Whole house seismic racking evaluation

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ABSTRACT: In New Zealand the racking strength of house bracing walls is currently determined from the BRANZ P21 test. House designers sum the racking strengths of all walls, using published data from sheathing manufacturers' wall systems, to ensure that actual house earthquake strength exceeds the demand loading stipulated in NZS 3604. Continuity of construction is simulated in the P21 test by a partial end uplift restraint. A revised BRANZ test and evaluation method called EM3 uses a far greater end restraint and multiplies the measured racking strength by three factors (F1, F2 and F3) to give the evaluated seismic resistance.

The paper explains the background to these factors and the additional provisions and recommendations. F1 was obtained by computer earthquake simulation to ensure houses would not deflect excessively under design level earthquakes. F2 is a systems effect factor based on racking tests on a full scale house and laboratory specimens. F3 is a factor used for specific construction and situations.

The paper also details house torsional analysis computer simulations, and outlines the current BRANZ test program on half-scale house assemblies which is designed to quantify the F2 factor and confirm the torsional analysis findings.

1 DESCRIPTION AND STATUS OF EM3

The BRANZ EM3 test and evaluation method (BRANZ 2004a) is intended to replace the BRANZ P21 method (Cooney and Collins 1979). In both methods the bracing strengths of lengths of wall (between windows/doors etc) is determined by testing the isolated wall under a cyclic racking regime and factoring the forces resisted such that the results are consistent with the basis under which the NZS 3604:1999 design loads were determined. This process is illustrated in Figure 1(a).

The P21 test method is called up by NZS 3604 (SNZ 1999). This standard is itself cited by the BIA as an "acceptable" solution for house design. BRANZ has submitted the EM3 method to Standards New Zealand for consideration for adoption into the next revision of NZS 3604. Until it is called up by NZS 3604, EM3 has no legal basis.

The EM3 method has a companion document called the EM3 "application" document (BRANZ 2004b) which, amongst other things, provides recommendations on applying bracing ratings determined by EM3. It is hoped that some of these recommendations will be also called up in the next revision of NZS 3604.

2 WALL END UPLIFT RESTRAINT

If bracing panels are isolated from the surrounding structure and laboratory tested under horizontal racking loads without any rocking restraint, they will generally uplift off the foundation beam at relatively low loads at the panel tension end (i.e., rock about one end of the panel) as shown in Figure 1(c). However, when panels are built into a house, the wall sheathing, framing continuity and gravity effects provide some resistance to uplifting, thereby significantly increasing the racking strength. To simulate wall continuity in actual buildings, both the P21 and EM3 test specimens incorporate a partial end uplift restraint to partially resist wall 'rocking'. This uses three nails in shear in the P21 method.

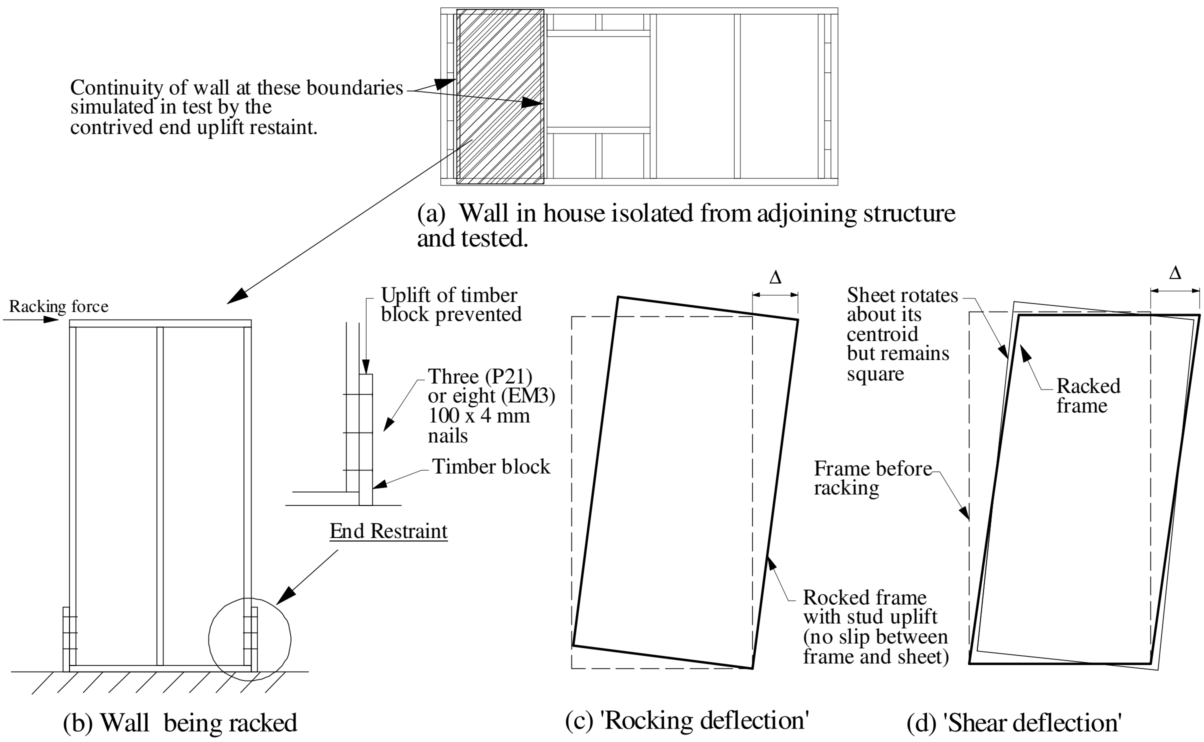

Figure 1: Illustration of a racking test

Based on tests by Thurston (1993) on long walls with openings, and a full scale house (Thurston 2003) it is expected that walls within buildings will generally have significantly greater uplift restraint than provided by the P21 uplift restraint in nearly all situations except where bracing walls terminate at a doorway. Axial load of roof, ceilings and perhaps a storey above is expected to significantly increase wall uplift restraint. Thus, the uplift restraint in the EM3 test has been increased to 8 nails which is expected to provide a more realistic (but still conservative) estimate of average panel uplift restraint. The additional uplift restraint is expected to result in a higher bracing rating for stronger sheathing systems, whose bracing resistance currently tends to be governed purely by the P21 '3-nail' end restraint rather than the shear strength of the sheathing fastening (Figure 1(d)). Currently strong brittle sheathing systems can appear to exhibit ductile behaviour in the P21 test, which is actually due to the low shear yield strength of the P21 uplift restraint, rather than the ductility of the wall sheathing itself. This apparent ductility is unlikely to be replicated in a real structure. In this regard the '3-nail' restraint may have unrealistically benefited brittle systems (such as plasterboard) relative to tougher systems (such as plywood or fibre cement).

3 EM3 TEST RACKING REGIME

Wall systems in EM3 tests are subjected to a cyclic displacement regime shown in Figure 2. The first and third cycle peak points shown in Figure 2 are obtained and used in the evaluation to determine a bracing rating. The bracing rating attributed to the wall system is the average from three specimens.

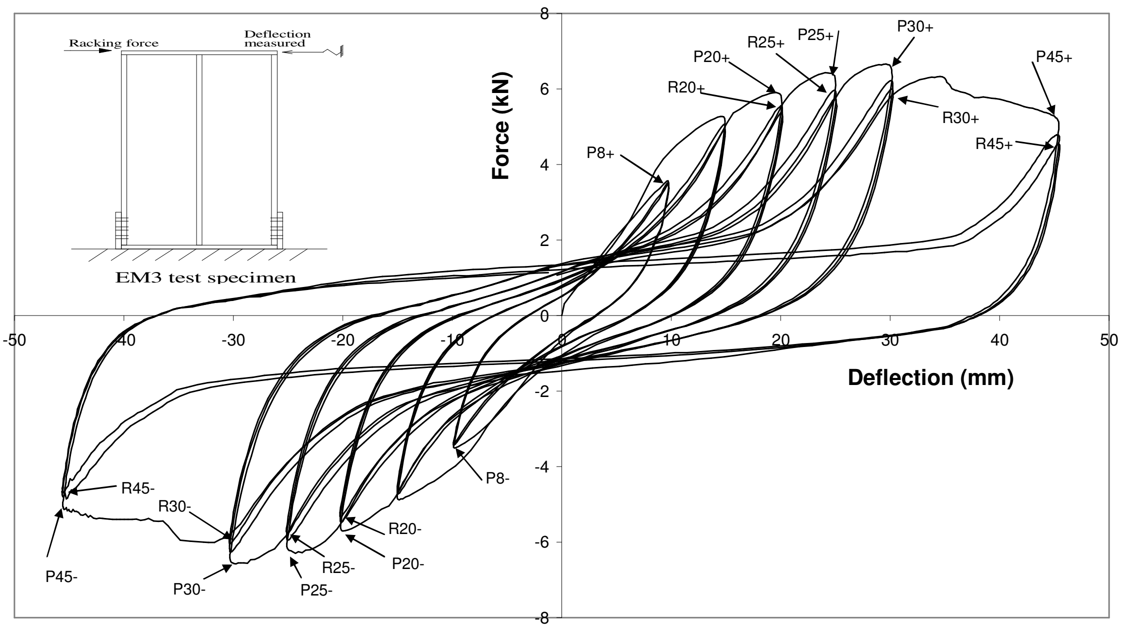

Figure 2. Hysteresis loops from an EM3 test

4 BASIS OF EM3 EVALUATION AND F1 FACTOR

The basis of the evaluation method to derive earthquake bracing ratings from test hysteresis loops was a computer study where buildings were analysed by inelastic time history seismic analysis using the Ruaumoko 2D software (Carr 2000). Full details are given by Thurston and Park (2004).

The analyses used a suite of earthquakes which had elastic spectra corresponding to the design elastic spectra of NZS 4203 (SNZ 1992) and also DZ 1170.5 (SNZ 2004). Computer models of single and two storey buildings, with wall elements having pinched hysteresis loop shapes defined to cover the usual range of sheathed timber framed wall behaviour, were analysed under excitation from these earthquakes. For each modelled structure, a series of computer runs was performed to compute the maximum deflection, Δ_{max}, for a range of the seismic weights, W. The third cycle peak strength, R, of the modelled loops was obtained from the loop shape for each Δ_{max}, which enabled a W/R versus Δ_{max} plot to be obtained.

As the first step to evaluate the bracing rating, BRANZ arbitrarily set the design seismic racking strength of a test wall to F1 x R where R is the peak wall strength after three cycles to a selected deflection, Δ. The challenge was to determine F1.

The tabulated seismic design loads given in NZS 3604 for Zone A were based on the formula 'demand load = 0.241 x W' (Shelton 2005). This originated from the loadings in NZS 4203 assuming a ductility = 3 (Thurston and Park 2004).

Setting the earthquake resistance (F1 x R) to the demand load (0.241 W) gives F1 = 0.241 x W/R. The results of the computer analysis provided W/R as a function of Δ_{max}, and thus F1 was obtained as a function of Δ_{max}. Additional factors F2 and F3 were introduced as discussed below.

5 SYSTEMS EFFECTS – F2 FACTOR

Houses tested under racking load are stiffer and stronger than predicted from the sum of isolated wall panels due to the holistic response of the complete system (Thurston 2004). This is due to load sharing and composite action, of both the structural and non-structural elements. House roof and upper floor weights resist wall panel 'rocking' action. In addition, the taped and stopped joints between plasterboard sheet lining at both wall ends and ceiling are expected to significantly increase wall racking strength, not only due to the increased uplift restraint at wall ends but also by changing the deformation mechanism from the sheet rotating about its centroid to close to pure translation along the bottom plate (Figure 1(d)). This is as illustrated in Figure 3. The sheet to bottom plate connection strength is also enhanced by the zone under the windows.

Thurston (2003) tested a full-sized single storey house under slow cyclic load. The house walls were lined with paper faced plasterboard and the cladding was lightly nailed weatherboards (which added little to the house racking strength). The measured house strength was 50% greater than the sum of all component walls as tested by the P21 test. However, the house was not torsionally susceptible and had no doorways in the direction in which it was tested. Thurston attributed the greater strength of the full house to 'systems effects' and considered it likely to be mainly due to the 'taped and stopped' plasterboard joints.

Collier (2005) performed a series of racking tests on 3 m high x 3 m wide walls. These were fully restrained against rocking. By comparing the strength of walls with and without end corner continuity and wall/ceiling junctions, Collier derived F2 factors which exceeded 2.0.

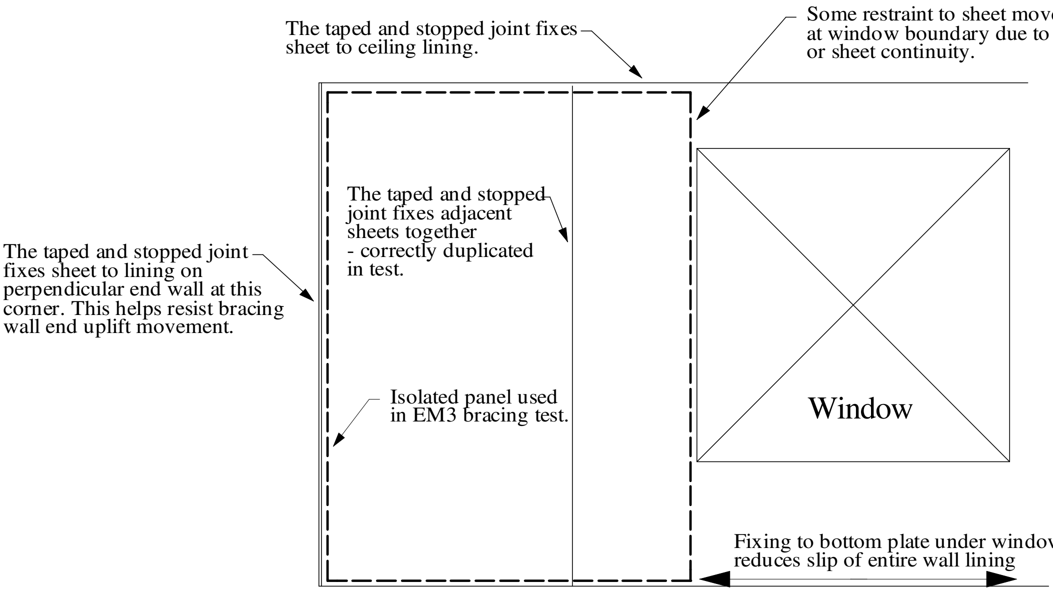

Figure 3. Restraint of wall lining in real buildings

Earthquake bracing ratings derived using EM3 are factored by F2 = 1.5 for the reasons given above (enhanced stiffness and strength due to 'systems effects'). This is also justified by noting the good historic performance of post-1978 New Zealand style houses under large earthquake events.

6 F3 FACTOR

Systems effects are expected to be lower where rooms are not lined on both the walls and ceilings with plasterboard with taped and stopped plasterboard joints or other lining systems having joints of comparable strengths using. For these situations F3 = 0.8, which effectively reduces F2 to 1.5 x 0.8 = 1.2.

An F3 factor of 0.5 is used for bracing walls in single storey or upper storey walls which terminate at large openings or wall free ends and do not have hold-down straps at these locations. This is because the '8-nail' end uplift restraint used in the EM3 test gives a better end fixity than can be expected in these circumstances (Thurston 1993).

7 COMPATIBLE DEFLECTIONS

Most houses in New Zealand are constructed with timber-framed walls and have a variety of wall lengths, sheathings and fastening systems. The result is many different bracing systems, each of which achieves its peak bracing resistance at different deflections. This incompatibility precludes simple addition of peak strengths to obtain total lateral resistance. For instance, plasterboard (without fibreglass in the core) wall bracing systems generally reach their peak resistance at 10–15 mm wall shear deflection and then drop in strength, while plywood systems continue providing dependable and increasing resistance up to approximately 50 mm deflection. EM3 addresses this problem by requiring that the bracing resistances be assessed in a small deflection band (20–30 mm) to ensure (at least moderate) compatibility between bracing wall systems in houses.

8 SPECIFIC DESIGN OF NON-NZS 3604 BUILDINGS

Non-NZS 3604 type buildings do not necessarily have the bracing wall ‘continuity’, nor the total-building ‘systems effects’, nor the damping inherent in NZS 3604 buildings.

To use EM3 bracing results the non-3604 buildings need to be designed to ensure that the predominant displacement mode is due to slip between sheathings and framing and that other brittle failure mechanisms are suppressed. Special end uplift restraints should be designed to resist panels overturning if the continuity features that usually exist in NZ 3604 buildings are not present.

Panel racking over-strength needs to be considered and other elements designed for the associated greater racking force using a capacity design procedure. The end uplift restraints, chords and sheathing need to be designed for this over-strength. A suitable over-strength factor needs to be chosen by the designer. Clause 5.2.4 in NZS 3603 (SNZ 1993) recommends an over-strength factor of 2.0.

Designers must ensure that bracing wall sheathing is fixed to framing on all edges, the top and bottom of the sheathing are fixed to a diaphragm at the (roof/ceiling/floor) and the bottom plate is held down and prevented from sliding.

The EM3 test will ensure that walls designed with the above procedure have an effective ductility of at least 3.0 at the assessed bracing deflection.

Published EM3 earthquake bracing ratings have been factored by F2=1.5. This is to simulate ‘systems effects’ and the strength enhancement in houses having taped and stopped plasterboard joints on all building interior walls. This is discussed in Section 5. The designer should modify published test EM3 earthquake strengths to reflect their assessment of an appropriate systems effect factor for the building being designed. For many engineered structures this will result in a downgrade of published ratings by 1.5.

Designers should be aware that the walls were assessed at ultimate limit state deflections between 20 and 30 mm and should design other aspects of the buildings to accommodate this movement.

9 OTHER ASPECTS

The EM3 “application” document (BRANZ 2004b) provides guidance and recommendations on the following:

- Suitable end hold-down straps at large openings or bracing wall free ends.
- Test procedure for bracing walls constructed on either timber or concrete foundations.
- Extrapolation of test results to walls of different length or height.
- Extrapolation of P21 bracing results to EM3.
- Minimum information to be provided by manufacturers.
- Distribution of bracing elements to alleviate torsion/diaphragm problems.

10 CURRENT PROJECT – COMPUTER SIMULATION OF TORSION EFFECTS

If the centre of rigidity of a house does not align with the centre of mass, then a house is expected to twist in an earthquake which will exacerbate maximum deflections in the less rigid portions and increase horizontal diaphragm stresses. NZS 3604 contains some minimal requirements on bracing distribution, which is intended to limit torsional effects in houses to satisfactory levels.

BRANZ is performing a desk computer study using Ruaumoko non-linear time history analysis, which considers various single and two-storey house designs and bracing wall distributions to examine whether torsion is likely to be a problem. A typical model is shown in Figure 4. The assumption is that the horizontal diaphragm is rigid. Slip at the diaphragm wall junction can be included in the model by altering the stiffness of the wall springs in the model. (With flexible diaphragms, load distributions into walls are usually based on a tributary area basis.)

Preliminary results suggest that torsion is unlikely to be too much of a problem with most realistic bracing wall distributions.

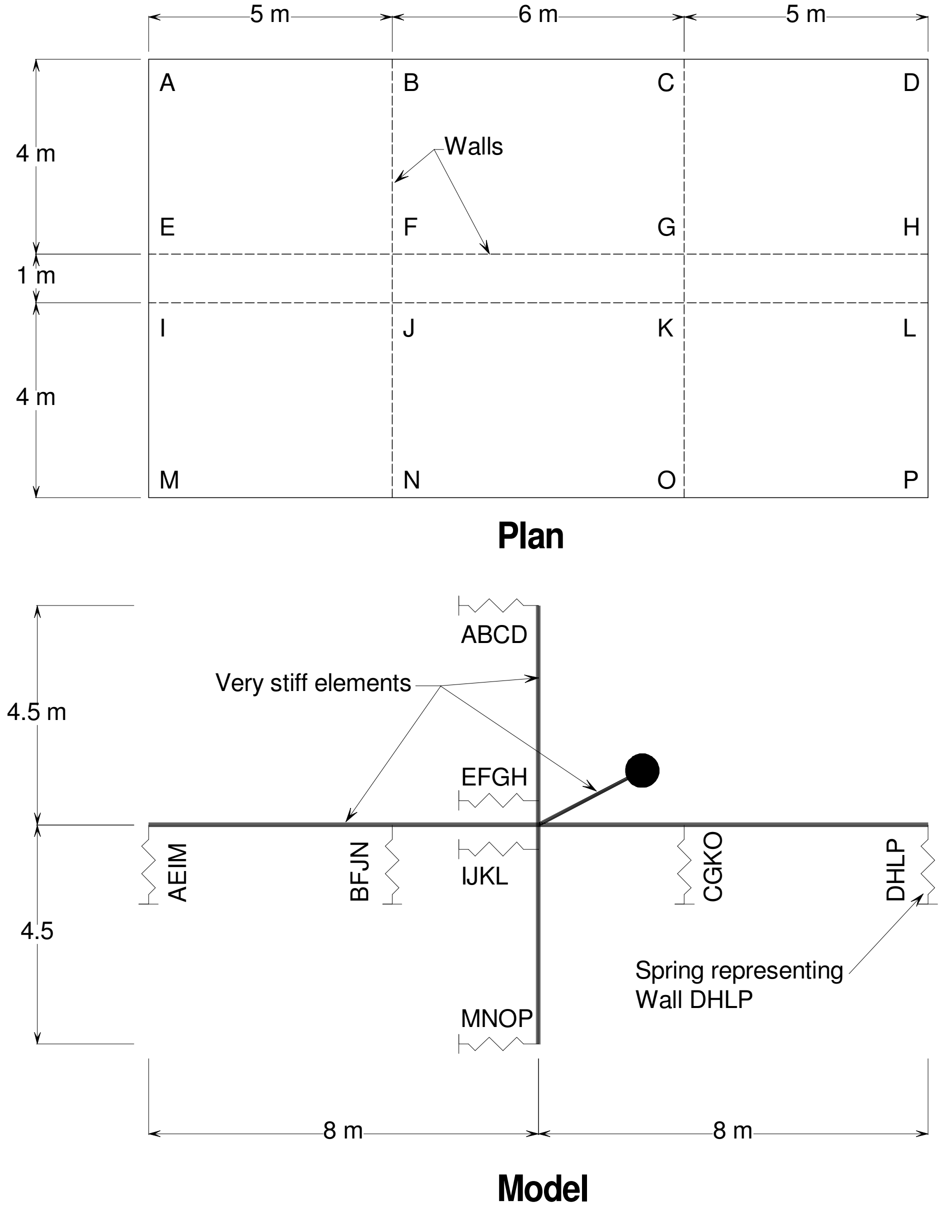

Figure 4. Pancake torsion computer model

11 CURRENT PROJECT – QUALIFICATION OF SYSTEM EFFECT FACTOR, F2.

Racking testing will shortly be underway on a prototype sized room 6.6 m x 4.2 m complete with plasterboard ceiling. However, the construction will be at half height/length/width with prototype sized framing/sheets thickness/nail size and spacing. The proposed test construction is shown in Figures 5 and 6. Theory has been developed to show the model will have the same strength per unit length as the prototype, although this will be verified by testing individual wall elements. Testing may be extended to half-scale constructions of complete houses.

The following constructions will be tested:

(1) Plasterboard on room interior and no joints taped and stopped.

(2) As per (1) but all joints taped and stopped. This wall is expected to be governed by shear strength, not rocking strength, and so strength enhancement is due to the different sheet rotation mechanism.

(3) As per (1) but MDF also to exterior.

(4) As per (2) but MDF also to exterior. This wall is expected to be governed by rocking strength, not shear strength, and so strength enhancement is due to the different sheet rotation mechanism and increased rocking restraint.

(5) Window (see Figure 6) replaced with a door and wall returns added. Plasterboard on room interior and exterior with with all joints taped and stopped. No hold-down straps are used at doorway opening.

(6) As per (5) but use straps at doorway opening.

The testing will enable the F2 factor to be derived for these typical constructions outlined above. The study will also to investigate the effect of omitting/using hold-down straps at large openings.

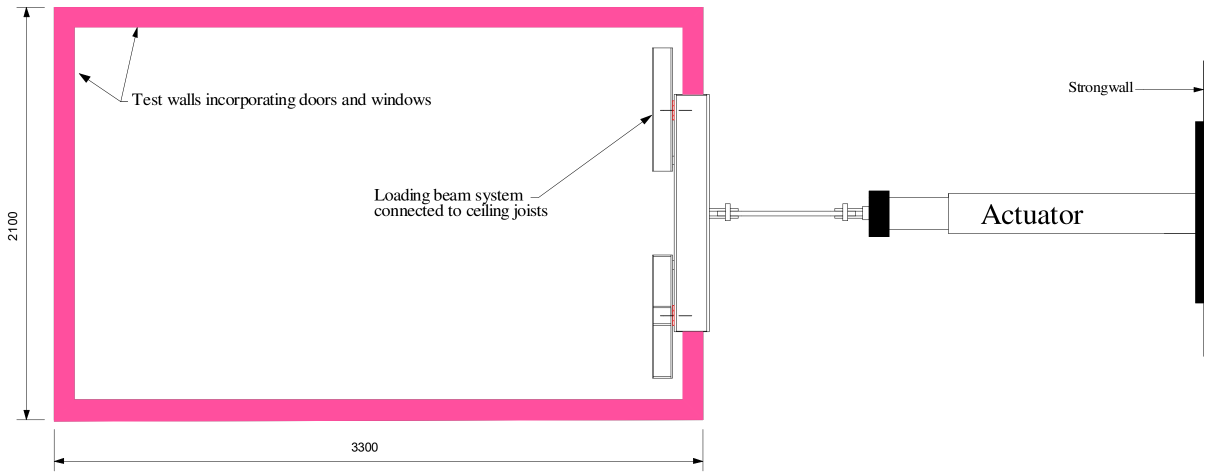

Figure 5. Room racking test – foundation beams and loading system

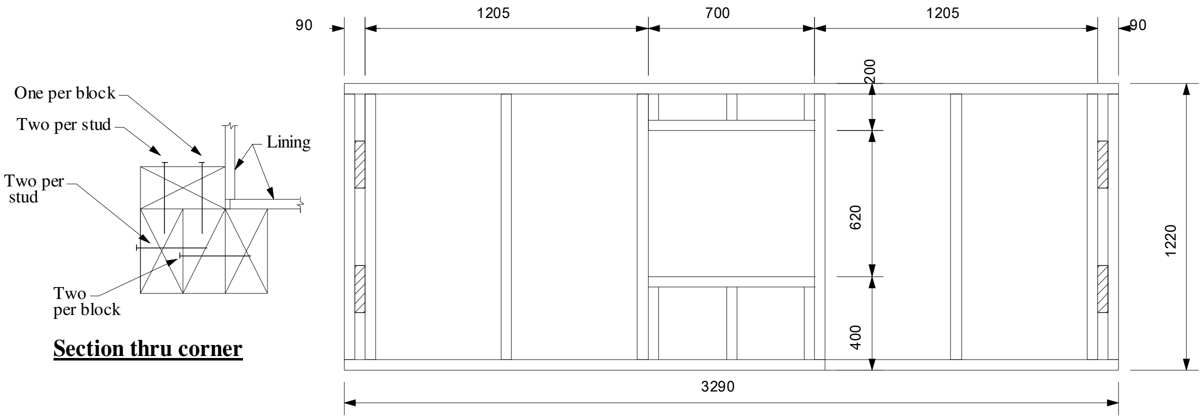

Figure 6. Room racking test – timber framing side walls

REFERENCES:

BIA 2001. The New Zealand Building Code handbook and approved documents. Building Industry Authority. Wellington, New Zealand.

BRANZ 2004a. Determination of bracing rating of bracing walls. BRANZ test and evaluation method EM3. BRANZ, Judgeford, Wellington.

BRANZ 2004b. Application of EM3 evaluated wall bracing ratings. BRANZ test and evaluation method EM3. BRANZ, Judgeford, Wellington.

Carr, A.J. 2000. Ruaumoko computer software user manual. University of Canterbury, Christchuch.

Collier, P.C. 2004. Post-earthquake performance of passive fire protection systems. BRANZ Study Report under preparation. Judgeford, Wellington.

Cooney, R.C. and Collins, M.J. 1979 (revised 1982, 1987, 1988 and 1990). A wall bracing test and evaluation procedure. BRANZ Technical Paper P21. Judgeford, Wellington.

Shelton, R.H. 2005. Engineering basis of NZS 3604:1999, Timber framed buildings. BRANZ Study Report under preparation. Judgeford, Wellington.

Standards New Zealand. 1992. General Structural Design and Design Loadings For Buildings. NZS 4203. Wellington.

Standards New Zealand. 1993. Timber structures standard. NZS 3603. Wellington.

Standards New Zealand. 1999. Timber framed buildings. NZS 3604. Wellington.

Standards New Zealand. 2004. Structural design actions Part 5: Earthquake actions – New Zealand Version 2. Draft New Zealand Standard DZ 1170.5:2004, Ballot Draft V2, 2 September 2004, Wellington.

Thurston, S.J. 1993. Report on racking resistance of long sheathed timber framed walls with openings. BRANZ Study Report No 54. Judgeford, Wellington.

Thurston, S.J. 2003. Full sized house cyclic racking test. BRANZ Study Report No 119. Judgeford, Wellington.

Thurston, S.J. and Park S.G. 2004. Seismic Design of New Zealand Houses. *Bulletin of the New Zealand Society for Earthquake Engineering,* 37(1). 1-12.

Thurston, S.J. 2004. BRANZ test and evaluation method EM3-V1 for bracing rating of walls to NZS 3604. BRANZ Study Report 131. Judgeford, Wellington.