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Rating Seismic Bracing Elements Analytically and by Pseudo-Dynamic Test

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RATING SEISMIC BRACING ELEMENTS ANALYTICALLY AND BY PSEUDO-DYNAMIC TEST

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SUMMARY

The seismic response of light timber framed systems has been shown to be inaccurately represented by the classical elastoplastic hysteresis rule used for time-history analysis. A new simple hysteresis rule has been developed which is easily fitted to reverse-cyclic test results. This rule is compared with the responses from recent pseudodynamic tests performed on a series of walls lined with plasterboard. A 'black-box' computer program has been developed to automatically rate the seismic capacity of bracing elements tested using reverse-cyclic loading by simulating their response to a range of design earthquakes. The ratings obtained using the new model and computer program are compared with the ratings calculated using the current New Zealand P21 rating method. A simple revision to the P21 rating method is proposed which gives ratings that are much closer to those obtained experimentally and analytically.

1. INTRODUCTION

A significant portion of New Zealand buildings are designed and constructed using the Code of Practice for Light Timber Framed Buildings not Requiring Specific Design, NZS 3604 [1]. This code is predominantly used by those from outside the engineering profession so simplified design methods are used for both wind and seismic loadings. Seismic design is carried out using the fundamental structural design equation 'resistance ≥ demand'. The bracing demand is estimated from a table of demands per square metre for specified construction styles and geographic regions or earthquake zones. These are multiplied by the floor or roof plan area to obtain the total demand in each of two perpendicular directions.

The required resistance is then provided by bracing elements which are placed into the building until the sums of the bracing element ratings match or exceed the demands in each direction. The bracing elements are distributed around the building in a prescribed manner in order to reduce the possibility of torsional failure. Bracing demands and ratings are both measured in Bracing Units (20 Bracing Units ≡ 1 kN) so that no decimal point is needed in the calculations.

BRANZ has recently completed a review [2] of the 1979 'P21' test and evaluation procedure [3] and its 1991 supplement [4] that are currently used to assess the resistance provided by bracing elements. A survey of the test and evaluation procedures used in other countries revealed some variations on the P21 test procedure but there is no commonly agreed procedure. The evaluation procedures, however, were limited to those which provided characteristics of the element which were able to be used for time-history analysis using either elastic or elasto-plastic elements.

Revised test and evaluation procedures were developed to provide more accurate ratings. These had the following four steps:

1. Conduct a monotonic racking test with one specimen to determine its ultimate strength.
2. Subject three more identically constructed specimens to a reverse-cyclic racking test.
3. Fit an analytical model to the responses of these specimens and use this to determine the mass which can be restrained by the specimen for a suite of design level earthquakes.
4. Conduct a pseudo-dynamic verification test with a fifth specimen to verify that it is capable of restraining the rated mass.

This paper describes the revised evaluation procedure (steps 3 and 4 above [7]) with brief reference to the test procedure (steps 1 and 2) which are detailed in a companion paper [5].

2. RATING PROCEDURES

The current 'P21' method of rating the resistance of bracing elements [4] uses a reverse-cyclic test. A typical specimen response is illustrated in Figure 1. Two of the three Figure 1 resistance forces (ie R and S) are used to calculate the earthquake rating, the other is used for a wind resistance rating. All three resistances are averaged over 3 identically constructed specimens to reduce the variability of the rating.

The earthquake rating is derived from the residual resistance, R (see Figure 1), converted to Bracing Units (1 kN = 20 Bracing Units) using the following equation [4]:

$$BU_{qu} = 20 \times K_4 \times R \tag{1}$$

where

20 converts the measured force in kN to Bracing Units

K_4 is a ductility modification factor.

The earthquake rating is reduced when the specimen 'ductility', μ, is less than μ = 4 which was used to derive the loads tabulated in NZS 3604. The ductility is defined as the ratio of the maximum test displacement, y, to the displacement, d, at half of the peak load. The rating is also reduced to a multiple of the service resistance, S, when the ratio of serviceability to ultimate resistance is smaller than the ratio of serviceability to ultimate load assumed when deriving the bracing tables within NZS 3604. The bracing rating is usually published as a rating per unit width of panel, rounded to the nearest 5 Bracing Units.

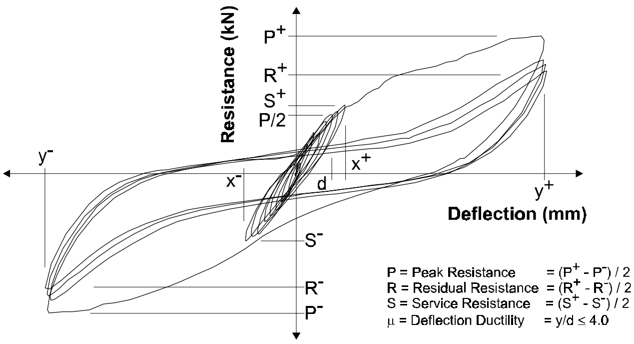

Figure 1. Test specimen response to the 'P21' test procedure [3].

The 'P21' test and evaluation procedures [2, 6] have been reassessed recently after a review of test and evaluation procedures used in other countries. As described in the introduction, the test procedure has been modified [4] to include an additional specimen. This is used to assesses whether there are any brittle failure modes. A second modification includes additional cycles (between x and y in Figure 1) to allow the specimen to be characterised more accurately and to allow the specimen to be rated at a smaller deflection if it fails before y is reached.

The specimen used to assess brittle failure modes is tested using a monotonic racking test. It is also used to evaluate the service displacement and to ensure that the strength of the overturning restraints and other components are not likely to fail during wind loading or a large earthquake acceleration pulse. This test is not necessary when this information is known from previous tests or is able to be calculated. The test procedure has since been amended [2, 6], with additional cycles to large displacements, in order to assess its response with stiff and weak restraints.

The racking test regime for step 2 was revised [2, 6] to both characterise the behaviour of the specimen more accurately and to make it an exploratory test. The original regime [3] required a target displacement to be estimated before the test was conducted. In practice this occasionally required a test to be repeated if the estimate was too optimistic. The test protocol is described elsewhere [6] so will not be fully described here.

The evaluation method is considered to be more rigorous than the original [3] which rated the specimen from its resistance during the fourth cycle to the estimated displacement (see Figure 1). The proposed method is based upon that developed by Dean et al [8]. This comprised fitting an analytical model and using the model to generate displacement spectra for a number of earthquakes. The mass which could be restrained by that element was then assessed from the least favourable design spectrum. Most of the process is able to be carried out in a computer program which conducts the analysis automatically. The complete procedure and its accompanying computer program are described later.

The pseudo-dynamic verification test is primarily used to ensure that the analytical model characterises the test specimen sufficiently accurately. A pseudo-dynamic test simulates the inertial response of the specimen restraining a mass on a shaketable. This test method exposes the specimen to almost the same displacement history as it would on the shaketable without requiring either the mass or the shaketable. It also has other advantages as will be described later. The verification is not likely to be needed once the analytical model is shown to be correct for specimens with a known range of characteristics.

3. ANALYTICAL MODEL

Most bracing systems degrade when subjected to reverse cyclic deformation. A number of methods have been used to fit the classic elastoplastic approximation (Figure 2b) to actual hysteresis loops of steel and concrete elements [9] since in real elements there is no distinctive point at which the onset of plastic deformation (yielding) occurs. The response of degrading elements (eg Figure 1) is even more poorly characterised by the elastoplastic approximation, particularly at large displacements.

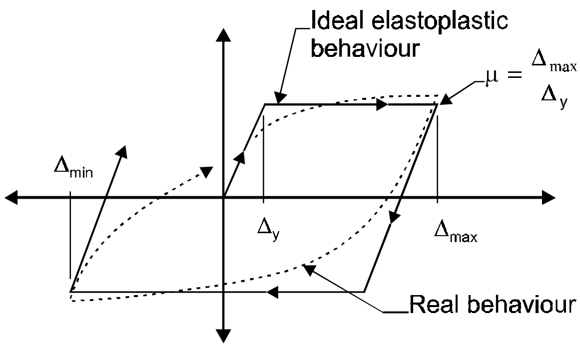

Figure 2 Elasto-plastic hysteretic behaviour approximation [9].

Many models have been developed to approximate the pinched response of timber elements. A simple method of generating realistic responses was developed by Dean [10] to eliminate the need for a complex set of mathematical rules. Dean's bar and spring model was revised as part of the current study (Figure 3) to simulate the response of a nail bearing on a timber substrate.

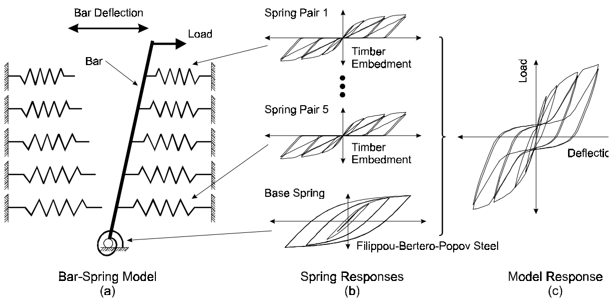

Figure 3. Revised bar-spring model.

The revised model uses five springs (Figure 3b) to model the embedment of the nail into the substrate. These develop slackness and decrease their reloading stiffness as they deform and follow a curved envelope to give a more realistic response at small displacements. The nail is represented as a rigid bar but has an in-elastic hinge at the base (modelled using the Fillipou-Bertero-Popov steel model [11]). The model produces a very realistic response (Figure 3c) which is defined by 7 characteristic values that are directly related to the shape of the hysteretic response.

4. AUTOMATED RATING PROCEDURE

Software has been developed to automate the process of characterising the test specimen responses and assessing their response to the level of earthquake ground motion required by the NZ Loadings Standard, NZS 4203 [12]. Non-linear time-history analyses are performed within the software, named BraceRate, using acceleration records from a suite of earthquakes. The earthquake records are natural records which were modified to generate acceleration spectra similar to the uniform risk spectrum for normal soils given in NZS 4203 [13]. The time-history analysis is carried out for a single degree-of-freedom oscillator using the constant acceleration step-by-step method [14]. A relatively small time-step (0.005 sec) is required for the analysis because the stiffness of the bar-spring model (Figure 3) is highly non-linear. Hysteresis loops, load-time records and displacement-time records are all able to be plotted on the screen.

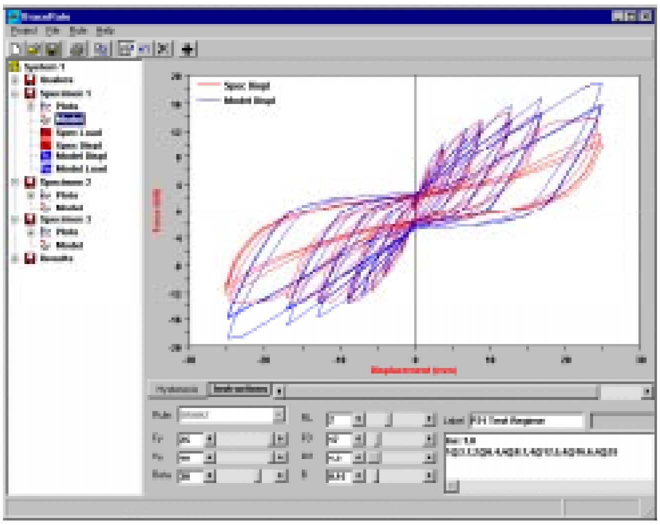

Figure 4. Fitting the bar-spring model to a test record using the BraceRate software.

To begin the procedure, the load-displacement records for the three reverse-cyclic test specimens are loaded into the BraceRate software. The bar-spring model is then fitted to each record in turn by altering the model characteristics at the bottom of the computer screen (Figure 4) until the shapes of the test and generated responses are similar. (These are plotted in different colours on the computer screen.)

Once the model has been fitted to each of the three specimens, a displacement spectrum is generated for each specimen subjected to each earthquake. The spectra are generated by incrementally increasing the mass in the single degree-of-freedom oscillator until the maximum displacement recorded during the time-history analysis exceeds a predefined displacement. These are plotted (Figure 5) with the displacements on the x-axis and the mass (in place of the period) on the y-axis once the analysis is completed. The mass able to be restrained by the specimen is then read off the plot at the maximum reliable test displacement.

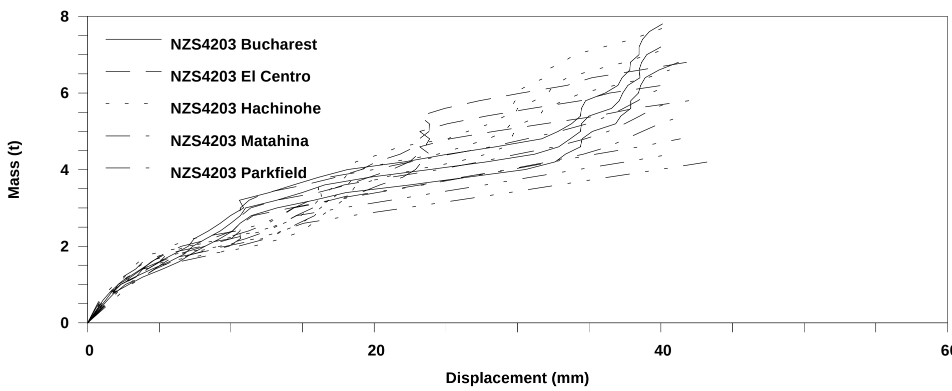

Figure 5. 'Displacement spectra' generated by the BraceRate software for the Figure 4 specimen.

Earthquake design loads in NZS 3604 [1] were derived from a draft version of the loadings standard NZS 4203 [12] for a building with a period of 0.4 seconds and ductility $\mu = 4$ [15]. The seismic design force, V, on a building of mass M is given by (from equation 4.6.2 (a) of NZS 4203):

$$V = C_h(T,\mu) \times S_p \times R \times Z \times L_u \times M \times g \qquad (2)$$

The other symbols used above are defined in equation 4.6.2 (a) of NZS 4203. Setting these to the values for NZS 3604 buildings, namely $R = L_u = 1$, $S_p = 0.67$, $g = 9.81$ m/sec^2, $Z = 1.2$ (Wellington) and $C_h(T,\mu) = 0.27$ (for $T = 0.4$ seconds, $\mu = 4$ and "intermediate" soil), gives:

$$V = 2.13\ M \qquad (3)$$

If the seismic design force is distributed among the bracing elements in proportion to their strength (ie they are all rated at the same displacement), the building force V and mass M in equation 3 can be replaced by the bracing element force, v, and a mass, m, that is able to be restrained by that element. Modifying equation 3 in this manner and converting the force, v, from kN to BU (Bracing Units) using the identity of 1 kN = 20 BU as defined previously, allows the bracing rating to be calculated from the mass m generated by BraceRate (ie from Figure 5) using:

$$v = 43\ m \qquad (4)$$

These simplistic assumptions are adequate for investigating the differences between the original and revised rating methods. However, they need further investigation because it is unlikely the individual element responses will be the same as the response of the whole system. Moreover, no account is made of the torsional response of the building.

BraceRate uses a suite of five earthquake accelerograms which were modified [13] so their elastic response spectra were similar to the elastic design response spectrum given in NZS 4203 for normal soils.

5. PSEUDO-DYNAMIC TESTING

Testing is acknowledged as the most accurate method of establishing how a structural system performs during an earthquake. Pseudo-static reverse cyclic tests have been used for many years to assess the deformation capacity of structural systems ranging from sub-assemblages to complete buildings. Shake-table tests have been used to both observe and verify system response under more realistic conditions. On-line, computer controlled or pseudo-dynamic testing is increasingly being used in Japanese and US laboratories to simulate the inertial response of a shake-table test.

In a pseudo-dynamic test, the test specimen is used in place of a numerical model in a dynamic time history analysis. The test equipment is similar to that used for a reverse cyclic test, with the addition of an interface between the physical specimen and the numerical analysis. The pseudo-dynamic test offers several significant advantages over the physically equivalent shake table-test:

- the duration of the test may be extended to allow more detailed observation of the specimen as the test proceeds;
- the building mass is simulated which makes it simpler to vary and reduces the danger for those observing the test;
- the damping is simulated so it may be used to model damping from sources external to the specimen;
- the fidelity of the reproduction of the ground motion is improved and specimens may be physically much larger because there is no shake-table to move at the dynamic rate; and
- the specimen may be tested so that it responds as though it is within a complete structure. The remainder of the structure may be modelled analytically or tested in another laboratory.

An adaptation of the pseudo-dynamic test has been developed at BRANZ to test degrading systems. The BRANZ test moves the specimen continuously throughout the test to avoid relaxation. The new method has been implemented for single test specimens and is shown to correlate very well with analytical results for linear systems.

6. MODEL VERIFICATION BY PSEUDO-DYNAMIC TESTING

Pseudodynamic tests were conducted on three full scale 6.4 m long wall specimens to assess the proposed rating system and the BRANZ analytical model. One wall was typical of internal wall construction and the other two of exterior wall construction. The internal wall specimen had two internal doorways, a segment of exterior wall at one end and segments of interior walls at the other end and adjacent to the central doorway. The exterior wall specimens each had two window openings, exterior wall segments at each end and an interior wall segment. The test specimens were identical to those tested by Thurston [16] except the internal wall had additional metal straps attaching the door trimmer studs to the foundation beam to make the wall strength in the weak direction similar to its strength in its strong direction.

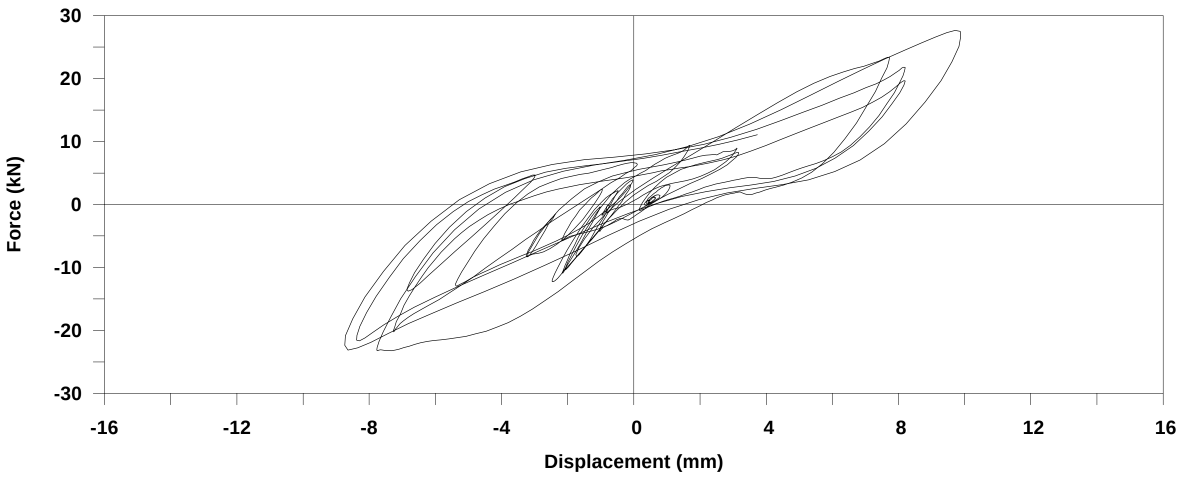

Figure 6. Pseudo-dynamic test response.

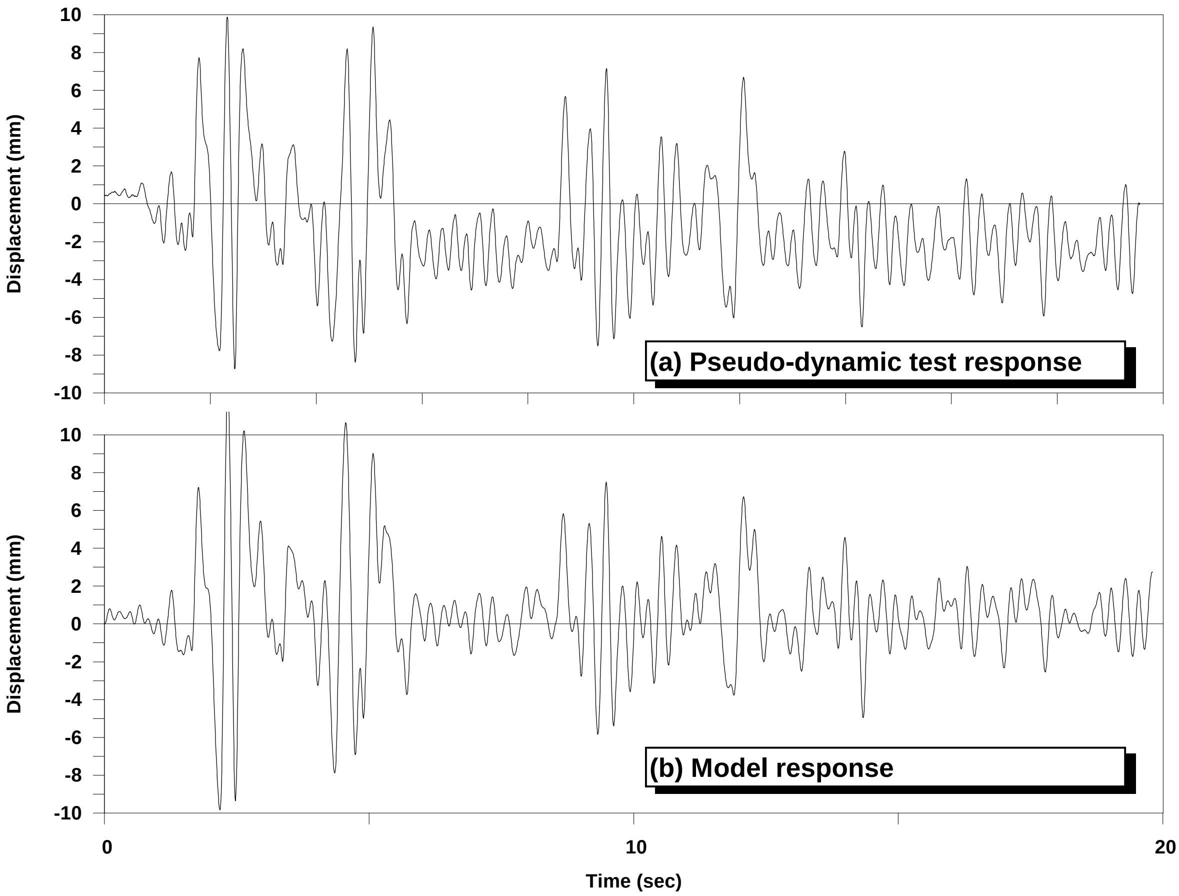

Figure 7. Interior wall responses with a mass of 5000 kg and subjected to 1.25 × El-Centro 1940 earthquake record (3.8 % damping).

An early version [10] of the BraceRate software was used to assess the seismic masses that the test specimens were capable of restraining. This matched Dean's bar-and-spring [10] model to the test specimen responses reported by Thurston (Figure 6) [16]. The mass was then assessed at a displacement of 16 mm (Table 1) using two earthquake records.

Specimen	Ultimate Strength (kN)	Initial Stiffness (kN/mm)	Earthquake Record	Rated Mass (kg)
Interior	27	5.7	1.25 × El-Centro 1940	5000
Exterior	14	3.0	1.25 × El-Centro 1940 NZS 4203 Matahina	3500 3500

Table 1 Specimen Ratings based on reverse cyclic tests.

The BRANZ analytical model was matched to the cyclic test specimen responses using the BraceRate software. The analytical model matched the cyclic response of the interior wall reasonably accurately up to 16 mm displacement (Figure 4) but was unable to match the exterior wall response for negative displacements or beyond 8 mm positive displacement.

The interior wall specimen was tested pseudo-dynamically with a mass of 5000 kg. A load-displacement plot for the test is given in Figure 6.

The displacement-time response of the pseudo-dynamic test specimen was very closely matched by a time-history analysis using the BRANZ model as shown in Figure 7.

The excellent agreement between the pseudo-dynamic test specimen responses (shown as points) and the mass-displacement responses predicted by the BRANZ model is illustrated in Figure 8.

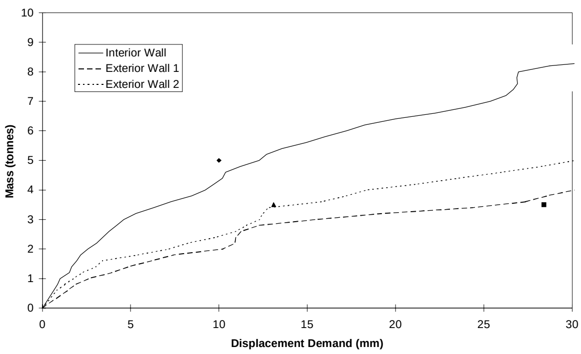

Figure 8. Mass-displacement demand plots for the three walls

7. COMPARISON WITH CURRENT P21 EVALUATION PROCEDURE

The newly developed rating method was used to check the ratings assigned by the current P21 evaluation procedure [4] described in Section 2. To do this, the mass that the plasterboard lined test walls are capable of restraining was evaluated for the suite of design earthquakes using BraceRate. The mass able to be restrained by the two specimens is plotted in Figure 9 for all five earthquakes and for displacement demands of up to 30 mm. The equivalent rating in Bracing Units is indicated on the right axis. This was calculated from the mass using Equation 4 (ie for a building with T = 0.4 seconds, a specimen ductility of μ = 4 and "intermediate" soil).

The ratings evaluated using the current P21 evaluation procedure are almost twice those evaluated using the new method. The ratings, evaluated using the current method at the 16 mm displacement cycles, are shown as points in Figure 9.

The most significant factors which lead to this major difference between the ratings obtained using the proposed and current methods are:

1. The current method assumes a natural building period of 0.4 seconds which would impose displacements of about 32 mm upon an elastically responding building. The inelastic displacement demand is expected to be greater than this because the natural period is within the transition zone between equal energy and equal displacement demands. This displacement demand is greater than most bracing elements are capable of sustaining in a single storey building. It may be acceptable for a two storey building when the strength is optimal in both storeys and half the drift develops in each but this situation will seldom occur in practise.

2. The current method assumes a structural ductility factor of μ = 4. The method of calculating this based upon a “yield” displacement at half of the peak load is open to question. This is discussed further below.

3. The proposed method rates the specimen at a “maximum reliable displacement” rather than the maximum test displacement. This may be unnecessarily conservative but the reserve displacement capacity is needed to provide life-safety protection against a “maximum credible earthquake” is not currently quantified in the Loadings Standard, NZS 4203. (This could be considered to be provided in concrete and steel structures by the definition of available ductility, $\mu_a = \Sigma\mu / 8$, proposed by Park [9].)

4. The viscous damping used with the proposed method (5 percent of critical, based on the initial stiffness) may be insufficient to account for damping provided by the additional “non-structural” walls that are normally present but not specifically detailed or counted as bracing elements. (The damping needs to be increased to thirty percent of critical to increase the mass to the levels plotted in Figure 9. However, it is unlikely that this level of damping will be developed by the other walls in a normal building.)

5. The Figure 9 comparison rated the whole wall as a single bracing element. Where only the full height segments of the walls are assumed to act as bracing elements, the bracing ratings for the exterior and interior walls reduce to 90 and 275 Bracing Units respectively (using the ratings published in the manufacturer’s literature). These are closer to the ratings calculated using the new method but this reflects the greater restraint and therefore strength provided by the return walls rather than “damping” provided by additional walls. (This damping has probably already been included in the nominal “5 percent” which isn’t attributed to a physical mechanism.)

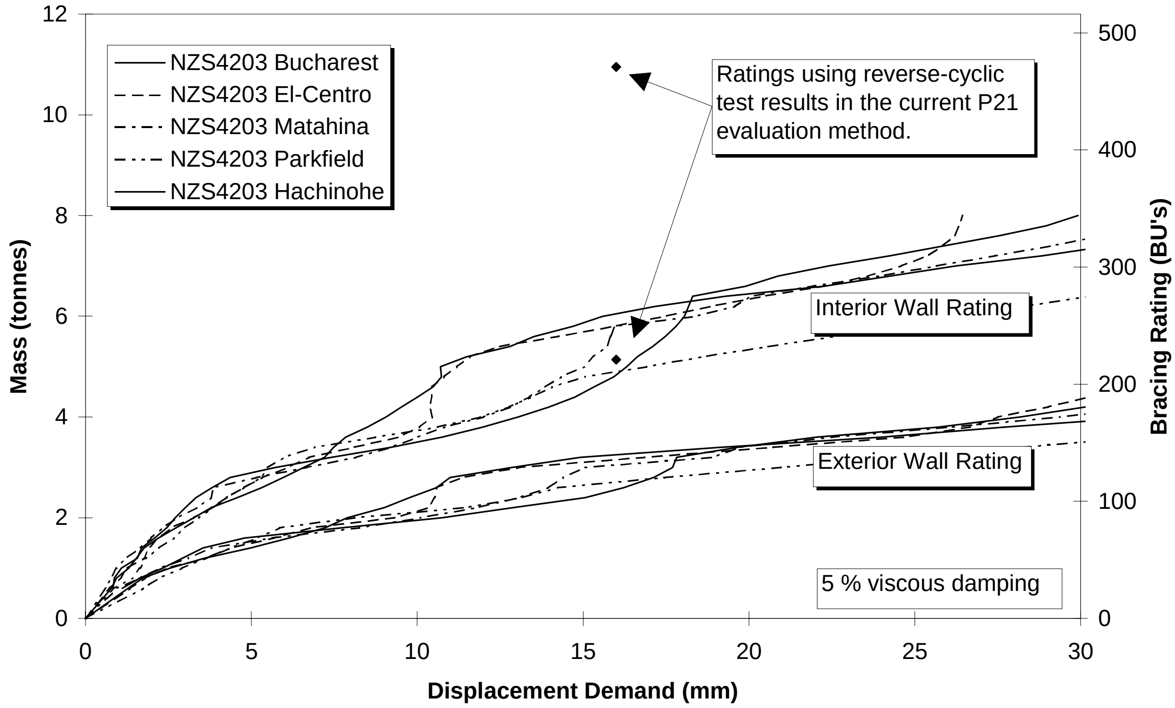

Figure 9. Mass-Displacement ratings for NZS 3604 Zone A.

The definition of yield given in the second factor above needs further examination because a modification to this definition could provide better correlation between the current evaluation method and the results obtained using the proposed method. This form of modification would simplify the re-evaluation of existing test results and allows it to be used with the inelastic NZS 4203 spectra with their implicit elastoplastic "ductility".

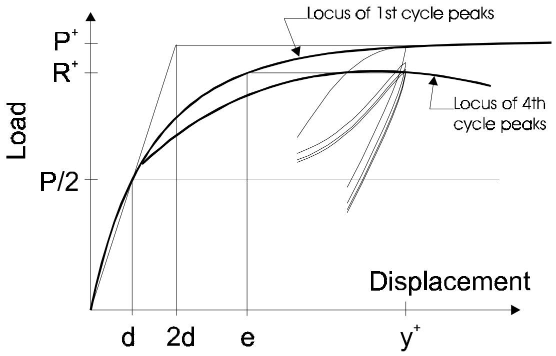

Figure 10. Definitions of yield for use with the current 'P21' rating procedure

The current definition of $\mu = y^+/d$ (Figure 10) was "… adopted as an interim measure while further investigation is continuing …" [4]. A "plastic" strength of P/2 may have been more appropriate than R for use with elasto-plastic response spectra but this could appear excessively conservative because the residual strength, R, is always greater than P/2.

The ductility could be reduced to $\mu = y^+/2d$ or $\mu = y^+/e$ (Figure 10) without significantly increasing the complexity of re-evaluating ratings for existing systems. Bracing ratings for the two walls calculated using the three different methods of calculating ductility are compared with the Figure 9 time-history ratings (ie, the average rating for the 5 earthquakes) in the following table:

Wall	$\mu = y^+/d$	$\mu = y^+/2d$	$\mu = y^+/e$	Time-History
Interior	470	445	327	250
Exterior	220	210	160	130

Table 2 Bracing Ratings from the different evaluation methods

The ratings calculated for $\mu = y^+/e$ are 25 to 30 percent higher than those produced by time-history analysis. This more modest difference is more likely to represented by the strength difference between that of an isolated test element and the same element attached to and strengthened by its surrounding walls.

Comparisons need to be undertaken for a range of bracing materials and systems because plasterboard is generally stiffer but weaker than wood- and cement-based lining materials.

8. CONCLUSIONS

A new method of rating the resistance of bracing elements has been proposed for use with NZS 3604. A new analytical model has been developed which accurately models the load-displacement responses of these bracing elements. A continuous pseudo-dynamic test method has been developed and implemented. Time-displacement responses of pseudo-dynamic tests on three specimens have been accurately predicted by the analytical model.

The current P21 rating procedure has been shown to be dangerously unconservative when compared with the new method. A simple modification to the current method has been proposed but still needs to be verified by the more rigorous method for a wider range of specimens.

9. ACKNOWLEDGMENTS

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