Impact of base conditions on bracing behaviour of light timber-framed walls

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ABSTRACT

The majority of residential buildings in NZ are low-rise light timber framed (LTF) buildings and their lateral load resisting systems are proprietary LTF walls, which are often LTF plasterboard walls. LTF residential building construction largely follows the prescriptive standard NZS 3604 (SNZ 2011). According to the engineering basis of NZS3604, the seismic design action (demand side) of a building is determined by the force-based approach. For the provision of seismic bracing capacity, NZS 3604 specifies the P21 test procedure (Shelton 2010) for evaluating seismic bracing capacity of proprietary LTF wall systems.

In the 2010/11 Canterbury earthquake sequence, hundreds of thousands LTF residential buildings were tested in real shakings, providing an unprecedent opportunity to examine our seismic settings of LTF buildings. LTF buildings all achieved the code-specified objective “life safety”. However, earthquake damage of LTF buildings was often significant and fell short of societal expectations. This provided an important impetus to advance our understanding of the bracing performance of LTF houses. A project was initiated to study seismic behaviour of LTF walls typical of NZ practice and a previous study was conducted by studying P21 test data of typical plasterboard walls where the walls are mounted on a fixed base.

This paper presents the experimental study of bracing behaviour of four LTF walls on suspended timber floors by conducting comparative study of the LTF walls on suspended timber floors with similar walls but tested using P21 procedure. The objective of this study is to advance our understanding of LTF bracing walls on suspended timber floors.

1 INTRODUCTION

Performance-based seismic design of building structures has significantly advanced over the last decade. The essence of performance-based seismic design of building structures is to design a building structure for multiple performance requirements, such as damage controls, collapse prevention etc. New Zealand (NZ) has a performance-based code environment. However, the current seismic design standards are generally prescriptive and were developed primarily to achieve life safety at ultimate limit state (ULS) (Brown 2022).

Earthquake damage observed in recent earthquakes showed that the building structures designed to modern codes, although likely to achieve life safety in an event equivalent to the ULS intensity, could have significant damage. It is often not clear what performance levels, except life safety, could be expected of the building structures designed to modern seismic codes. This indicates apparent gaps between the performance-based code objectives and the design standards, subsequently providing a significant impetus to advance performance-based seismic engineering. There have been great research efforts on performance-based seismic designs of reinforced concrete building structures in recent times. In comparison, only limited research has been undertaken on LTF buildings, especially on LTF buildings as commonly built in NZ.

Most of residential buildings in NZ are low-rise LTF buildings. In the 2010/11 Canterbury earthquake sequence, hundreds of thousands LTF residential buildings underwent the real shakings. This created an unprecedent opportunity to examine our seismic settings of LTF buildings. In 2010/2011 Canterbury Earthquake sequences, LTF buildings all achieved the code-specified objective “life safety”. However the damage varied significantly, some had negligible damage while the others had damage beyond repair and were demolished afterwards. This demonstrated that the current seismic design settings of LTF houses had significant limitations and more work is needed to move the seismic design settings of LTF buildings towards performance-based seismic design (damage mitigation designs).

The lateral seismic resisting systems of LTF residential buildings in NZ are LTF proprietary walls, which are often LTF plasterboard walls. Seismic performance of LTF buildings in a major earthquake strongly depends on the bracing performance of LTF proprietary wall systems. A project was initiated at BRANZ to advance our understanding of the bracing behaviour of LTF proprietary walls as typical of NZ practice. One component of the project, which is complete now, examined seismic bracing performance of LTF walls using available P21 test results, where the LTF walls were tested as isolated cantilever walls on a relatively rigid foundation.

The seismic performance of a wall is strongly influenced by the base fixity and the principles are true for LTF timber walls as well. In fact, the base condition of LTF walls in LTF houses varies greatly because of the unique construction technique used for LTF houses - platform construction technique. In details, LTF walls, which act as lateral load resisting systems, are often offsets between storeys in LTF houses, causing significant challenge to resolve the uplift action at wall base. As such, seismic performance of the walls on upper level(s) is strongly dependent on the floor conditions, especially when the walls on upper level are offset from the walls below.

The objective of this study is to understand the effect of the base condition, being on a suspended timber floor rather than on the ground floor, on the seismic behaviour of LTF walls. In the first part of this study, the seismic engineering characteristics of LTF residential buildings in NZ are examined. Then the test arrangements and test results of LTF walls mounted on suspended timber floors are presented. The test results obtained from this study were compared with test results of otherwise identical tests except the base conditions of the walls.

2 SEISMIC ENGINEERING CHARACTERISTICS OF LOW-RISE LTF BUILDINGS

NZS 3604 has been developed for constructing simple low-rise LTF buildings. For typical LTF buildings, the lateral seismic-resisting systems are plasterboard-lined LTF walls, and therefore, LTF buildings perform in earthquakes in a similar way to other wall structures. The plasterboard-lined LTF walls are also the gravity load-carrying systems. The lateral deflections experienced by these walls in design earthquakes would be small in comparison with the wall lengths. In addition, low-rise LTF residential buildings are light in nature, and subsequently, P-Δ effects in earthquakes usually are not significant enough to cause instability problems.

Therefore, the LTF buildings of mainly NZS 3604 construction could easily achieve life safety requirement in design earthquakes.

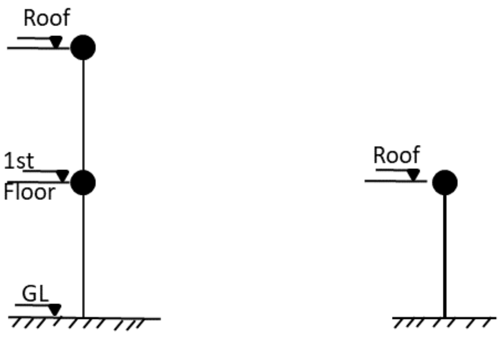
One overseas study showed that the low-rise timber building did not collapse even when the storey drift reached more than 6% (Bahmani 2013). The construction of LTF buildings in NZ is similar to that in other countries except for the wall lining materials. Hence, the collapse potential of LTF buildings in NZ should be of similar magnitude as reported overseas. A storey drift of 6% is significantly higher than the ULS deflection limit, 2.5%, as specified in the New Zealand seismic loading standard (SNZ 2004). This means that the life safety requirement at ULS as per NZS 3604 is almost irrelevant.

While LTF buildings have a low probability of collapse in earthquakes, they are vulnerable to earthquake damage, and their seismic performance varies markedly from building to building. Apart from the force-based approach, many other factors also contributed to the inconsistent seismic performance of LTF buildings as observed in the Canterbury earthquake sequence. For instance, LTF buildings often have significant structural weaknesses, such as irregular arrangement of bracing elements across the floor plan, stiffness/deformation incompatibilities of different bracing systems and less-effective floor diaphragms for distributing the seismic actions to different bracing systems across the building. Due to the presence of significant structural weaknesses, the seismic actions induced in different bracing systems can significantly deviate from a force-based theoretical prediction according to NZS 3604, causing greater variations of the expected seismic performance (Liu 2017).

2.1 Determination of Seismic Demand in NZS 3604:2011

The seismic bracing demand was derived using an equivalent static method as recommended by NZS 1170.5, assuming a fundamental period of 0.4 seconds and a ductility of $\mu = 3.5$.

The model used to derive the seismic demand in NZS 3604 is an elemental lumped mass model as shown in Figure 1 (Shelton 2013).



(a) Two-level building *(b) Single-level building*

Figure 1: Models used in deriving earthquake demand

The governing equation for seismic base shear action is as follows:

$$V = C_d(T_1)\, W_t \qquad (1)$$

where:

V = horizontal seismic shear force at the base of the structure

$C_d(T_1)$ is the horizontal seismic action coefficient derived by assuming a ductility of $\mu = 3.5$ and a fundamental period of $T_1 = 0.4$ seconds

W_t is the seismic weight of the building.

The vertical distribution of seismic actions between levels has used the provisions of NZS 1170.5 as follows:

The seismic action distributed to floor level i, Fi, is calculated from Equation 2 with an additional 8% V applied at the roof level:

$$F_i = 0.92\,V\,\frac{Mi\,hi}{\sum_1^n Mi\,hi} \qquad (2)$$

where:

M_i = seismic mass lumped at level i

h_i = height from the ground to floor level i or roof.

2.2 Provision of Seismic Bracing Capacity

For the provision of bracing capacity, NZS 3604 adopted the P21 test procedure (Shelton 2010) to evaluate the seismic and wind bracing capacity of proprietary LTF wall elements.

The P21 test is a slow cyclic racking test on a cantilever LTF wall element, and a horizontal load is applied at the top of the wall as a series of three displacement-controlled cycles to displacements of ±9, ±15, ±22, ±29, ±36 and ±43 mm. The test arrangement and the load protocol for a typical P21 test are respectively illustrated in Figure 2 and Figure 3.

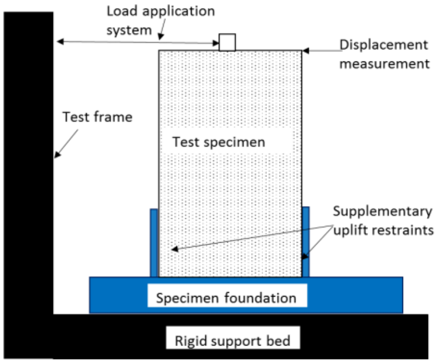


Figure 2: P21 test arrangement

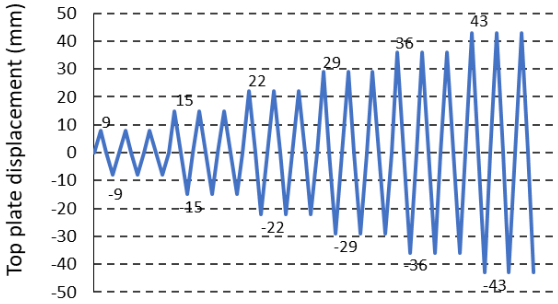


Figure 3: Load protocol used in P21 tests

The P21 test procedure only requires that the applied load and the in-plane deflection be measured at the top of the specimen. The lateral displacement measured at the top of the specimen is the sum of all contributions from different deformation mechanisms including uplift at the wall base, screw slip and elastic deformation within the sheathing as well as the deformation of the frames.

The seismic rating of the wall element is determined from the fourth cycle force at an elected deflection level between 15 mm and 36 mm, depending on when significant strength degradation occurs. P21 tests are often conducted on standard wall lengths, 0.4 m, 0.6 m, 1.2 m and 2.4 m. The determined rating may be applied to walls up to twice the length of the tested specimens. If the rated LTF walls are used in a taller storey height situation, the seismic rating of the walls can be adjusted, based on the testified rating, and the adjusted seismic rating is equal to the rated seismic capacity multiplied by the ratio of 2.4 m versus the wall height in the intended applications.

2.3 Seismic Bracing Design of Low-rise LTF Buildings

With regards to the seismic bracing design of LTF buildings within the scope of NZS 3604, the designers just need to demonstrate that the total seismic bracing capacity provided for a building is at least equal to the total seismic demand as derived from NZS 3604.

3 EXPERIMENTAL STUDIES

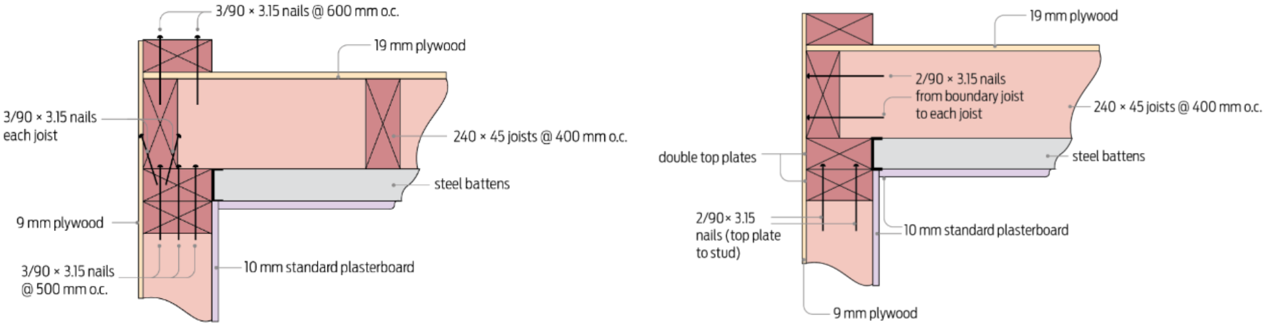
3.1 The test specimen of LTF walls on timber floors

The test programme included four LTF walls on a suspended timber floor. The four tests are identical except for the wall lengths and the wall orientation relative to the floor joist orientation.

With regards to the suspended timber floor of the test specimen, the plan dimensions of the suspended timber floor were 3.6 m x 3.6 m, and the floor framing construction of the test specimen follows conventional LTF residential construction practice. The floor joists are SG8 240 by 45 at a spacing of 400 mm and the flooring was 19 mm plywood. The floor also has a ceiling, which is constructed using metal battens and 10 mm standard plasterboard sheathing as commonly used in modern house construction. Figure 4 shows the edge details of the suspended timber floor construction.

With regards to the walls of the test specimens, two specimens are 1.2 meters long walls while the other two specimens are 2.4 meters long walls. For each pair of tests of the same wall lengths, one test has the wall orientation parallel to the joist orientation while the other test has the wall orientation perpendicular to joist orientation.

For the four tests, the wall height is 2.4 meters, all the walls are lined with 10 mm braceline plasterboard on both faces with Handibrac hold down devices at each end of the walls.



(a) Cross section of floor edge parallel to joists *(b) Cross section of floor edge perpendicular to joists*

Figure 4 Edge details of the floor construction

The bottom plates of the walls were nailed (3 nails, 90x3.15) at each joist or each blocking. Apart from the nails, Handibrac® hold-down devices were installed at both ends of each wall from the studs through the bottom plate to blockings or joists.

3.2 Instrumentation

The test specimen was extensively instrumented using displacement potentiometers and load cells. These instruments were arranged to quantify the behaviour of different parts of the system. In detail, linear potentiometers were used to record the horizontal displacements at the wall top plate relative to the strong floor within the wall plane, the vertical displacements of the wall end studs relative to the floor, the vertical displacements of the floor at the wall end stud locations relative to the strong floor (as illustrated in Figure 5). Applied loads and actuator's displacements were also recorded using the built-in instrumentations.

These measurements enabled the derivations of the inter-storey drifts between floor levels in buildings and are directly related to damage levels experienced by LTF walls and other vertical building systems such as windows and doors in earthquakes. These drifts are used to establish the relationships between damage states of the LTF walls with building responses.

3.3 Test setup and loading protocol

The testing was carried out in the BRANZ structures laboratory and the test setup is shown in Figure 5. The test was conducted using a displacement-based quasi-static fully reversed cyclic loading protocol. For all the tests, the actuator displacement cycles continued well over ± 60 mm, which was well beyond the conventional displacement range of P21 tests. All the testing was terminated due to significant floor damage and reduction of the applied loads.

Figure 5. Test setup of LTF walls on suspended timber floors

4 TEST OBSERVATIONS AND TEST RESULTS

4.1 Damage observation

For each test, damage observation was made after each loading cycle by taking photographs and visual inspections. For all the four wall tests, the damage was found to be primarily associated with the damage of the floor, the walls parallel to the joist orientation performed significantly better than the otherwise identical walls but oriented perpendicular to the joist orientation. The damage observation is described in the following for the four tests.

4.1.1 The 1.2 m long wall parallel to the joist orientation

The 1.2 m long wall parallel to the joist orientation was the first test conducted in this test program. During the early loading cycles of the test, no visible damage was observed in any parts of the test specimen until the loading cycle of 36 mm when some screw distressing appeared close to the wall base. The attained load was peaked at the loading cycle of 43 mm and the peak strength attained was 8.3 kN. As the test progressed to the loading cycle of 50 mm, screw detachment and wall lift-up were observed. In addition, loud noise was heard from the timber crushing within the floor. At the loading cycles of 65 mm, more timber crushing was heard and Handibrac bolts were pulled out from the floor. The attained load dropped significantly and the test was terminated at the loading cycle of 75 mm where the attained load dropped to 2.0 kN. Figure 6 shows the damage progression and the exposed view of Handibrac at the completion of the test.

4.1.2 The 1.2 m long wall perpendicular to the joist orientation

The test specimen of the 1.2 m long wall perpendicular to the joist orientation was identical to the test specimen of the 1.2 m long wall parallel to the joist orientation except the wall orientation. During the early loading cycles of the test, no visible damage was observed in any parts of the test specimen until the loading cycle of 29 mm when a slight floor lift-up at one wall end was observed.

As the test progressed, the attained loading continued to increase and the damage progression is limited to the floor lift-up development only. The peak strength was reached at the loading cycles of 57 mm. A piece of the 19 mm flooring close to Handibrac was significantly lifted up at the loading cycle of 75 mm and the attained loading started to drop. The attained peak strength was 8.3 kN. Subsequent loading cycles caused some screw damage from plasterboard to timber framing at one wall end and the test was terminated at the loading cycle of 95 mm due to significant load drop. Figure 7 shows the flooring lift up and the exposed view of Handibrac bolt connection after the completion of the test.

(a) Screw detachment initiated *(b) Handibrac pulled out of the floor*

(c) Exposed view of Handibrac screw pulled out

Figure 6. Damage development and the exposed view of Handibrac (1.2 m wall parallel to joist orientation)

(a) Floor damage *(b) exposed view of Handibrac hold-down device*

Figure 7. Floor damage and the exposed view of Handibrac (1.2 m perpendicular to joist orientation)

4.1.3 The 2.4 m long wall parallel to the joist orientation

The test specimen of the 2.4 m long wall parallel to the joist orientation was identical to the test specimen of the 1.2 m long wall parallel to the joist orientation except the wall length. During the early loading cycles of the test, no visible damage was observed in the wall. However loud timber crushing within the floor was heard as early as the loading cycles of 15 mm.

As the loading continued, the noise continued and the Handibrac bolt started to be pulled out at the up-lifting end of the wall during the loading cycles of 36 mm. The bolt pull-out continued and screw distressing around the wall ends at the wall base was also observed as the loading continued. The sustained load started to drop at the loading cycles of 50 mm. Subsequent loading caused more significant bolt pull-out as well as screw detachments around the wall ends at the wall base. The test was terminated at the completion of the loading cycles of 65 mm. Figure 8 shows the revealed the Handibrac connection after the completion of the test.

(a) Wall up-lifting (Handibrac bolt pull-out) *(b) exposed view of Handibrac hold-down device*

Figure 8. Uplift of the wall and the exposed view of Handibrac (2.4 m parallel to Joist orientation)

4.1.4 The 2.4 m long wall perpendicular to the joist orientation

The test specimen of the 2.4 m long wall perpendicular to the joist orientation was identical to the test specimen of the 2.4 m long wall parallel to the joist orientation except the wall orientation, and it was identical to the test specimen of the 1.2 m long wall perpendicular to the joist orientation except the wall length. During the loading cycles, no visible damage was observed until the loading cycles of 15 mm when timber crushing was heard within the floor.

As the loading cycles continued, the noise of timber crushing continued. However no apparent damage to the wall was observed and the attained load continued to increase. During the loading cycles of 36 mm, the floor displayed apparent out-of-plane bowing and the attained load was peaked. When the loading progressed to cycles of 50 mm, significant flooring lift-up initiated and the attained load started to drop slightly. Subsequent loading cycles caused more significant flooring lift-up but the wall remained unscathed. The test was terminated at the completion of the loading cycles of 65 mm. Figure 9 shows the various damage and the final appearance of the 2.4 m long wall perpendicular to joint orientation.

After the four wall tests were completed, the floor framing was exposed to see the damage within the floor framing. Figure 10 shows the damage to the floor framing, including the splitting of the blocking under the walls perpendicular to the joint orientation, the vertical movements of the blockings. The ceiling has maintained its integrity and had no damage at all.

(a) Out-of-plane bowing of the floor *(b) Flooring lift up along the flooring joint*

(c) Final appearance of the 2.4 m wall on suspended timber floor (perpendicular to joist orientation)

Figure 9. Deformation and damage of the floor, the exposed view of Handibrac (2.4 m wall perpendicular to joist orientation)

(a) Splitting of the blocking framing *(b) Out-of-plane movement of the floor timber*

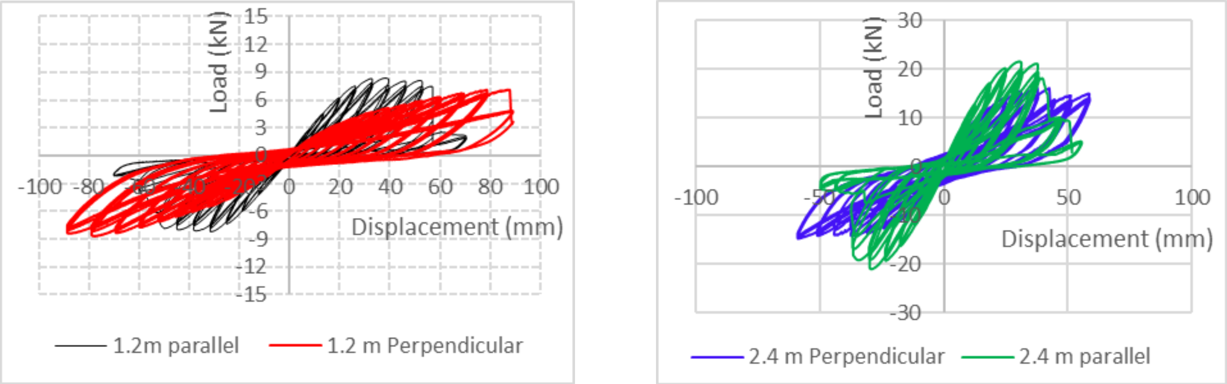
(c). Final appearance of the ceiling

Figure 10. Summary of damage within the floor at the completion of all the four tests

4.2 Load -displacement responses

Seismic performance of LTF houses is directly dependent on the hysteresis behaviour of the LTF walls. As such, the hysteresis behaviour of the tested walls in this project was studied by comparing the hysteresis behaviour of the two walls of the same length but different orientations and also by comparing the hysteresis behaviour of the tested walls included in this study with that of conventional P21 tests of the same length and identical linings.

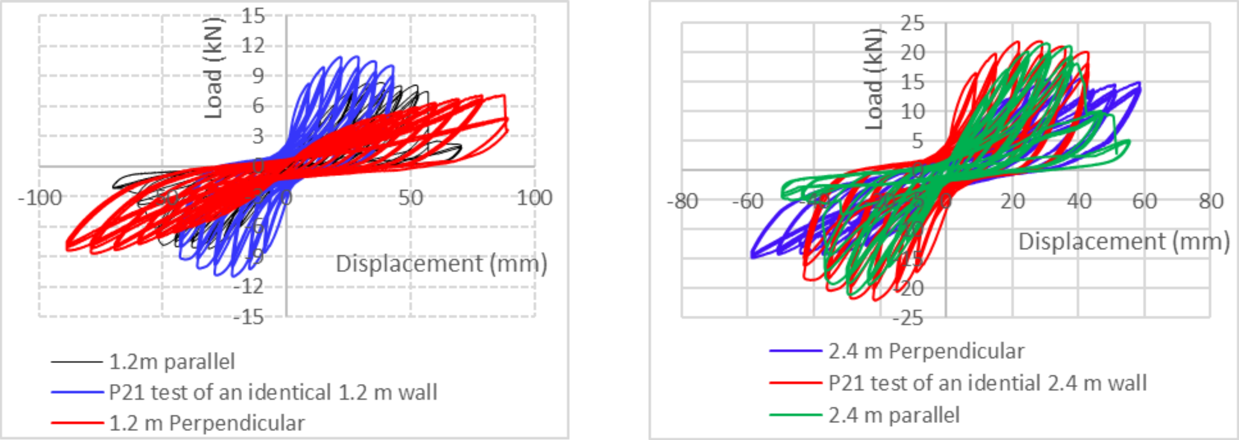
Figure 11 shows the hysteresis behaviour comparison of the walls on the suspended timber floor, where the illustrated two walls had the same lengths but different wall orientations. Figure 12 compares the hysteresis behaviour comparison of the walls on the suspended timber floor with conventional LTF walls tested using P21 method.



(a). the 1.2 m long walls

(b). the 2.4 m long walls

Figure 11. Comparison of the hysteresis behaviour of 1.2m and 2.4 m long walls on suspended timber floor



(a). the 1.2 m long walls

(b). the 2.4 m long walls

Figure 12. Comparison of the hysteresis behaviour of 1.2 m and 2.4 m long walls on suspended timber floor

Analysis of the test data showed that the attained strength and stiffness of the walls on suspended timber floors, at a specific displacement level, are significantly lower than the correspondent strength and stiffness obtained from similar P21 tests. For instance, the attained bracing strengths and stiffness for 1.2 m walls were only about 21% to 35%, 31% to 56%, 38% to 70%, 46% to 80% of the correspondent values obtained from P21 tests at the displacement of around 9 mm, 22 mm, 30 mm and 36 mm respectively. Clearly the rated bracing capacity by P21 tests is significantly higher than the measured bracing capacity of the walls on suspended timber floors undertaken in this study.

4.3 Discussions

Standard P21 test procedure, which is an essential part of the acceptable solution of NZS3604 for LTF house construction, specifies that proprietary LTF walls are mounted on a fixed base and the rated bracing capacities of the walls by P21 tests do not vary with the base conditions. For example, the rated seismic bracing resistances of the walls by P21 test method are used as the bracing resistances even the walls are on a suspended timber floor. In fact, the failure mechanism and the hysteresis behaviour of the walls are significantly influenced by the base conditions of the walls.

For standard P21 tests, the damage of LTF walls when subjected to horizontal actions could only occur in the walls because the walls are mounted on a rigid foundation. In comparison, the test observation reported here reveals that the LTF walls on suspended timber floors primarily have damage limited to the floors, and any damage to the walls on suspended timber floors is likely to occur much later than the damage to the floor. Clearly the failure mechanism of the walls is strongly related to the systems at wall bases, and this indicates that P21 tests are indicative only and will not reflect the effect of the flexibility of the base systems. The hypothesis is that, similar to the undesirable foundation failure, the failure of within the floor under LTF walls could be more challenging and costly to repair than the failure of screw attachments of plasterboard walls after a major event. To improve the seismic performance of LTF walls on suspended timber floors, it is necessary to enhance the floor framing by enhancing the connection details from wall bottom plate to the floor framing and enhancing floor framing requirements under the LTF walls.

With regards to the hysteresis behaviour, comparisons of hysteresis behaviour of the LTF walls on suspended floors reported here with that of the counterparts of standard P21 tests reveal:

- P21 test procedure is likely to overestimate the strength and stiffness performance of LTF walls on suspended timber floors. The discrepancy is greater for shorter walls in comparison with longer walls and the discrepancy is greater for the walls oriented perpendicular to the joist orientation in comparison with the walls orientated parallel to joist orientation.
- LTF walls on suspended timber floors, when orientated along the joist orientation, are likely to have higher bracing strengths and higher stiffness than the counterparts oriented perpendicular to the joist orientation.

5 CONCLUSIONS

One objective of a research project about LTF houses initiated at BRANZ was to obtain information on seismic bracing behaviour of LTF plasterboard walls constructed according to NZ residential practice. One element of this study was to quantify the effect of base conditions on seismic behaviour of LTF walls by experimentally studying LTF walls on suspended timber floors, compared with LTF walls on a rigid foundation as in P21 tests.

Many interesting observations were made, and they are summarised as follows.

- Unlike the conventional P21 tests on LTF plasterboard walls where the final failure often occurred due to the failure of screw attachments, the failure of the LTF walls on suspended timber floors is likely to initiate within the floor and the damage progression is primarily limited to the floors.
- Shifting the damage from the screw attachments of the walls to the floor framing would be undesirable. This suggests that timber framing improvement be needed to improve the wall performance on suspended timber floors.
- P21 tests are likely to overstate seismic bracing rating of LTF walls on suspended timber floors, especially for short walls because of the challenge to resolve the up-lift actions at wall base. This indicates that P21 test procedure needs to be examined if it is used to rate LTF walls used in multi-storey timber buildings beyond the current scope of NZS3604.

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