Seismic Damage States and Damage Quantification of Light Timber Framed Walls in Residential Houses

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ABSTRACT

New Zealand (NZ) has a performance-based code environment, and this means that the seismic design of buildings aims to achieve multiple performance requirements including quantifications of seismic damage severity and subsequent repair costs. However, current seismic designs of buildings were developed primarily to achieve life safety at ultimate limit state (ULS) design level. Earthquake damage observed in recent earthquakes showed that light timber framed (LTF) houses all achieved life safety but often suffered significant damage. Damage surveys revealed that the damage to houses was often limited to the LTF walls and non-structural systems within the walls. Recent studies (MBIE 2020, Brown 2022) raised important questions on how other seismic performance requirements than life safety could be evaluated and suggested that the seismic design methods for residential buildings go beyond life safety and include broader societal recovery.

Presented in this paper is an experimental study about damage state quantification of LTF walls to help advance the performance-based seismic design of LTF buildings. The cyclic testing and damage observations of a full-scale LTF wall and floor system, constructed according to NZ residential practice, are described. The damage state definitions of LTF plasterboard walls are established, and the relationships of damage states with the drift levels are developed.

1 INTRODUCTION

New Zealand has a performance-based code environment. Essence of performance-based seismic design of building structures is to design a building structure for multiple performance requirements, such as building damage quantification and subsequent repair costs, rather than one single requirement of life safety at ultimate limit state (ULS) as per the current seismic design standard.

However, the current seismic design standard, NZS1170.5:2004 (SNZ 2004) is generally prescriptive and was developed to achieve life safety at ULS only. Earthquake damage observations in recent earthquakes, such as the 2011 Canterbury earthquake sequences and 2016 Kaikoura earthquake, showed that the buildings designed to modern codes, although likely to achieve life safety in an event equivalent to the ULS intensity, had unacceptable damage and caused significant interruptions. Of interest was that the observed earthquake damage varied significantly, some buildings had no damage while other buildings had damage beyond economical repair (Mayes et al 2013). This brough about the realisation that current seismic design regimes are inadequate for quantifying seismic damage and there is a need for the move from a single performance requirement of life safety towards multiple performance requirements for buildings (MBIE 2020).

Earthquake damage to buildings is often the result of excessive deformations. The predominant methodology used in current seismic design standards, is the force-based approach. The force-based approach is well-known to be inadequate in assessing seismic deflections thus damage (Liu 2017). As a consequence, it is often not clear what performance levels, except life safety, could be expected of the building structures designed to modern seismic codes.

While there has been research on performance-based seismic designs of concrete structures, there has been very limited research on performance-based seismic design of light timber-framed (LTF) buildings as commonly built in New Zealand (NZ).

Majority of NZ residential buildings are low-rise LTF buildings with suspended timber joist floors. LTF houses are supported and braced by LTF walls, they are not susceptible to collapse in earthquakes and thus their seismic designs should focus on damage limitations. A recent study about societal expectations for seismic performance of residential buildings (Brown et al 2022) suggested that seismic designs of residential buildings go beyond life safety by including damage control requirements to enable broader recovery.

A research project at BRANZ was initiated to help advance performance-based seismic design of LTF residential buildings in NZ. One component of the project deals with quantifying seismic performance of NZ LTF residential buildings, based on a series of cyclic tests on LTF building components and systems. This paper presents (1) a cyclic loading test on a full-scale LTF wall-floor system constructed according to NZ practice, (2) the establishment of the relationships of the damage states of LTF walls versus inter-storey drifts, based on the test observations.

2 LTF RESIDENTIAL BUILDINGS IN NEW ZEALAND

2.1 Typical construction

The majority of LTF residential buildings in NZ are constructed according to the prescriptive standard NZS 3604:2011 Timber-framed buildings (SNZ 2011). NZS 3604 has an engineering basis (Shelton 2013), which includes the seismic design basis developed using a force-based approach. The seismic demands are expressed in tabulated forms, according to the site information and the building information. With regards to seismic capacity provision, NZS 3604 specifies that the P21 test and evaluation procedure, published by BRANZ (Shelton 2010), be used to evaluate seismic bracing capacity of proprietary LTF wall elements. Designers need to use the provided tables to obtain seismic demand and then to ensure that bracing capacity provided at least matches bracing demand. According to the P21 test procedure, the bracing capacity of a proprietary LTF wall is a rated horizontal load resisting capacity within a wide deflection range and the rated bracing capacity has no specific relationship to the associated damage or deformation of the walls. As such, there is no information on the expected damage state(s) of these LTF wall systems in a major earthquake event. Therefore, the engineering basis of NZS3604 is inadequate to enable earthquake damage quantification of LTF houses.

2.2 Observed damage to LTF houses

In recent years, a large number of LTF residential buildings in NZ had been tested in earthquakes. These events provided rare opportunities for reviewing seismic performance of LTF residential houses (Buchanan et al 2011). Damage surveys in recent earthquakes showed that LTF residential buildings all achieved life safety, but thousands of houses had some degree of damage and thus unprecedented economic losses.

The reported earthquake damage to LTF houses varied considerably but the damage was largely limited to the vertical systems, including LTF walls, windows, doors etc. One interesting observation was that the ceilings and the floors of typical LTF houses maintained their integrity and often survived the events unscathed, even for severely damaged houses.

Damage to the vertical systems was often a result of large lateral deflections experienced by the building. As such, this research component focused on quantifying earthquake damage to LTF walls and on establishing the relationships between damage states and associated storey drifts, based on a cyclic test of a full-scale LTF wall-floor system constructed according to typical NZ residential practice.

3 A FULL-SCALE LTF WALL-FLOOR SYSTEM TEST AT BRANZ

3.1 The wall-floor test system

The full-scale LTF wall-floor test system was detailed according to current LTF residential practice. The plan dimensions were 7.2 m x 3. 6 m, as shown in Figure 1, and the storey height was 2.4 m. The bracing walls were arranged symmetrically in both directions. Each short side was a 3.6 m long wall and each long side included two 1.2 m long walls and one 2.4 m long wall with two 1.2 m wide openings. Elevation of a long side wall is illustrated in Figure 2.

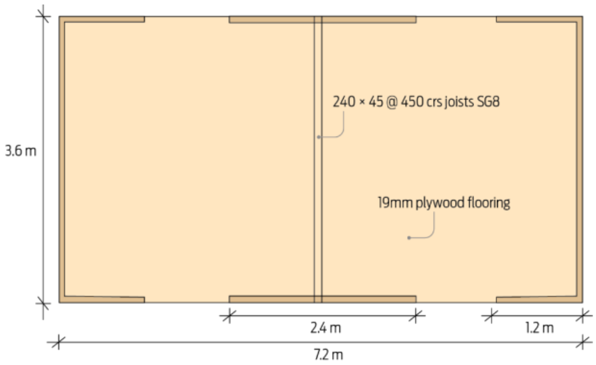

Figure 1. Plan of the test specimen

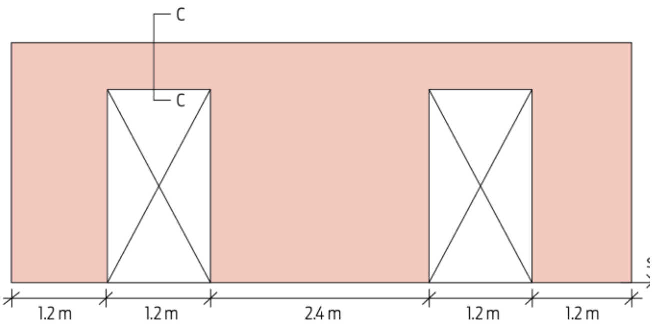

Figure 2. Elevation of specimen long sides

All timber frame members were grade SG8 Radiata Pine. The floor has a 19 mm plywood flooring and a 10 mm plasterboard ceiling constructed using light-gauged metal battens. The wall linings were 10 mm thick standard plasterboard on the inside and 9 mm thick F8 grade plywood sheets on the exterior.

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. The engineering responses of various components within the system and the engineering responses of the system as a whole during the testing have been extensively studied and are reported in a study report (Liu and Carradine 2022).

For the damage quantification of LTF walls, the relevant measurements included the displacements of the walls recorded at the top plates of the walls and referenced off the laboratory floor. These measurements represent the inter-storey drifts that occur 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 full-scale test of the LTF wall and floor system was carried out in the BRANZ structures laboratory and Figure 3 shows the test setup. The test was conducted using a displacement-based quasi-static fully reversed cyclic loading protocol. The testing was completed following the ±60 mm actuator displacement cycles due to significant wall damage and reduction of the applied loads.

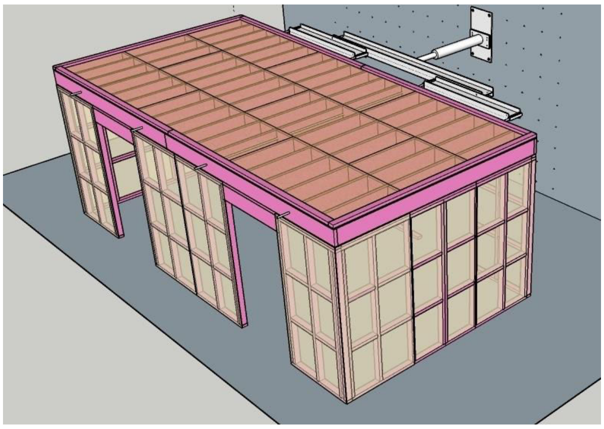

Figure 3. Test setup doe LTF wall-floor system

4 DAMAGE OBSERVATIONS AND QUANTIFICATION

4.1 Overview of the damage

Damage observations were made after each loading cycle by taking photographs and visual inspections. The frame members were found to have no damage after the areas of interest were exposed at the end of the test.

Throughout the entire test, the floor and the ceiling had no visible damage, and the external ply linings of the walls had no apparent damage either, with only a few areas where the nails started to work themselves out of the plywood. Instead, the damage was primarily limited to the plasterboard sheathings of east and west walls, and the damage was either within the wallboards or around the screw attachments along the joints of the plasterboard sheets. The loading resistance started to degrade when the plasterboard at the lower corners of the walls developed significant local damage. At later loading cycles, local plasterboard damage at the base corners of east and west walls progressed considerably. Meanwhile the screw attachments along the vertical wallboard sheet joints also started to fail in east and west walls quickly and this led to extensive out-of-plane buckling failure of plasterboards and drop of attained loading capacity. The test was subsequently stopped.

4.2 Description of detailed damage progression

In the early test cycles, only cosmetic tape wrinkling and screw distressing were visible. When the top plates of walls deflected 8.7 mm (0.36% drift), tape breakages (Figure 4) initiated along the joint lines between ceiling and walls, screw distressing and slotting were also visible. As the test progressed, the damage progressed but the bracing capacity maintained. Damage was limited within the tape joints up to the drift levels of 14.0 mm.

When the top plate deflections reached 17.3 mm (0.72% drift), the damage extended beyond the tape joints and local plasterboard damage occurred at the bottom corner of the east and west walls (Figure 5). Plasterboard cracks were as wide as 3.5 mm at the completion of the third cycle of the deflection of 17.3mm.

As the test continued, damage progressed too. At the loading cycles where the top of the walls deflected 24 mm (1% drift), local plasterboard damage spread to the bottom corners of the west wall adjacent to the north and south walls (Figure 6). Also observed was the failure initiating of vertical sheet joints of plasterboard sheets in east and west walls (Figure 7). This phenomenon was accompanied by noticeable load degradation.

As the loading continued, the screw slotting in the plasterboard and thus detachment of plasterboard sheets progressed significantly. When the top of the walls deflected 35 mm (1.45% drift), out-of-plane buckling of plasterboard sheets occurred in a brittle manner in both east and west walls (Figure 8). The test was subsequently terminated. Following the testing, the linings over the areas of interest were taken off and no visible damage was observed to either the timber frames or the hold-down brackets.

Figure 4. Significant tape breakage

Figure 5. Local plasterboard damage

Figure 6. Significant local plasterboard damage in east and west walls

Figure 7. Opening of vertical plasterboard sheet joints

4.3 Damage state quantifications of LTF Plasterboard walls

As described previously, there has been very little research conducted on the earthquake damage quantification of LTF plasterboard walls typical of New Zealand residential construction. However some work has been done in quantifying the earthquake damage to plasterboard partition walls within commercial buildings of concrete or steel construction (Mulligan et al. 2020 and Tasligedik et al. 2015).

Plasterboard partition walls in commercial buildings, although often being light steel framed with different construction details around the boundaries, have similar linings to LTF plasterboard walls in NZ residential buildings. Due to the fact that the observed damage to LTF walls in the test reported here was limited to the plasterboard only, the damage state definitions developed for plasterboard partition walls could be used to establish the damage state definitions of LTF plasterboard walls. Damage state definitions of plasterboard partition walls by Taghavi and Miranda (2003), shown in Table 1, is viewed as a good tool because it establishes the relations between different levels of physical damage and the repair actions. Table 1 was used as a basis for damage quantification studies conducted in this research. Table 2 details damage states and potential repair actions in relation to the storey drifts derived from the full-scale LTF wall-floor test.

Figure 8. Out-of-plane buckling of plasterboard along the sheet joint

Table 1. Damage state definitions of plasterboard walls based on Taghavi and Miranda (2003).

Damage state	**Damage definition**	**Potential repair actions**
0	Cosmetic wrinkling or hairline cracking of paint over tape at joints	No repair needed
1	Cracking that can be repaired with tape, plaster, and paint	Add more screws if necessary Tape Plaster, finish and paint
2	Replacement of plasterboard sheets but not timber framing	Replace damaged plasterboard with new sheets Attach new plasterboard to frames Tape Plaster, finish and paint
3	Total replacement	Demolish plasterboard walls/ ceilings Build new walls/ceilings

5 DISCUSSION

Current seismic designs for LTF residential buildings in New Zealand primarily aim at achieving life safety and the only relevant requirement associated with damage quantification is the specification for serviceability limit states (SLS) in AS/NZS1170.0:2002 (SNZ 2002). AS/NZS1170.0 specifies that the seismic design actions for residential houses are the actions associated with the annual probability of exceedance (APE) of 1/25, or once every 25 years. The performance requirement for SLS is to ensure that the structure and the non-structural components do not require any repair after an SLS earthquake event.

For LTF residential buildings in NZ, plasterboard walls are often the primary seismic bracing system. According to AS/NZS1170.0:2002, the mid-height deflection of LTF plasterboard walls at SLS shall be no greater than the height divided by 200 when subjected to face actions, and no greater than the height dived by 300, about 8mm, when subjected to in-plane actions. These limits are specified to protect plasterboard damage and do not necessarily reflect the bracing function of the walls. The damage observed in this test showed that the damage to LTF walls is only limited to the tape wrinkling and screw stressing before the inter-storey deflection reached up to 8.7mm. As such, in-plane deflection limits for LTF plasterboard walls at SLS, adopted by P21 test procedure, appears to be appropriate.

Table 2. Damage states, repair actions and storey drifts.

Damage state	Description	Potential repair action	Storey drift % (top plate deflection)
1	Tape wrinkling, screw distress, tape tearing in isolated area	Retape, repair stressed screws and paint	<= 0.6% (14 mm)
2a	Plasterboard damage - local crushing or cracking within sheets (Figure 6)	Replace damaged plasterboard, retape the joints and paint	0.7% (17mm)
2b	Plasterboard sheet joints opening (Figure 7). Loading capacity dropped	Replace the damaged plasterboard, reinstall the screws, retape and paint	1% (24mm)
2c	Plasterboards detached from the framing, Out-of-plane buckling of plasterboards, Apparent loading capacity drops	Replace the board, refix the boards to frames, retape and paint.	1.5% (35mm)
3	Plasterboard significantly damaged and uneconomical to repair	Repair is uneconomical. Demolition is required.	1.8% (43 mm)

On the other hand, the test observations also suggest that the in-plane deflection limit at ULS for LTF residential buildings be taken as a storey drift of 1%. This is considerably lower than the storey drift limit of 2.5% at ULS in AS/NZS 1170.5:2004 (SNZ 2004). The limit of 1% was suggested because the bracing capacities of LTF plasterboard walls start to degrade and/or lose integrity at the drift level of 1%. Limiting the storey drift within 1% at ULS could ensure that the LTF houses won't be damaged beyond repair.

6 CONCLUSIONS

A research project was initiated at BRANZ and one of the objectives was to obtain information on damage quantification of LTF plasterboard walls constructed according to NZ residential practice. Past studies on LTF plasterboard walls have been undertaken using an elemental approach with a focus on the maximum bracing capacity. In this study, a full-scale wall and floor system as typical of LTF residential construction in NZ was studied to enable identification of the damage vulnerability between the floor diaphragm and the supporting wall systems using a wholistic systems approach. Many interesting observations were made, and they are summarised as follows.

- Unlike the elemental tests on isolated LTF walls where the final failure often occurred due to the failure of screw attachments, the test on the full-scale LTF wall-floor system reported here revealed that out-of-plane buckling of plasterboard sheathing triggered the final failure of the system.
- Plasterboard sheathing of LTF walls is the most vulnerable elements of LTF building systems.
- Based on damage state classifications of plasterboard partition walls developed overseas, the relationships of the inter-storey drifts and the damage states of LTF plasterboard walls typical of NZ residential practice have been suggested.
- The current in-plane deflection limit of LTF plasterboard walls under serviceability limit state (SLS) earthquake actions, which is 8 mm according to P21, appears appropriate to achieve the code specified SLS performance criterion.
- The deflection limit at ULS for LTF residential buildings should be more in realm of 1% in order to prevent LTF buildings from having unrepairable damage. This would increase the resilience of houses and communities in New Zealand and decreases carbon footprints for residential construction.

References

Brown, C., Abeling, S., Horsfall, S., Ferner, H. and Cowan, H. (2022). "*Societal Expectations for Seismic Performance of Buildings (March 2022)"*. Toka Tū Ake EQC, Wellington, New Zealand.

Buchanan, A, Carradine, D., Beattie, G.,and Morris H (2011). "Performance of houses during the Christchurch Earthquake of 22 February 2011". *Bulletin of the New Zealand Society for Earthquake Engineering*, **44** (4): 342-357.

Liu, A. and Carradine, D., (2022). "*Seismic Design of Low-Rise and Mid-Rise Hybrid Residential Buildings: In-plane behaviour of timber floor diaphragm",* EQC report (in Press).

Liu, A. (2017). "Need for a systematic approach in damage control design for light timber-framed buildings". *Proceedings of the 16th World Conference on Earthquake Engineering*, Santiago, Chile, 9–13 January 2017

MBIE Seismic Risk Working Group. (2020). *"Seismic Risk and Building Regulation in New Zealand Findings of the Seismic Risk Working Group"*. Ministry of Building, Innovation and Employment (MBIE),

Mulligan, J., Sullivan, T., & Dhakal, R. (2020). "Experimental study of the seismic performance of plasterboard partition walls with seismic gaps". *Bulletin of the New Zealand Society for Earthquake Engineering*, **53**(4), 175–188.

Shelton, R. (2010). "*Technical Paper P21: A wall bracing test and evaluation procedure"*. BRANZ, Judgeford, New Zealand.

Shelton, R. (2013). "*Engineering Basis of NZS 3604"*. BRANZ, Judgeford, New Zealand

SNZ. (2002). "*NZS 1170.0:2002. Structural Design Actions – Part 0: General Principals"*. Standards New Zealand (SNZ), Wellington.

SNZ. (2004). *"NZS 1170.5:2004. Structural Design Actions – Part 5: Earthquake Actions"*. Standards New Zealand (SNZ), Wellington.

SNZ. (2011). *"NZS 3604:2011. Timber Framed Buildings"*. Standards New Zealand (SNZ), Wellington,.

Taghavi, S. and Miranda, E. (2003). *"Response Assessment of Nonstructural Building Elements. Report 2003/05*". Pacific Earthquake Engineering Research (PEER) Centre, Berkley, CA, USA.

Tasligedik S., Pampanin, S. and Palermo, A. (2015). "Low damage seismic solutions for non-structural drywall partitions". *Bulletin of Earthquake Engineering*, **13**(4): 1029–1050.