function of the level of checking and rigor of the analysis (number of runs, sensitivity analysis and well-defined analysis parameters).

Some consultants in California (Searer et al, 2008) have observed that the use of these sophisticated analyses (e.g. 3D modal analysis or non-linear pushover) by engineers who are inexperienced in earthquake engineering may result both in a false sense of security and in buildings that will not behave as expected.

3.3 Myth No 3 - Building performance expectation above the design level shaking

There is a prevalent idea that the current design and assessment approach only delivers acceptable performance for the design level shaking (say 500 years return period), and that “all bets are off” (i.e. it is acceptable for the building to perform poorly and collapse could well occur) if the shaking level is higher than the design level shaking (e.g. Au et al, 2013). An aligned myth is that a building that satisfactorily performs in a particular earthquake can then be said to meet the standard implied by the return period of the shaking in that earthquake.

It is suggested that specific checking of building structure or critical structural weaknesses for “collapse” at a higher level of shaking (say 2500 years return period) is necessary to confirm an adequate level of overall performance. This concept of two-level check is somewhat inherent in the FEMA-273 / ASCE-41 guidelines.

Given the uncertainties in predicting when a building will collapse, the authors do not consider it practical or necessary to design new buildings to a collapse limit state. Traditionally Standards, such as AS/NZS 1170.5, have relied on engineers designing to a limit state, defined as the Ultimate Limit State (ULS) and through this process achieving buildings expected to achieve an acceptable holistic performance (i.e. probability of collapse and fatality risk) – if not the ULS requirements have been be revised to ensure the appropriate level of performance is achieved. Careful consideration of observed performance (irrespective of the assessed return period of the earthquake shaking) and fine tuning of design requirements to correct poor performance have served us well.

While it might be expected that nominally ductile structures subjected to shaking levels significantly in excess of design levels might perform poorly, there is no evidence from Canterbury earthquakes to suggest that they perform, in general, any worse than highly ductile buildings proportioned for very low levels of strength. Kam et al, 2011 concluded from studying the performance of reinforced concrete structures in Christchurch that there is a need for a departure from a force-based emphasis in the seismic design practice to a more displacement-based and ductile inelastic mechanism-focused approach (irrespective of the prescribed loading).

We argue that buildings are not expected solely to survive 100% of the design demand shaking, and then to suddenly fail and collapse in 110%, 150% or even 180% of this shaking. Figure 3 reinforces that this is largely achieved in practice, at least for buildings in Christchurch. While there are instances where the levels of inherent resilience assumed to be available by AS/NZS1170.5 are not always achieved, these have generally been due to a mode of behaviour that has not been considered in design rather than simply running out of code defined capacity.

3.4 Myth No 4 – Seismic assessment should be focused on the seismic lateral load resisting system only

We have observed that a significant amount of seismic assessment effort is typically expended assessing the ability of the primary seismic lateral load resisting system to resist the require demands and often the other elements in the building receive, at best, only scant attention.

It is clear, however, that collapses of buildings occur due to failures in the gravity load resisting systems. These occur because the primary seismic system has provided inadequate protection to the gravity system, particularly when the lateral and vertical resisting systems are separate and the gravity systems are heavily loaded.

While properly detailed and configured primary lateral load resisting systems have rarely failed due to a lack of strength capacity there are numerous instances of gravity failures due to inadequate deformation capacity in the gravity system to sustain the applied deformations.

Often the deformations that have been applied have significantly exceeded those which would have been estimated during the design process due to unexpected behaviour of the lateral system once this goes inelastic, particularly when this also causes torsion behaviour due to unexpected eccentricities.

It is clear that assessment of seismic performance must include an adequate assessment of both the lateral and gravity systems, with perhaps greater attention placed on the gravity system and how well protected is the load path (e.g. diaphragm detachment and punching shear of flat slab-to-column connection). Higher levels of conservatism may be required in assessing gravity systems particularly when high levels of ductility are expected in the lateral system, irregularities are present and when the gravity system is heavily loaded.

3.5 Myth No 5 – That use of probable capacities and fully developed mechanisms in assessment significantly alters the risk profile of existing buildings compared with new

Au *et al* (2013) has argued that the use of probable material strengths has significantly diminished the 'seismic resilience' of an existing building when assessed to the NZSEE Guidelines (2006); such that two buildings of the *%NBS* rating as per NZSEE guidelines may have very different performance expectations.

The use of probable capacities has been part of assessment practice in New Zealand for at least the last ten years. It reflects, in part, that the building being assessed exists and that the correct implementation of design and construction objectives can be fully assessed.

This is not the case for new buildings which initially exist only as a concept on a drawing where design assumptions can remain untested and unverified.

While from a regulatory point of view it may be appropriate to assume that all new buildings comply fully with the requirements NZBC, this does not apply to the estimation of expected performance once the building is constructed.

It is contended that the benefit provided from assuming probable capacities is insignificant compared with the uncertainties involved in assessing seismic performance that have been discussed above. Any benefit will be potentially over shadowed by the effect of any unintended failures of the designer or constructor to achieve code objectives.

4 PERFORMANCE-BASED SEISMIC ASSESSMENT IN NEW ZEALAND CONTEXT

We have explored some "myths" and challenges in predicting performance of building in earthquake. In the following sub-sections, we offer some thoughts on how performance-based seismic assessment can be used in New Zealand– generally as a starting point for further discussion within the industry.

4.1 Set expectations for seismic performance of existing buildings

The first step is to establish and agree on a set of performance descriptors or a risk matrix for existing buildings. A preliminary version of this performance description for varying levels of seismic rating (*%NBS*) and ground shaking is given in Table 1. Table 1 sets out the expected performance for a population of buildings given a specific seismic rating and an earthquake event. Performance is associated with a level of 'damage' and the likelihood of exceedance. The uncertainties involved mean that it is not appropriate to predict the performance of a particular building in a particular earthquake deterministically.

This is similar to the risk matrix (probability and consequence) proposed to define "tolerable levels of performance" for new buildings for the New Zealand Building Code (NZBC) B1 clause. The B1 review is intended to add clarity to the performance-based philosophy in NZBC and to better define building performance requirements for a range of natural hazard events (Lawrance et al, 2014).

Once a set of performance descriptors is established, it is important to ensure the risk and consequences of existing buildings are well understood and communicated to all stakeholders.

We believe it is necessary to dispel the myth that somehow an existing building achieving 100% of new building standard (*%NBS*) achieves a minimum performance level that is different from a new building. above; and the corresponding risk matrix from Clause B1 review, together could form the basis of discussion in order to align the thinking within the engineering fraternity.

We consider a 100*%NBS* rating for an existing building therefore implies a similar level of performance as the minimum considered acceptable for new buildings. The corollaries of this assumption are:

- A structure with 100*%NBS* rating implies there should be a high degree of reliability that the global building capacity and global lateral stability (inter-storey drift, load path stability, robustness) is not exceeded at the conventional new building design level shaking (e.g. 1 in 500 years earthquake for IL2 building).
- Beyond this level of shaking, a 100*%NBS* rating implies a good degree of protection and structural resilience against catastrophic collapse.

We argue that the rational being that the uncertainties around predicting performance are so great that there is no reason to believe the slight differences in approach between assessment and new building design lead to a significantly different level of performance.

Table 1 – Preliminary *%NBS* Descriptors for Structural Damage and Existing Buildings (developed for discussion for NZSEE guideline review)

	Seismic Rating			
Level of Ground Shaking/Return Period	**34 *%NBS***	**50 *%NBS***	**67 *%NBS***	**100 *%NBS***
50 year return period *(One-third ULS loading?)*	*None* AALAN *≥Minor* AALAN *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely	*None* likely *≥Minor* unlikely *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely	*None* very likely *≥Minor* unlikely *≥Moderate* unlikely *≥Major* extremely unlikely *Collapse* exceptionally unlikely	*None* almost certain *≥Minor* unlikely *≥Moderate* extremely unlikely *≥Major* exceptionally unlikely *Collapse* exceptionally unlikely
100 year return period *(One-half ULS loading?)*	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* AALAN *≥Minor* AALAN *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely	*None* likely *≥Minor* unlikely *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely	*None* very likely *≥Minor* unlikely *≥Moderate* unlikely *≥Major* extremely unlikely *Collapse* exceptionally unlikely
200 year return period *(Two-thirds ULS loading?)*	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* AALAN *≥Minor* AALAN *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely	*None* likely *≥Minor* unlikely *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely
500 year return period *(ULS loading)*	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* AALAN *≥Minor* AALAN *≥Moderate* unlikely *≥Major* unlikely *Collapse* exceptionally unlikely
2500 year return period *(1.8 times ULS loading?)*	*None* extremely unlikely *≥Minor* almost certain *≥Moderate* very likely *≥Major* likely *Collapse* AALAN	*None* extremely unlikely *≥Minor* almost certain *≥Moderate* very likely *≥Major* likely *Collapse* AALAN	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*None* very unlikely *≥Minor* almost certain *≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely
5000 year return period	*None* exceptionally unlikely	*None* extremely unlikely	*None* very unlikely *≥Minor* almost certain	*None* very unlikely *≥Minor* almost certain
(2.2 times ULS loading?)	*≥Minor* almost certain *≥Moderate* almost certain *≥Major* very likely *Collapse* very likely	*≥Minor* almost certain *≥Moderate* very likely *≥Major* likely *Collapse* AALAN	*≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely	*≥Moderate* AALAN *≥Major* unlikely *Collapse* unlikely

Suggested Descriptors/ Categories

Damage:

None; Slight (damage to non-structural items only);

Minor (damage to structural items that can be repair easily);

Moderate (damage to structural items that can be repaired with significant effort)

Major (damage to structural items not worth repairing)

Collapse

Likelihood:

Almost certain >95%

Very likely >90-95%

Likely >67-90%

About as likely as not (AALAN) ≥34-67%

Unlikely >1-34%

Very unlikely >0.1-1%

Extremely unlikely >0.01-0.1%

Exceptionally unlikely <.01%

Interpretation

≥Major unlikely : means that the likelihood of major or greater damage is between 1 and 34%. Or loosely stated, between 1 and 33 buildings out of 100 of a similar type are expected to perform to this degree.

None : means less than minor damage

One-half of ULS loading (ULS shaking) does not necessarily have a return period of 100 years. The requirement to keep the duration and therefore the relative contribution of the various magnitude earthquakes the same means that a direct correlation with return period via the risk factor is not strictly correct.

4.2 Performance-based seismic assessment with the NZSEE Guidelines

The current NZSEE guidelines provide several concessions to existing buildings which in effect allows a form of performance-based seismic assessment. It does encourage/require an understanding of the eventual non-linear behaviour of the building as a whole (not just a predetermined earthquake load level). These include:

- use of probable material strengths (and therefore strength reduction factors approaching 1.0
- mobilization of available inelastic mechanisms - i.e. *%NBS* is not governed by first elements exceeding its strength/ductility capacity if it doesn't lead to a mechanism. Available inelastic mechanisms can be utilised as long as the gravity-load carrying capacity and global stability are not compromised, with appropriate levels of reliability (e.g. in Brook et al (2007).
- remove the need to check all the code clauses - and focuses on understanding/assessing the behaviour and life-safety performance of building under ULS levels of earthquake load. The expectation, however, is that the expected effect on the resilience of the building of not complying with a particular requirement is understood and considered to be acceptable in the context of the performance expected.
- focus on life safety risk - and not necessarily damage/serviceability issues - as such some elements are allowed to 'fail' prematurely.

Assessing the seismic capacity of an existing building is fundamentally different from designing a new building for seismic actions. Seismic assessment requires a clear understanding and reliable evaluation of the existing load paths, the probable inelastic deformation mechanisms, the probable "collapse mechanism", and the available ductility/displacement capacity of the structure.

This relies on an understanding of the hierarchy of strength and sequence of failure of a structure in an earthquake, by undertaking simplified hand calculation such as the Simplified Lateral Mechanism Analysis (SLaMA) outlined in the NZSEE guidelines (2006). The comparison of capacities of various mechanisms (e.g. flexural versus shear) and within connected elements (e.g. wall-to-foundation) generally provides an indication of the hierarchy of strength and the likely post-elastic behaviour of a building in a severe earthquake (Kam et al, 2014).

Fundamentally, we suggest that there is a need to re-set the thinking on the fundamental idea that 'earthquake does not read the loading standards' and that our quantitative analysis, however sophisticated, is at the end of the day, a proxy measure of expected seismic behaviour.

Some considerations for the analysis method for seismic assessment:

- For **relatively simple** structures that conform with certain established criteria where complex analysis may not be warranted, the calculated demand and capacity of the building may be modified with appropriate factors based on the identified governing inelastic mechanism e.g. the use of different allowable μ/ S_p and φ-phi factors.
- For **complex / more significant** structures (e.g. with regard to occupancy, consequence of failure), and/ or where greater levels of reliability of assessment are sought, the assessor is expected to qualitatively and quantitatively predict the seismic behaviour of the building across a range of seismic shaking with consideration of the inelastic behaviour and eventual governing mode(s) of failure, using appropriate methods.

Irrespective of analysis methods, consideration of non-linear behaviour is fundamental for a performance-based assessment and the assessor can mobilise all available inelastic mechanisms - i.e. the *%NBS* is not necessarily governed by the first elements exceeding its strength/strain/ULS capacity provided that local behaviour doesn't lead to loss of gravity-load path and/ or lateral instability that could reasonably lead to a life safety issue.

For some complex circumstances where commonly used analysis is unable to predict the behaviour well, a set of prescriptive clauses or assessment of specific critical structural weaknesses would be put in place to penalise the building design (e.g. torsional instability of irregular and ductile systems).

4.3 Outcome of a performance-based seismic assessment

In our opinion, the outcome of a *practical* performance-based seismic assessment should deliver a clear understanding of the likely building behaviour and the governing inelastic mechanism, in conjunction with a simple seismic risk / performance metric. In the New Zealand context this is currently the *%NBS* score or rating.

The simplicity of a performance metric means informed commercial decision can be made of the implied seismic risk and possible seismic strengthening by non-technical decision-makers and the marketplace; this can be done without being too carried away with sophisticated analysis and black-box computation of losses etc.

Often our clients are sufficiently sophisticated that an understanding of likely building behaviour and a simple seismic risk / performance metric can be fed into a larger risk/cost analysis before any decision is made with respect to seismic strengthening or for exiting a building.

Conversely, a less sophisticated client and the regulatory authorities would similarly prefer as simple seismic risk / performance metric that can be consistently derived by different sets of engineers. Even if sophisticated structural analyses (e.g. non-linear time history) were undertaken, these type of clients may prefer a more straight forward answer "does my building meet a level of acceptable safety or not?"

We see value in communicating some performance measures such as 'damage, repair cost and downtime' to our clients; but only if these outputs are material, defensible and easily derived. However, we also foresee a number of challenges in calculating and providing this information (e.g. reliability of the "black box" procedure, liability issues of predicting losses / fatalities etc.), similar to those highlighted in the workshop on communication of seismic risk for Phase 2 of FEMA P-58 (Heintz et al, 2014).

We have observed significant confusion in the market place when the building is rated (*%NBS*) based on the lateral load resisting system and then a separate and often lower score for other items. We recommend against this practice and believe it is better to score the building based on the lowest score (consistent with the life safety objective) and then note the effect of correcting these aspects.

4.4 Treatment of seismic resilience and performance beyond the "design level shaking"

One of the challenges of performance-based seismic assessment is to be able to assess the performance of buildings over a full range of earthquake shaking, not just the arbitrary design level shaking, but in a manner that does not overly complicate the process or not be cognisant of the considerable uncertainties involved in predicting seismic performance.

ASCE-41 and its earlier versions have elected for a two-limit states check – at "life safety" and "collapse prevention" levels, as a means to assess the seismic resilience beyond the traditional "life-safety" limit state.

The current proposal for the NZSEE Guidelines is for a relationship between *%NBS* and seismic performance is set out in Section 4.2. It outlines the high-level performance objectives for existing buildings at different risk levels, and provides the verification methods (i.e. benchmarking to the Ultimate Limit State as per NZS1170.5 and material standards) in determining *%NBS* and acceptable/non-acceptable performance in terms of risk to life. In taking this approach ULS is seen as a holistic limit state embodying all requirements that are considered necessary to achieve an acceptable overall risk once the shaking rises to significant levels.

We believe that the collapse prevention approach of ASCE-41 has several disadvantages:

- It assumes that the point of collapse can be reliably predicted – which observations suggest it can't
- It has the, perhaps unintended, consequence of suggesting to the assessor that there is an upper limit to the level of shaking that a building can be subjected to – which clearly is incorrect. This may lead to a building satisfying the ASCE-4 collapse prevention criteria but still being very poorly configured for larger shaking.

- Because of the difficulties with analysing close to a collapse point the criteria set for this performance state are often simply factored up criteria for lower performance states – this negates the benefit of the additional effort involved in more sophisticated analysis.

5 FUTURE RESEARCH

There are still a number of unresolved issues and areas in active research to further progress performance-based seismic assessment.

- Guidance on identifying "killer" non-ductile buildings with very little resilience.
- Better analytical tools to assess and predict local and global mechanisms that could lead to partial or total collapse of buildings (e.g. diaphragm unzipping, beam-column joint axial failure, column shear failure, flat-slab punching shear failure), e.g. Shoraka (2013) research on non-ductile columns effects on building collapse
- Simple and consistent approach to account for the influence of geotechnical behaviour to overall building performance, without necessarily resolving to extensive site specific testing and complex soil-structure interaction modelling. (ASCE-41, Clayton et al, 2014)
- Industry-wide consensus on the use of non-linear time history analysis and non-linear pushover tools; including ways to incorporate international non-linear procedures in a manner consistent with New Zealand practice.
- Development of practical methods for adequately incorporating uncertainty into the assessment process without resolving to 'black box' tool such as the PACT programme from the FEMA P-58 project.

6 CONCLUSIONS

The mismatch of building performance and societal expectation is one of the key drivers for performance-based earthquake engineering. More than fourteen years have gone by since the late Prof Cornell and Prof Krawinkler wrote their influential letter on their vision for the performance-based earthquake engineering (and by extension seismic assessment) (Cornell and Krawinkler, 2000a).

While significant progress has been made in the past decade of research, the late Prof Krawinkler reflected on the future challenges of performance-based earthquake engineering in 2011 (Krawinkler and Deierlein, 2014), when a number of similar issues were discussed:

- Our understanding of ground hazard and seismicity is always stretched and improved by major events such as the Canterbury earthquake sequences. Research will be on-going to address near-fault effects and other site-specific effects.
- The ability of structural analysis model to determine damage parameters such as local deformation, large deformation effects, brittle failure mechanism, residual drift, and floor acceleration is still limited.
- The library of damage data and fragility function is incomplete and limited even after significant testing in the 10 years of the ATC-58 programme.
- Limited ability to precisely translate structural behaviour to 'performance metric' such as financial losses, downtime and fatalities/injuries. Available module is often based on limited data and judgement.
- Lack of consideration of the seismic resilience and vulnerability of the wider community and city; and post-disaster functionality, repair and recovery.

We have observed a gradual drift in the research and code-development fraternity in both North American and Europe towards a more analytically rigorous approach towards performance-based seismic assessment.

On the other hand, we have promoted in this paper what we considered a more pragmatic first-principle approach in which is possibly 'less sophisticated in practice' and relies on a good fundamental understanding of seismic behaviour of structures.

Pragmatic performance-based seismic assessment, pragmatic being the operative word, would be a key tool for engineers to deliver the seismic risk mitigation. A narrow focus on the five myths outlined in this paper will only lead earthquake engineering down a computational intensive approach while resulting in less time and opportunity for engineers to spend thinking about a building's likely structural behaviour or investigating the actual structure on site.

Engineers need to be cognizant that seismic assessment of buildings is only one aspect of seismic risk mitigation for any particular asset owner and only one particular type of natural hazard risks. The challenges are for earthquake engineers to think more broadly of seismic risk and resilience, to beyond individual building and individual clients – but on a broader community, regional and national level.

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