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# THE PREDICTION OF BUILDING PERFORMANCE DURING EARTHQUAKES – AN ART OR A SCIENCE?

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## ABSTRACT

Procedures for the seismic design of new buildings to achieve a minimum acceptable performance are well established. However, it is concluded in this paper that the actual performance of structures will not be predicted with any certainty using the same procedures, given the uncertainties associated with the assumptions that must be made. Sole reliance on design procedures to predict performance is likely to lead to unnecessary conservatism and this must be taken into account when setting standards for design.

It is also concluded that there is currently insufficient data available in a suitable form to enable the correlation between analysis and actual performance to be assessed in any way other than by judgement.

The prediction of seismic performance remains very much an art.

## BIOGRAPHICAL NOTE

Graduated from Canterbury University in 1978 having completed a Masters degree in Civil Engineering under the supervision of Professor Tom Paulay and Dr Athol Carr. On graduation, joined engineering consultancy Beca Carter Hollings and Ferner Limited where he is now a senior shareholder. Over the last 25 years has been associated with the design of a number of notable structures and projects in New Zealand and overseas including; Auckland Sky Tower (as structural design manager), Macau Tower, Hapuawhenua Railway Bridge, Thorndon Overbridge Seismic Retrofit and Wellington Town Hall and Hunter Building (Victoria University of Wellington) seismic retrofits. Has been responsible for seismic hazard assessments for numerous projects including those listed above, the Maui B offshore platform, Otira Viaduct and Auckland Harbour Bridge seismic retrofit. Was a member of the NZSEE reconnaissance team to Mexico after the Mexico City earthquake in 1985 and was a member of the recovery team on several industrial sites after the 1989 Edgecumbe earthquake. Is currently a member of the Standards Committee preparing the joint NZ/Australian structural loadings standard and NZSEE study groups deliberating on the seismic design of storage tanks and seismic strengthening of earthquake risk buildings.

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## 1 INTRODUCTION

Although ever-greater knowledge is being gained on how structures respond to earthquakes and what characterises the earthquake shaking, there are still significant uncertainties involved in the prediction of structure performance during earthquake shaking.

Codified approaches for the seismic design of new structures are generally well understood by designers but because they have been tailored to produce structures which can be relied on to produce a minimum level of performance (what ever that might be), they will not necessarily provide the designer with clear insight of what actual performance might be achieved.

Uncertainties abound in the basic assumptions that a designer must make in order to apply a modern seismic design standard, and as a result the precision that some designers assume is available from the application of these procedures is just not warranted.

Structural design professionals are often called on to give an opinion as to whether an existing structure is likely to perform well in a severe earthquake. Many will rely on often very detailed investigations of the structure, at an elemental level, to predict the performance of the building as a whole. An impression of precision might be gained but, really, how good are these techniques at predicting actual performance?

In this paper some of the issues relating to the prediction of structure performance are discussed. It is surmised that the prediction of actual performance still relies on significant judgement, as the science available, although vast, is currently not adequate to allow the uncertainties in the significant number of variables that characterise the seismic performance of structures to be easily accounted for. It is also surmised that the state of knowledge does not justify anything other than the simple Performance Factor approach currently adopted in the New Zealand earthquake loadings standard.

## 2 SEISMIC PERFORMANCE OBJECTIVES

Most modern seismic design standards have stated objectives outlining what they are attempting to achieve. These objectives form the basis for the provisions that have been developed.

For example the draft joint Australian/ New Zealand earthquake standard (AS/NZS 1170.4, 2002) has three stated objectives. They are;

1. The structure should be capable of resisting frequent earthquake shaking with an expectation of a low probability of damage sufficient to prevent the structure from being used as originally intended without repair,
2. The structure should be capable of withstanding major earthquake shaking with a reasonable margin against:
    a) Structural collapse
    b) Failure of parts and elements which would be life threatening to people within or around buildings
    c) Failure of parts or elements or systems whose function is critical for the safe evacuation of people from the building or for the emergency period after the earthquake,
3. The structure should be able to withstand the most severe shaking that it is likely to be subjected to with at least a small margin against collapse.

Objective 1 above relates to performance at a serviceability limit state which is not the subject of this paper so will not be considered further. Objective 2 is the primary objective for the ultimate limit state. Objective 3, also an ultimate limit state requirement, is stated in the draft as being only necessary for low seismic areas to ensure an adequate level of performance if the severity of major earthquake shaking is defined in terms of a specified return period.

As a further example, a major utility operator might have the following objectives;

1. Essential equipment and facilities are required to continue to operate without interruption, with unimpaired operational ability during and after frequent earthquake shaking,
2. Essential equipment and facilities are required to have damage limited to that which can be repaired sufficiently to restore supply in five working days following major earthquake shaking.

Objective 1 is a serviceability limit state objective and as for the previous example is not considered further. It is apparent that both of these examples state the objectives in a very generic form.

Although these two examples state the acceptance criteria for the performance objectives in slightly different terms it is apparent that in order to apply them, an ability to predict the performance of structures / equipment to a reasonable level of certainty is required. It should also be apparent that if compliance with these objectives is to be easily verified, the objectives must be able to be related to the commonly applied design procedures.

How can concepts such as "reasonable margin" and "restore supply in five working days" be related to seismic design requirements?

## 3 ACTUAL VERSUS CALCULATED PERFORMANCE

Over 50 years ago it was recognised that structures with relatively low strengths could survive large earthquake shaking provided that they had some inherent toughness and no obvious weaknesses.

This behaviour has now been codified so that designers can choose between the provision of toughness (described in terms of levels of ductility) and strength. The higher the available ductility the lower the required strength and visa versa.

It must be remembered, however, that the observations made 50 years ago were typically of structures that had not received any specific seismic design. Their toughness was achieved through good configuration and by virtue of the fact that they were well tied together. It is of interest to note that these factors are not easily amenable to codification and rely on the judgement and skill of the designer for application.

So how can the performance of structures be assessed?

It is clear that deterministic procedures such as are contained in design standards cannot make adequate allowance for the considerable uncertainties that exist.

Some attempts (Singhai, Kiremidjian 1996) have been made to evaluate performance using probabilistic techniques such as Monte-Carlo simulation to deal with the uncertainties involved.

These methods, through necessity, include only a superficial assessment of the parameters, however, the results, presented in terms of fragility curves (refer Figure 1 for the typical form) or damage matrices, provide an indication of the considerable range of performance outcomes that could be expected for a specified level of ground shaking.

When the fragility curves are combined with the probability of the ground shaking and an integration of possible outcomes is carried out, an estimate of the expected performance can be obtained.

It is suspected that even these methods, which have significant advantages over pure analysis (even sophisticated inelastic time history procedures), will not provide an adequate estimate of actual performance.

Some studies have been carried out that provide an insight into what might be found if adequate data on actual performance was available.

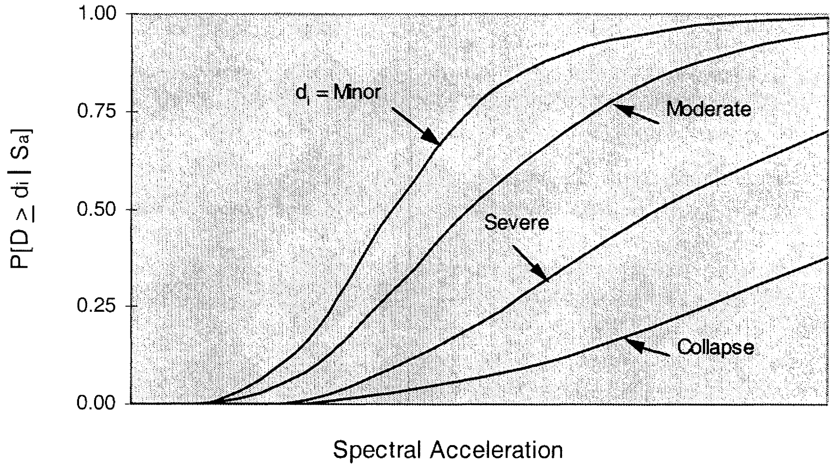

***Figure 1: Standard Form for Fragility Curves***

A study to determine the fragility curves for on-grade steel tanks (O'Rourke, Pak So 2000) investigated the actual performance of 400 tanks during nine earthquake events. The study concluded that the actual performance of the tanks was better than predicted by analysis methods and also better than predicted by methods solely employing engineering judgement.

Studies into the damage that occurred during the Hawke's Bay 1931 Earthquake in New Zealand (Dowrick, 1998) also concluded that well built buildings performed well during this $M_w$= 7.8 earthquake notwithstanding that they had not been specifically designed to resist earthquake shaking.

The point to be made is that in neither the case of the tanks or of the older buildings in the Hawke's Bay would analysis methods be able to predict the actual performance without the intervention of a correlation factor.

## 4 IMPLICATIONS FOR DESIGN OF NEW BUILDINGS

### 4.1 Structural Performance Factor, $S_p$

In 1992 the concept of a Structural Performance Factor, $S_p$, was introduced into the New Zealand earthquake standard (NZS4203: 1992). For convenience the factor was applied to the design earthquake loading but more logically it was always intended that $1/S_p$ would reflect how well buildings (structures) might react (perform) when subjected to the specified design loading, and in particular how well a building designed using codified materials standards and a codified earthquake loading regime might perform compared with specified broad performance objectives. $S_p$ therefore provides the 'glue' or the correlation between application of the design process and actual performance observed in practice. The introduction of $S_p$, what it represents and how it is assessed was not without controversy in 1992, a situation that persists to the present day.

NZS4203: 1992 applies a uniform value $S_p = 0.67$ for all structures and describes the rationale for $S_p$ as being to allow for the following;

1. The effect of a sustained number of cycles rather than the peak structural response defined by the hazard spectra,
2. The effect of design conservatisms

These are just two of many factors that might be expected to require consideration when comparing the outcome of design against actual performance. Others would include:

- Duration of shaking
- Use of the hazard spectrum rather than an actual earthquake spectrum
- How accurately the analysis modelling, including representation of the foundation, is likely to match reality
- How well the designer has met the design objectives
- How well the constructor has reflected the design objectives in the construction
- The level of redundancy that can be called on in the structure
- The actual live loading and its distribution at the time of the earthquake
- Near fault effects
- The actual stiffnesses of the structural members and their variance within the structure
- Layout of structural elements
- Actual distribution of plasticity within the structure
- Effect of non structural elements (both detrimental and beneficial)
- The importance of the structure (required reliability of the predicted result)

It might be expected that the correlation between actual performance and the design process will vary between structures of different types. However, given the large number of factors that are likely to influence the correlation it almost belies belief that, with the current state of understanding, anything other than the simplest derivation of $S_p$, based primarily on a judgement call, can be justified.

Some of the factors listed could lead to a lower level of actual performance compared with the design expectation, however, it is considered that in the majority of situations where modern design standards have been correctly applied the design process is likely to underestimate actual performance.

The value of 2/3rds adopted for $S_p$ in NZS4203: 1992 (1.5 for $1/S_p$) must be considered a judgement call. It will be low for some structures for some earthquakes and high for others. In light of other assumptions made during design it seems to be set at a reasonable level for the typical situation but should always be reviewed by the designer in special situations.

The author has adopted values of $S_p$ ranging from 0.67 to 1.0 in the design of structures he has been involved with over the last 10 to 15 years. For example, a very conservative stance was taken in the design of Sky Tower, a 328 m high concrete communications and observation tower built in downtown Auckland in 1997 and quite appropriately $S_p$ =1.0 was used during its design. $S_p$ values closer to 1.0 have been adopted for some major motorway structures. These structures typically fall outside the scope of NZS4203.

Designers of structures which meet modern standards but which are expected to possess little or no ductility should not expect superior performance, especially if, as the designer should expect, the actual circumstances are not quite as assumed during design. The adoption of $S_p$ =1.0 would appear to be a minimum for these structures. The draft joint NZ/ AS Earthquake Standard (AS/NZS 1170.4) is proposing to set $S_p$ = 1.0 whenever the available ductility, $\mu$, is assessed to be less than 1.25 which will correct this anomaly in the current standard.

## 4.2 **Foundation Performance**

An assessment of seismic performance of a structure is not complete without an assessment of the performance of the structure foundations and/or foundation soils. When attempting to match the design of structure foundations and/or foundation soils to performance objectives it is also necessary to assess an appropriate correlation between the result obtained from assessment procedures and actual performance. It is a commonly held view amongst structural engineers that the analysis methods typically employed by geotechnical engineers are conservative. This is understandable in the context of achieving a reliable design, given the large uncertainties that the geotechnical engineer is often forced to deal with. However, when assessing the seismic performance of foundation soils an unrealistic assessment can result if the conservatism in standard geotechnical methods is not at least partly accounted for.

The implication for design is that perhaps a performance factor less than 2/3rds could be justified when some standard geotechnical methods are being used.

## 5 IMPLICATIONS FOR ASSESSMENT OF EXISTING BUILDINGS

The initial evaluation procedure (IEP) set out in the draft study group report of the NZSEE Study Group on Earthquake Risk Buildings (NZSEE Study Group Draft 2003) recognises many of the points made above. This evaluation procedure seeks to determine the performance of existing buildings by identifying "significant structural weaknesses" and to "score" the building by comparing its performance with that of a similar new building. It also includes a scoring system for unreinforced masonry buildings.

In the detailed assessment procedures of this document a structural performance factor = 0.67 is suggested. This would appear to be appropriate notwithstanding that the resistance of the structure is assessed using actual material strengths.

## 6 CONCLUSIONS

Significant uncertainty exists in many of the parameters that could be expected to influence actual seismic performance of structures.

It has been concluded that, for many structures the seismic performance will be underestimated by any analysis that does not make some allowance for the observed difference between calculated and actual performance.

It has also been concluded that until more data has been collected on actual performance, sufficient to construct actual fragility curves, the correlation between actual and analysed performance must necessarily be set by judgement.

Indeed, although the science continues to develop, the prediction of seismic performance and good earthquake engineering remains very much an art.

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