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Inflated *%NBS* ratings in conventional seismic assessments due to unintentional scaling down of gravity demand

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ABSTRACT

For the seismic assessment of existing structures, it is common practice to analyse the structure under the combined effects of gravity and 100%ULS shaking demand and take the resulting minimum capacity/demand ratio as the seismic rating of the structure; the ubiquitous *%NBS* (New Building Standard) rating.

The *%NBS* rating should reflect the ability of the structure to resist the seismic demand, not necessarily the critical component utilisation. The paper argues that where *%NBS* scores fall below 100%, the Conventional approach may yield misleadingly Inflated *%NBS* scores due to consideration of overall component utilisations inclusive of gravity, as opposed to reflecting the %ULS shaking demand that can be resisted. Two factors are found to yield errors in a Conventional seismic assessment; (1) the *%NBS* assessment process being direct rather than iterative and (2) scaling down of the gravity demand at the same rate as the seismic demand. The error magnitude is sensitive to the relative level of gravity demand co-existent with seismic demand.

The iterative process to assess the *%NBS* can be time consuming and may make little commercial sense for much of the NZ building stock. An alternative practical approach is proposed to modify the Conventional *%NBS* by a factor which is dependent upon the gravity demand/capacity ratio in the structural member.

A significant number of already completed seismic assessments industry-wide may potentially have an Inflated *%NBS* rating while the Real *%NBS* calculated through the method proposed may potentially reduce the building grading using the MBIE grading system.

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1 INTRODUCTION

The Canterbury earthquake sequence of 2010 and 2011 drew attention to the possibility that a significant portion of the New Zealand building stock may not be able to resist moderate earthquake shaking. Regulatory changes following the earthquake sequence put responsibilities on building owners to assess the ability of their buildings to resist earthquake loads and act to strengthen these buildings if appropriate.

Numerous buildings throughout New Zealand have now been the subject of Detailed Seismic Assessments (DSA) to quantify their ability to resist earthquake demand. The seismic rating of the building is communicated using a *%NBS* rating which compares the expected performance of the building to that of a new building on the same site, designed to meet the requirements of the Building Code (Schedule 1 to the Building Regulations 1992). This process is familiar to structural engineers throughout New Zealand.

This paper discusses the common industry practice in assessing *%NBS* and highlights a possible confusion in the definition of *%NBS*. This confusion may result in relevant parties believing a building's seismic capacity, in relation to current code requirements, is greater than it really is.

A proposed improvement to the assessment of *%NBS* is presented for use during building seismic assessments to address this issue.

2 DEFINITIONS

The following terms used throughout this paper require definition:

Conventional %NBS – The rating given to a structure following a force-based elastic analysis where the *%NBS* is taken as the minimum capacity/demand ratio based on loading including 100%ULS shaking demand.

Real %NBS – The rating given to a structure following an iterative assessment process, where the *%NBS* represents the %ULS shaking demand that the structure can resist in combination with 100% gravity demand.

Inflated %NBS – A rating < *100%NBS* calculated using the Conventional approach, where the governing element is subject to gravity demand in addition to 100%ULS shaking demand.

3 COMMON INDUSTRY PRACTICE

The recommended industry best practice for the seismic assessment of existing buildings is given in The Guidelines (MBIE 2017). The Guidelines establish the use of *%NBS* rating as a means of assessing the capacity of the structure, as a whole or as individual elements, and comparing this ultimate capacity against the ULS shaking demand. Section A6.2 of The Guidelines contains a simple equation which is used routinely by structural engineers throughout New Zealand:

$$\%NBS = \frac{Ultimate\ capacity\ (seismic)}{ULS\ seismic\ demand} \times 100 \qquad (1)$$

The term 'ultimate capacity (seismic)' is defined in the Building Regulations 2005, clause 7 as "the probable capacity to withstand earthquake actions and maintain gravity load support assessed by reference to the building as a whole and its individual elements or parts."

For the purposes of seismic assessment, the ULS seismic demand is defined by The Guidelines as "100%ULS shaking demand determined from the appropriate version of NZS 1170.5".

The generic approach for undertaking a quantitative assessment, as shown in Figure A4.1 of The Guidelines, can be summarised as:

1. Identify the primary lateral load resisting systems.
2. Assess the global strength and deformation capacity of the building.
3. Determine the 100%ULS shaking demand.
4. Compare the capacity from ‘step 2’ to the demand from ‘step 3’ and report as a *%NBS* value.

By definition, the *%NBS* is concerned only with seismic demand. The demand is defined by the earthquake actions part (NZS 1170.5); not the general principles part (NZS 1170.0) which defines ULS combinations of actions which include the application of gravity and earthquake loads simultaneously. However, structural engineers recognise that the demand on a structure during an earthquake does not come only from the earthquake, but also from the gravity loads which are concurrently applied. The ‘ULS seismic demand’ term in Equation 1 is therefore routinely taken to be the demand arising from a ULS combination loading including the earthquake:

$$E_d = [G, E_u, \psi_E Q] \quad (2)$$

where G = permanent loads; E_u = ULS earthquake loads; Q = imposed loads.

Consider a hypothetical single storey steel portal building, where the portal forms the lateral load resisting and gravity load resisting system. For simplicity, consider only the moment demand and capacity, ignoring any axial force effects; $G + E_u + \psi_E Q$ gives the worst case demand; and that the capacity of the building is governed by the capacity of the portal columns.

Hypothetical gravity and seismic demands of 150 kNm each and member capacity of 200 kNm have been assumed and tabulated in Table 1 and following loading scenarios are discussed.

3.1 Case 1: 100% ULS shaking demand applied - Conventional

The ratio of capacity to demand gives a direct *%NBS* score when 100%ULS shaking demand is applied. The frame score is therefore 67*%NBS* for member capacity of 200 kNm and combined demand of 300 kNm.

The authors consider this to be the Conventional approach adopted by many practicing engineers using a force-based approach to assess the building rating. The Guidelines promote the use of displacement-based methods in preference to force-based methods, but force-based methods are still widely used by practicing engineers, particularly for more routine building assessments.

3.2 Case 2: 67% ULS shaking demand applied (shaking demand = assumed *%NBS* rating)

It would be logical to assume that a building rated as 67*%NBS* would be able to withstand 67% of the earthquake loading that a new building would be designed for, i.e. 67%ULS shaking; and that 67%ULS shaking demand should result in the capacity/demand ratio (C/D) being unity (1.0). From Table 1, the C/D is 0.8 as opposed to 1.0.

The C/D ratio is below unity, so the building cannot withstand the load combination that included 67%ULS shaking demand. Is it therefore accurate or logical to rate this building as 67*%NBS*?

Table 1: %NBS calculation for different loading scenarios

	Case 1 **100%ULS shaking**	**Case 2** **67%ULS shaking**	**Case 3** **100%ULS shaking**
	Conventional, Inflated *%NBS*	Seismic demand = *%NBS* rating	Real *%NBS*
Gravity demand, $M_G^* + M_{\psi_E Q}^*$	150	150	150
ULS shaking demand, M_E^*	150	100	150
Total demand, M^*	300	250	-
Capacity, ϕM_n	200	200	200
Capacity/Demand (C/D)	200/300 = 0.67	200/250 = 0.80	(200-150)/150 = 0.33
%NBS	67%	0.8x0.67 = 54% *	33%

* This demonstrates inconsistency of method when communicating capacity to resist seismic loading. It is not appropriate to multiply C/D ratio (0.80) by the %ULS shaking demand (67%) to calculate the *%NBS*.

3.3 Case 3: 100% ULS shaking demand applied – Real *%NBS*

The cause of the confusion with the Conventional *%NBS* rating presented above is obvious: earthquake loads do not act in isolation of gravity loads. In calculating this rating using Conventional approach (Case 1), the gravity effects get scaled down at the same rate as the earthquake effects. Therefore 67*%NBS* rating means the building can resist 67%ULS shaking demand, concurrently with 67% gravity loads. It does not mean the building can resist 67%ULS shaking in addition to 100% gravity loads.

A proportion of the capacity of the building is already utilised in resisting gravity (permanent and imposed) loads. It is therefore only the remaining capacity of the building that is available to resist the earthquake induced demand. If the *%NBS* rating is to reflect the ability of the structure to resist earthquake loads, then it should be calculated as follows as the Real *%NBS*:

Remaining capacity, $\phi M = \phi M_n - \left(M_G^* + M_{\psi_E Q}^*\right) = 200 - 150 = 50\ kNm$

$M_{E,100}^* = 150\ kNm$

C/D ratio $= 50/150 = 0.33 = 33\%NBS$

It is to be noted that remaining capacity of those elements only shall be calculated where gravity and earthquake loads have same force sense.

This rating is clearly significantly lower than that which was calculated previously using the commonly understood procedure, familiar to structural engineers throughout New Zealand. The discrepancy comes from the consideration of constant gravity loads which must not be scaled down with the earthquake loads where *%NBS* < 100%.

4 CONVENTIONAL VS REAL *%NBS*

The commonly adopted assessment procedure only establishes whether a building is above or below a certain capacity threshold. If 100%ULS shaking demand is applied and a C/D ratio, commonly taken as *%NBS* and named here 'Conventional' *%NBS*, of 0.80 is calculated, this does not prove that the structure can withstand 80%ULS shaking. It merely shows that the structure is not able to resist 100*%ULS* shaking. To learn the exact level of earthquake shaking that the structure can resist requires an iterative process whereby the %ULS shaking applied in combination with gravity loads is varied until a C/D ratio = 1.00 is achieved. That level of earthquake shaking is the Real *%NBS* rating for the structure.

Such an iterative process was laid out in the April 2012 edition of The Guidelines; Figure 6.1. A target *%NBS* is chosen at the start of the assessment process and a C/D ratio ≥ 1.00 is aimed for. If assessment results in C/D < 1.00, either retrofit is required, or a reassessment of *%NBS* is required. If reassessment is desired, a new lower *%NBS* rating is chosen, the earthquake demand is revised accordingly and the assessment process is iterated until C/D ratio ⪆ 1.00 . The *%NBS* rating is then reported.

This iterative process would be time consuming and may potentially have insignificant effect on the more refined *%NBS* in some circumstances.

The relative error between the Conventional and Real *%NBS* ratings is dependent upon the level of gravity induced effects in the building or part thereof. The axial demand in a diagonal brace of a lateral load resisting system (LLRS) would be negligible under gravity loads and there would consequently be very little difference between the Conventional and Real *%NBS* scores. Conversely, the moment demand at the knee of a portal frame could be appreciable under gravity loads and the error between the different *%NBS* scores could therefore be significant; with the Conventional score markedly over reporting the ability of the structure to resist earthquake demand.

The sensitivity of *%NBS* due to gravity loads is presented in the Figure 1. It shows that as the gravity demand increases, the gap between Conventional and Real *%NBS* widens. The chart is plotted for a specific situation where member capacity equals 100%ULS shaking demand. The exact ordinates of the chart would change depending upon the relative seismic demand level in a given member, but the trend for increasing error with increasing gravity demand is universal.

For this example, when gravity load demand is half the capacity of the structural member under scrutiny, the percentage error in the Conventional *%NBS* is approximately 25%. Real 50*%NBS* is 0.75 times the Conventional 67*%NBS*.

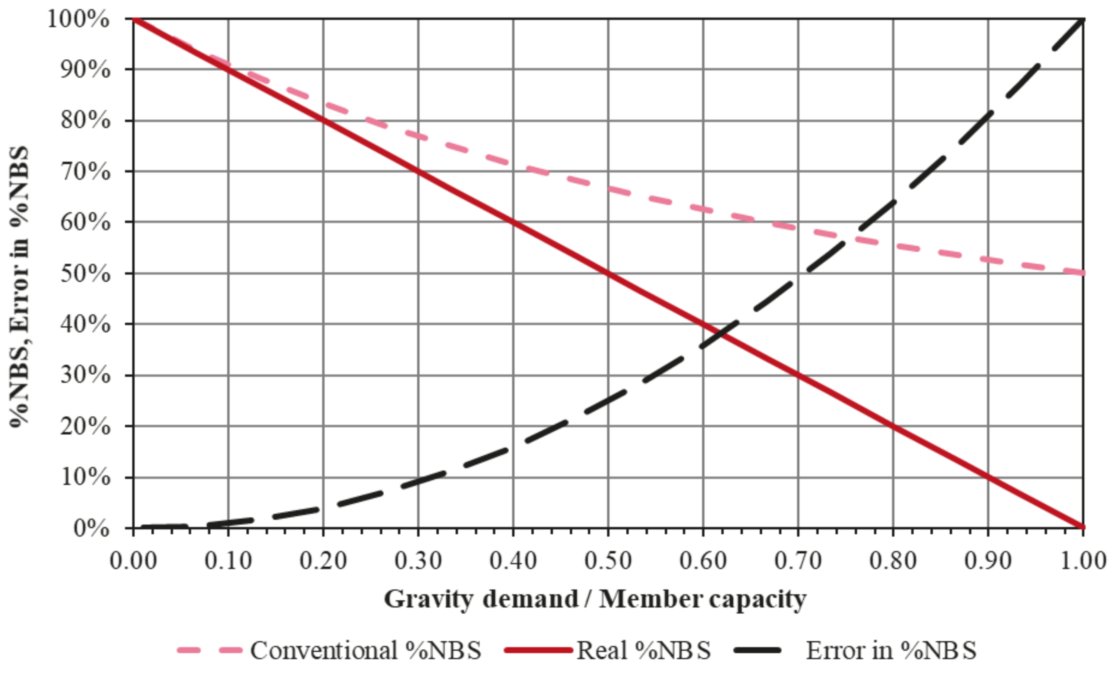

Figure 1: Effect of gravity induced demand on %NBS

5 PROPOSED METHODOLOGY

As discussed previously, a more correct method for calculating *%NBS* is iterative, time consuming and, depending on the design action (shear, moment, axial force) being investigated, may make little practical difference to decisions concerning the building. The difference in reported *%NBS* ratings between the two methods may be of little consequence where the *%NBS* is not close to the thresholds of 33*%NBS* or 67*%NBS*; or some other threshold relevant to insurers, local government, or the client. However, the legal and financial consequences of being a small margin one side or the other of a threshold can be significant.

The authors developed Figure 2 as a tool for shortcutting the iterative process but still improving the accuracy of the assessment process. The chart plots the results of a series of theoretical *%NBS* assessments with varying relative levels of gravity and earthquake demand. For different levels of gravity utilisation, the Conventional *%NBS* scores calculated as in section 3.1 are plotted against the Real *%NBS* calculated in accordance with section 3.3. This chart can therefore be used to convert a Conventional score into an approximation of the Real score, based on the level of gravity demand within the element under consideration.

A proposed methodology for improving the assessment process is now presented.

1. Conventional *%NBS*: Calculate the Conventional *%NBS* as described in Section 3. *%NBS* = capacity / ULS demand, where ULS demand includes gravity and 100%ULS shaking demand.
2. Gravity demand: Calculate the demand induced by gravity loads when the earthquake occurs, i.e. demand from $G + \psi_E Q$.
3. Real *%NBS*: Use Figure 2 to approximate the Real *%NBS* based on the level of utilisation (D/C) under gravity demand: $(M_G^* + M_{\psi_E Q}^*)/\phi M_n$. Select the appropriate curve for the calculated gravity induced utilisation. Reference the Conventional *%NBS* along the X-axis and read off the approximate Real *%NBS* on the Y-axis.

It can be noted from Figure 2 that the error between the different *%NBS* scores increases appreciably with an increase in the gravity induced utilisation. The error may be small and acceptable for low gravity demands. However, the error could be appreciable if the utilisation under gravity loads is significant.

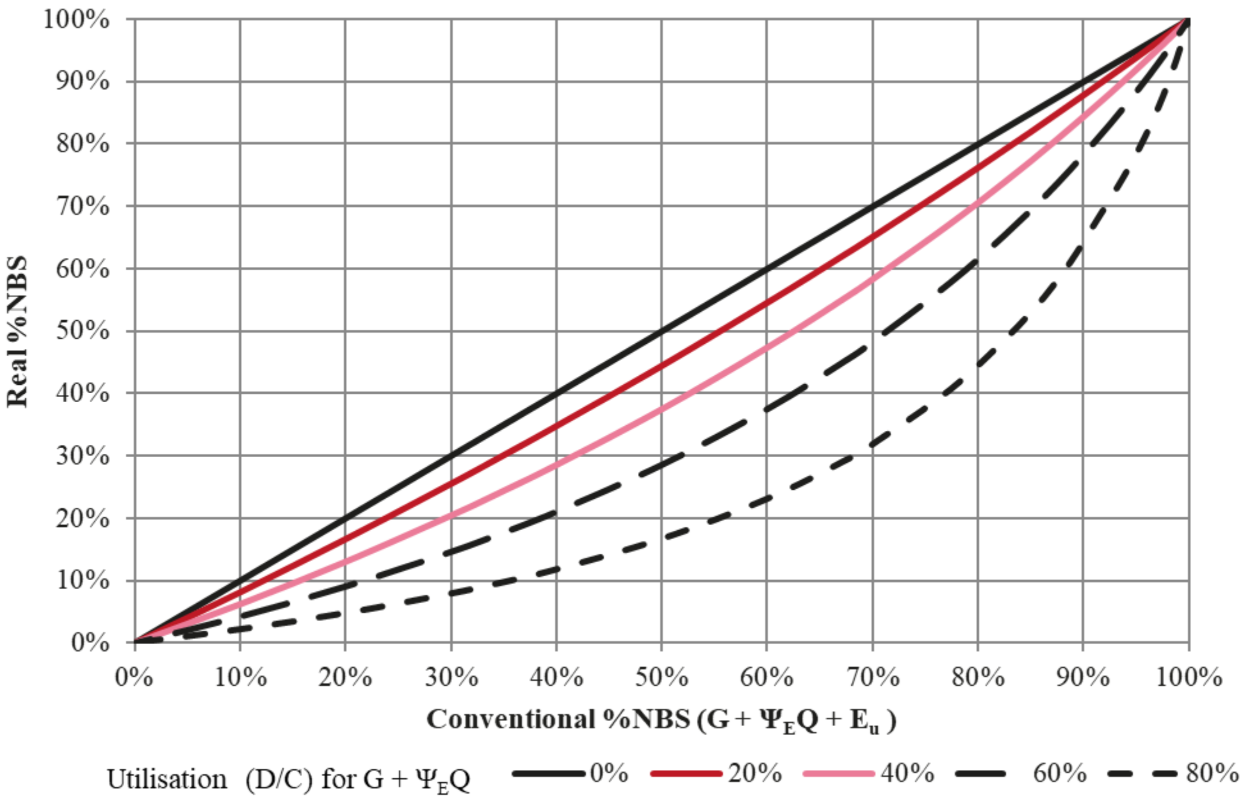

Figure 2: Conventional vs. Real %NBS for different levels of gravity demand

6 SIMPLIFICATIONS, APPROXIMATIONS AND COMPLICATIONS

The Real *%NBS* read from Figure 2 is only an approximation due to simplifications made. The proposed assessment method considers load effects in isolation. If combined axial and bending actions govern the assessment, then both axial and bending actions are assumed to increase at the same rate as %ULS shaking is increased.

The method inherently assumes that capacity is independent of demand. For instance, the method does not account for the effective loss of moment capacity which would come from an increase in axial load in a portal column due to an increase in earthquake loading. The proposed method, which essentially uses superposition of the gravity load and earthquake load, does not account for the different α_m factors associated with bending moment shapes in steel structures which can potentially be different for gravity and earthquake loads. For example, the shape of the bending moment diagram in a portal frame is different under earthquake loads than it is under gravity loads. The proposed method will not account for changes in this moment modification factor correctly.

The only way to accurately calculate the Real *%NBS* using force-based methods is via the iterative process described in Section 4 but the proposed methodology presents a pragmatic approach to improving the accuracy of the calculated *%NBS*. Engineering judgement must be used to decide whether the inherent simplifications in the method are consequential to the outcome, and whether the in-depth iterative process should subsequently be followed.

7 PRACTICAL EXAMPLE

A single bay steel portal frame of 30m span as shown in Figure 3 is considered. Calculations do not consider tension member forces and α_m is assumed to be unity; shear force is found not governing. The governing action is assumed to be column bending and elastic behaviour is adopted for simplicity.

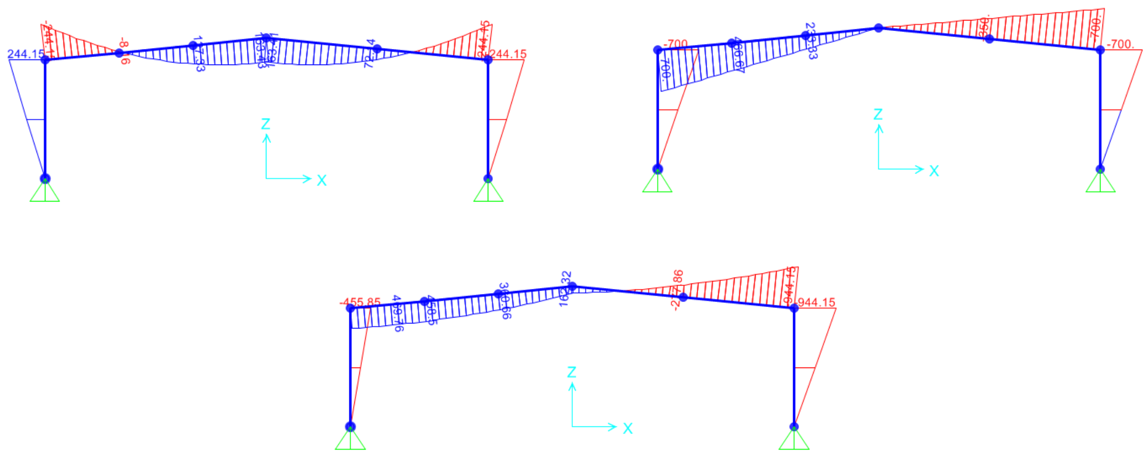

Figure 3: Example portal frame. $(M_G^* + M_{\psi_E Q}^*)$ *top left;* (M_E^*) *top right;* $(M_G^* + M_{\psi_E Q}^* + M_E^*)$ *bottom.*

Calculations for the assessment of this portal frame are tabulated in Table 2.

- Case 1: Full gravity and 100%ULS shaking demand applied. The resulting Conventional *%NBS* is 62%.
- Case 2: Full gravity and 62%ULS shaking demand applied. The resulting capacity/demand ratio is well under unity.
- Case 3: Full gravity loads and 100%ULS shaking demand applied like in Case 1 but takes the Conventional 62*%NBS* and gravity demand/capacity ratio of 0.40, then uses the Figure 2 to calculate the Real *%NBS* of 48%.
- Case 4: Full gravity loads and 48%ULS shaking demand. The resulting capacity/demand ratio is unity. This shows that the approximate method followed for Case 3 is confirmed by a more rigorous iterative assessment methodology.

Table 2: Calculations for example portal frame

		Case 1	**Case 2**	**Case 3**	**Case 4**
Method		Conventional		Real, approximate	Real, iterative
ULS shaking		100%ULS shaking	62%ULS shaking	100%ULS shaking	48%ULS shaking
$M_G^* + M_{\psi_E Q}^*$	kNm	245	245	245	245
M_E^*	kNm	700	434	700	336
Total demand M^*	kNm	945	684	945	581
Capacity ϕM_n	kNm	582	582	582	582

Demand/Capacity (D/C)	1.62	1.18	Gravity D/C = 0.42	1.0
Capacity/Demand (C/D)	0.62	0.85	-	1.0
%NBS	62%	0.85x0.62=53% *	48%	48%

* This demonstrates inconsistency of method when communicating capacity to resist seismic loading. It is not appropriate to multiply C/D ratio (0.85) by the %ULS shaking demand (62%) to calculate the *%NBS*.

8 COMMUNICATION

The underlying problem addressed by this paper is one of communication. Standard industry practice has been to report *%NBS* ratings calculated from applying load combinations including 100%ULS shaking and gravity. Many property owners, insurers, regulators, and engineers would understandably believe that, for instance, a 67*%NBS* building could withstand 67%ULS shaking, but this may not be the case across all the elements of a building. The industry needs to develop a clear consensus on what exactly the *%NBS* means and ensure that this is reflected in the public's understanding of the rating.

9 FURTHER WORK

Development of the proposed assessment methodology would benefit from a number of case studies for realistically dimensioned and loaded buildings. Different structural systems and building heights could be analysed to assess the relative error between the Conventional and Real *%NBS* ratings. This work would help inform practicing structural engineers which types of structures or elements within structures are most likely to require a more rigorous approach to assessing the *%NBS* than is routinely used in the industry today.

10 CONCLUSION

There is a wide and long-held misunderstanding of the meaning of *%NBS* rating within the building industry. In many cases, relevant parties may believe their buildings have been assessed to be able to withstand a higher level of shaking than they are in fact capable of resisting. The proposed method of assessment presented in this paper provides a means to more accurately assess the capacity of the building against new building standards, whilst shortcutting the time consuming, costly and potentially avoidable iterative assessment process. Engineering judgement must still be exercised during each assessment to consider whether the method's inherent simplifications are acceptable or whether a more accurate iterative process is still appropriate for certain assessments.

REFERENCES

MBIE, 2017. *The Seismic Assessment of Existing Buildings*.