In-situ lateral load test performance of Christchurch houses

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ABSTRACT:
There is very little research on total house strength that includes contributions of non-structural elements. This testing programme provides inclusive stiffness and response data for five houses of varying ages. These light timber framed houses in Christchurch, New Zealand had minor earthquake damage from the 2011 earthquakes and were lateral load tested on site to determine their strength and/or stiffness, and to identify damage thresholds. Dynamic characteristics including natural periods, which ranged from 0.14 to 0.29s were also investigated. Two houses were quasi-statically loaded up to approximately 130kN above the foundation in one direction. Another unidirectional test was undertaken on a slab-on-grade two-storey house, which was also snapback tested. Two other houses were tested using cyclic quasi-static loading, and between cycles snapback tests were undertaken to identify the natural period of each house, including foundation and damage effects. A more detailed dynamic analysis on one of the houses provided important information on seismic safety levels of post-quake houses with respect to different hazard levels in the Christchurch area. While compared to New Zealand Building Standards all tested houses had an excess of strength, damage is a significant consideration in earthquake resilience and was observed in all of the houses.

1 INTRODUCTION

1.1 House performance evaluations and non-structural components

A significant body of research has been done on house wall panel shear testing to determine house stiffness and load resistance provided by the main structural components. Whole-house Light Timber Frame (LTF) systems include many more contributing aspects and far fewer of these complex tests have been undertaken. In 2014 a state-of-the-art review was undertaken of 200 papers related to LTF residential structures, and it identified 3 static and 3 cyclic pseudo-static tests and about 6 shake table tests conducted on near full-scale houses. There were additionally shear wall, horizontal diaphragm, analytical and small size and multi-storey shake table tests reported. Significant findings included the need to better utilise the contribution of gypsum plasterboard panels, to correlate damage with loads, and for more in depth damage reports (Kirkham et al. 2014). Full-house quasi-static tests undertaken in Australia, without windows or doors (Paevere 2002), and in New Zealand by Thurston (2003) provided relevant contributions considering Australasian construction methods. Subsequent to the series of Christchurch earthquakes in 2010, and 2011 (Bradley & Cubrinovski, 2011), two-storey blocks of government housing (Connor-Woodley 2015) and schools of similar LTF construction in New Zealand (Ministry of Education 2014) were tested using fully reversed cyclic displacements. All of these tests showed that LTF buildings had significantly greater strength and stiffness than predicted using accepted engineering practice. Non-structural elements such as minor walls, doors and windows and contribute to higher strength and stiffness, but the actual values need to be better quantified. This will enable the prediction of potential damage and risk, ensure the appropriateness of retrofitting strategies when required, and to avoid unnecessary demolitions.

Lateral load testing on whole houses that were due for demolition in Christchurch has been performed. Although some houses were only moderately damaged, where the land was classified as “red zone” and not suitable for long term use, it provided the opportunity for this work. Timber houses provided good life safety during the Christchurch seismic events with the most widespread damage due to lateral and vertical lateral deformations caused by ground liquefaction. Studies such as those by Buchanan et al. (2012), Thomas et al. (2012) and Wilkinson et al. (2012) have undertaken damage evaluations on houses but with little data on local accelerations or the applied loadings.

1.2 The Christchurch test series

This paper extends the work reported by Morris and Carradine (2014) and Morris et al. (2015) where tests were undertaken on houses due for demolition. Initial uni-directional lateral load tests were conducted in 2012 on two houses which validated the testing procedure (Morris et al. 2012). Two further houses were obtained and more comprehensive testing was undertaken in 2013, and in 2014 a two-storey house was tested. This paper provides an overview of the test series with a brief discussion of the test methods and results, and includes additional dynamic analytical work, details the final two-storey test and proposes a full-scale laboratory test.

2 METHODOLOGY

The initial test methodology was to load the house from a beam at the end of the house propped on a pivot to avoid vertically loading the walls. Two 7.5T chain blocks running diagonally along each side of the nearly rectangular houses were loaded up to 65kN to provide total uni-directional loading of 130kN (see Figures 1 and 2.) Load was applied in steps, including unloading at some stages. Damage was reviewed and recorded during pauses between load increases. The load reaction was applied from the top of the foundation for both houses tested in 2012. Both the 1983 and 1947 houses used a similar loading system, but the reaction points for the 1947 house were part way along the foundation.

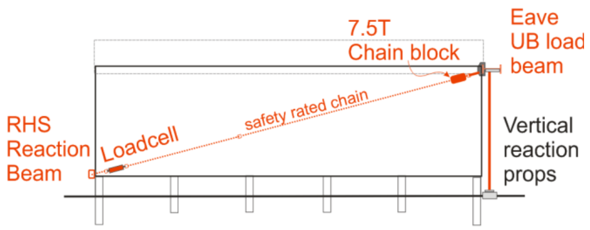


Figure 1: *Load concept for Initial House Testing.*

Figure 2: *Panoramamic view of 1983 House (13m x 6.2m) showing the chain block load system.*

The second 2013 test series objective was to measure full-house deflections and evaluate damage under reversing loads. In addition, snap-back tests allowed for the determination of fundamental frequencies of the 1923 and 1970 test houses so the dynamic responses could be correlated more accurately with building standards. The test procedure used a timber flitch beam with double steel inserts that could be added into the ceiling of a house without adding too much mass and thus altering the dynamic response. Loads were applied via a beam across the middle of the houses so compression closing deformations at the member junctions were not accumulated. A hydraulic load system was used to apply load to the houses including the house foundations. The reaction rig used for the 1970's house included 8m timber piles raked and driven to 5m depths with a steel universal beam connecting the pile tops (Figure 3) but was less stiff than the house. The rigidity of the load system was significantly increased for the 1923 house, where two substantial reinforced concrete foundation beams were fixed to the driven timber piles and a steel reaction frame was added. Figure 4, shows Laminated Veneer Lumber (LVL) load props being manually installed into the end of the house.

Details of the load application system as used for the 1923 house are shown in Figure 5, and the concept is represented in the 3-D illustration in Figure 6. The load spreading system used timber rivet plates connected to the LVL props. This loading system included a snap release for dynamic tests that was used at several different load levels. By removing the red packer components (Figure 6) tension load could be released via the yellow snap release to determine the dynamic response of the loaded houses. The 1970's house was loaded to 120kN and the 1923 house was loaded to 215kN, both using fully reversed cyclic displacements.

Figure 3: *1970's House test rig reaction frame with timber piles and steel beam.*

Figure 4: *1923 House with load props being installed. A concrete foundation and steel reaction frame were used in addition to the raking timber piles.*

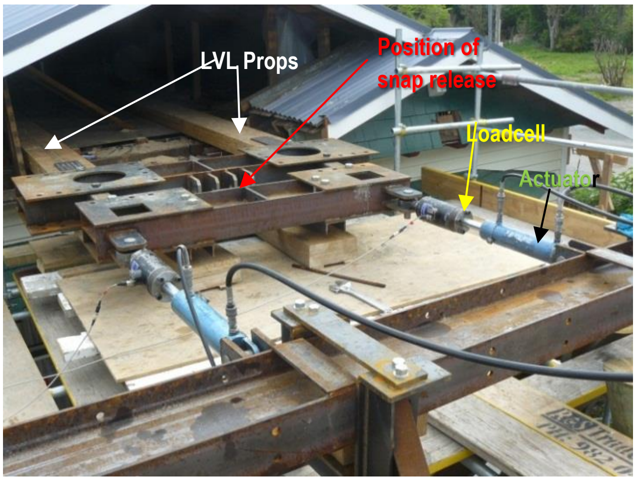


Figure 5: *Reaction frame above the scaffold with hydraulic load system, load cells and connector beams with space for snap release.*

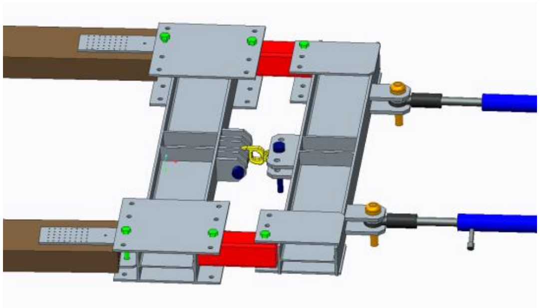


Figure 6: *Hydraulic Load system, showing brown LVL props, red reverse load packers and yellow snap release*

The rigidity of the 2014 load system was increased for the final uni-directional 1993 house test where a reinforced concrete foundation beam and slab were fixed to six screw piles, as shown in Figure 7. Two 7.5T chain blocks were fastened to the foundation block and to lengths of Reidbar. The Reidbars ran the length of the house and were fastened along their length to 190x45mm timber members. This was then fastened to 20mm thick plywood sheets and attached to the floor at regular intervals to ensure the load distribution was as even as possible. A support frame was constructed (Fig. 8) to aid the conversion of the tensile force in the chain blocks to horizontal forces running through the Reidbars and transfer vertical forces into the frame. Load was applied to the house in increments up to a maximum of 144 kN. Between each step, new damage to the house was observed and recorded. Five snap-back tests were completed in increasing loads, the highest being 80kN.

All houses tested were instrumented with numerous displacement monitoring gauges to correlate the movements of the buildings with the applied loads. Some measurements were recorded using computer controlled data acquisition, while others were monitored manually by personnel on site during testing. These data allowed for extensive analyses of the load-displacement and dynamic behaviour of these houses, as described in following sections.

Figure 7: *Reaction anchor, screw piled and embedded in ground beam, load cells and chain blocks, snap release ready to action1993 house.*

Figure 8: *Detail of vertical Props and top chain block*

3 HOUSES TESTED

The overview of the house construction, test methodology and key results are listed in Tables 1a and 1b below. Note the table row titles in Table 1a are represented by number in Table 1b.

Table 1a. Houses tested, descriptions and key results

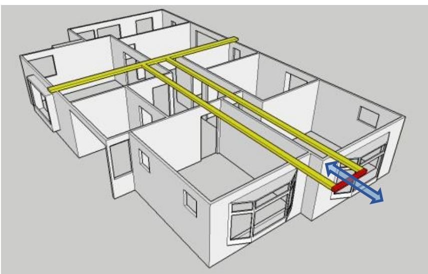
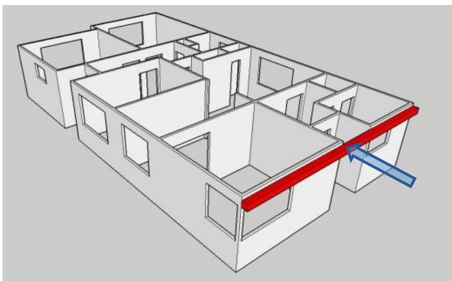
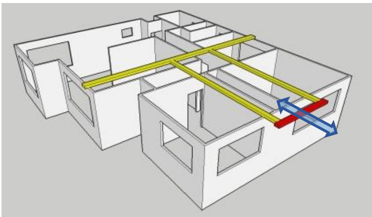
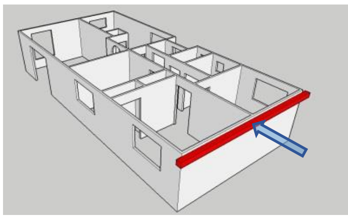
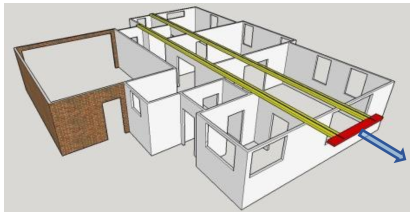
	1923 - RETREAT ROAD	**1947 - BEXLEY ROAD**
1 Cladding	Weatherboard	Weatherboard
2 Lining	Plaster on lath	Fibrous plaster & light timber panelling
3 Floor	Suspended floorboards on piles	Suspended floorboards on piles
4 Foundation	Small upstand on concrete perimeter foundation	Concrete perimeter foundation
5 Year &Test	2013 Hydraulic cyclic & snap-back	2012 - Diagonal uni - directional
6 Photo		
7 Load setup		
8 Built	1923	1947
9 Stiffness / Period	3.8 kN/mm / 0.29s	9.0 kN/mm / 0.23s*
10 Damping	12% (snapback linear)	-

Table 1b. Houses Tested, Descriptions and Key Results

	1970 - CARDRONA STREET	1983 –WAIROA STREET	1993 -NORCROSS STREET
1	Brick Veneer	Light fibre cement boards	Part brick veneer, part light fibre cement boards, solid brick garage boundary wall
2	Gypsum board linings	Gypsum board linings	Gypsum board linings
3	Suspended floorboards on piles	Suspended particle board on piles	Particle board on timber joist upper floor
4	Concrete piles, concrete perimeter foundation	Timber piles	Slab on grade lower floor
5	2013 - Hydraulic cyclic & snap-back	2012 - Diagonal unidirectional	2014 - Unidirectional & snap– back
6			
7			
8	1970 +	1983	1993
9	7.5-8kN/mm / 0.20s	18kN/mm / 0.14s*	27 kN/mm / 0.14s
10	>6% (10% by int walls)	-	2% ambient, ~6% hammer

* Building period in static tests was calculated from measured stiffness and estimated mass.

The tables above overview the house types and diagramatically represent the wall configurations (lower level 1993 house) and the load systems used. The stiffnesses are based on quasi-static tests.

The 1993 house had a very rigid garage wall with considerable torsion under load and had 11mm maximum displacement. Damping varied with deformation and was difficult to identify precisely and was therefore calculated using a hammer blow at lower storey eave level after the final 144kN load test was completed.

4 ANALYSIS AND RESULTS

4.1 *Overview of Test Results*

Maximum loads applied to all but one of the houses were limited by the load system but were well in excess of the previous earthquakes and design levels. The most comprehensive sequence and highest loads were applied to the 1923 house. The load deformation curve is shown in Figure 9. The load system was changed between push and pull cycles so the initial load was negative. The loading lifted the house off the foundation tie downs in both directions and required additional tie downs to reach the 215kN maximum load. At this extreme load condition, glass shards presented the greatest hazard.

Figure 10 shows a typical dynamic response from a snapback test clearly showing the damping decay. The initial period is also clear but the torsional effects and panel stiffness effects require further analysis. The period of the house increased from 0.25s to 0.32s as the tests progressed.

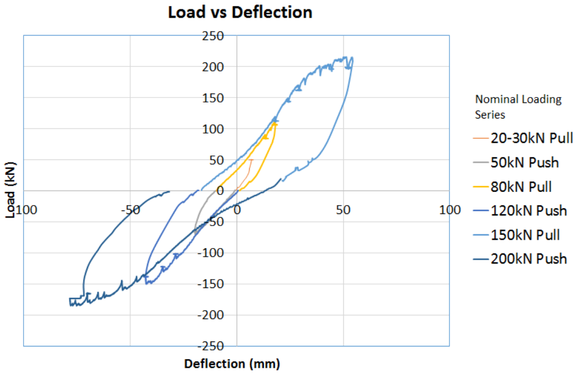


Figure 9. *Load deflection plot for 1923 house.*

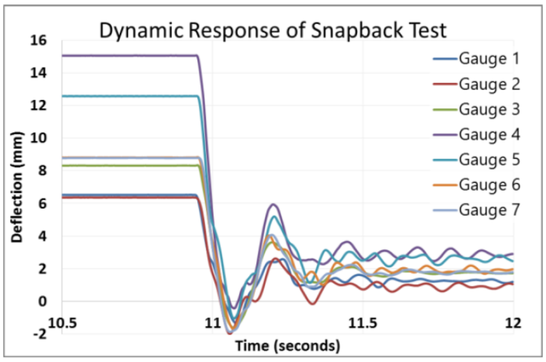


Figure 10. *Snapback response of 1923 house*

4.2 *Seismic performance under two design earthquake hazard levels*

Based on the above lateral strength and stiffness test results, seismic fragility analyses can be carried out to develop a better understanding of the seismic safety levels of these post-quake houses with respect to different hazard levels in the Christchurch area.

To perform seismic simulations, the single-storey houses can be simplified as a single-degree of freedom nonlinear spring with its load-deflection hysteresis calculated by an in-house FORTRAN finite element model called “HYST”(Figure 11). Details and successful applications of the HYST model in shear wall and building models have been published (Foschi, 2000; Li, et al. 2012a, 2012b). Originally developed to model the load-slip hysteresis F(Δ) of a single dowel-type fastener connection under lateral loads, the HYST model can also be used to represent the load-displacement hysteresis of a timber shear wall or a light-timber-framed building under lateral loads since their hysteretic behaviour share similar features such as strength and stiffness degradation and pinching. The model parameters need to be calibrated to match the load and displacement for a wall or building.

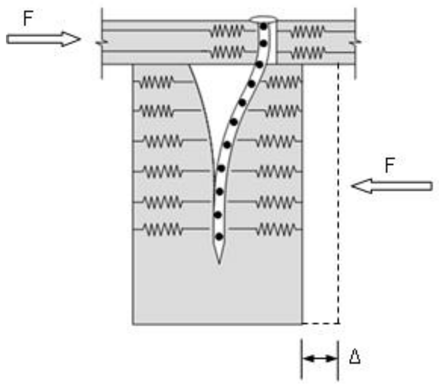


Figure 11. *HYST model schematics*

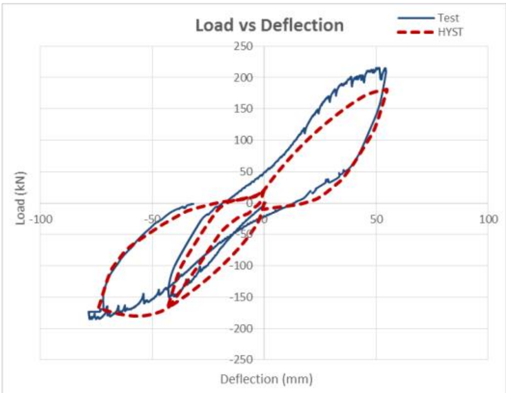


Figure 12. *HYST predictions vs test curves*

A case study was done on the 1923 house. As shown in Figure 9, the house behaved differently under push and pull loads. For simplicity, the average of the curves was used to calibrate the HYST model parameters. Figure 12 shows the calibrated HYST slightly over-predicted the response in the push part but under-predicted the strength and stiffness of the pull part. Assymetry of the house may contribute to this. With the calibrated HYST model, seismic simulations were carried out using a total of 19 earthquake records from the 2011 M6.3 Christchurch earthquake (Bradley and Cubrinovski 2011). 16 of the records were obtained from strong motion stations with soil class D or E and the others class B and C. The original records were scaled to match two design earthquake levels with a return period of 500 years and 2500 years, respectively. Table 2 lists three selected records and the scale factors for the two design levels of earthquakes. The scaling process of the 19 records followed the method in NZS 1170.5 (Standards NZ 2004) so that the scaled ground motions will match the design elastic response spectra in a range of period 0.2s to ~0.5s for soil class D. Based on the test results, the seismic weight of the house was estimated to be 121 kN and the elastic damping ratio was assumed to be 0.02.

Table 2. Earthquake ground motions used for seismic fragility analysis

Station ID-Component ID	Soil Class	Orig. PGA (g)	Scale factor k_1 for return period	
			500 years	2500 years
LYT-CACS-2	D	0.23	1.61	2.91
LYT-CBGS-1	D	0.55	0.70	1.25
LYT-CCCC-2	D	0.37	0.81	1.46

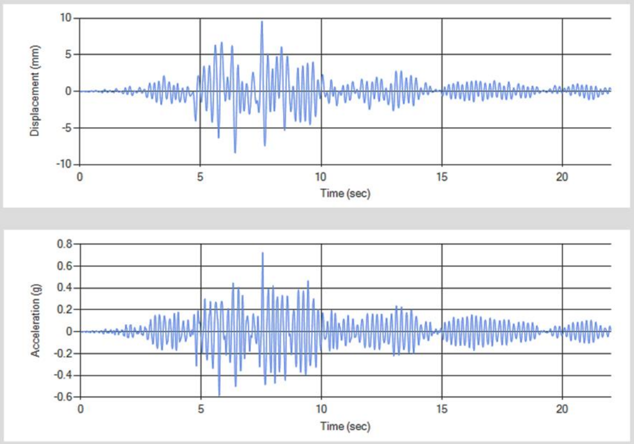


Figure 13. *Deflection and acceleration responses subjected to LYT-CACS-2 (500-year return period).*

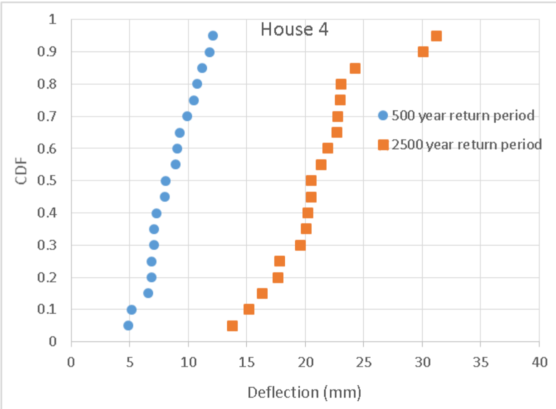


Figure 14. *Cumulative distribution of peak deflection responses 1923 house.*

Figure 13 shows the deflection and acceleration responses of the house subjected to LYT-CACS-2 record scaled to a 500-year return period. Figure 14 shows the cumulative distribution of peak deflection responses of the house subjected to 19 records scaled to two design earthquake levels. The results showed that at the 500 year return period design level, the average peak deflection response was only 9 mm (0.4% drift ratio) with a COV of 0.25. At the 2500-year return period, the average peak deflection response was 22 mm with a COV of 0.20. The simulation results indicated this house retains very significant residual capacity and performs well under two design levels of earthquakes.

5 DISCUSSION

The houses tested had all been through a major earthquake that was near to design level prior to the on-site tests, and had initial damage. All had adequate post-earthquake stiffness, and after 120-144kN of load had large residual capacity remaining. This residual strength must be accounted for when life safety earthquake performance is assessed for these types of structures.

Kirkham et al. (2014) identified earthquake damage evaluation in houses is needed. A rigorous approach is to develop fragility curves using the numerical approach demonstrated above. In addition damage terms need to be defined relating specifically to LTF buildings as outlined by Rosowsky and Ellingwood (2002). Work has commenced on evaluating damage threshold categories for these houses relevant to fragility curves.

6 CONCLUSIONS AND RECOMMENDATIONS

A successful series of full-scale house tests have been undertaken that have confirmed the performance of light timber framed houses and provided the residual strength and stiffness and a basis for further analysis to understand fragility of this type of structure. On-site testing, especially under disaster management restrictions makes such testing difficult, but the understanding of real house residual performance is important to avoid unnecessary strengthening and demolitions.

To extend this work, full house testing is proposed in the University of Auckland laboratory within a controlled and secure environment. A 13m x7m new house has been designed for bi-directional quasi-static loading to determine precise initial damage, followed by dynamic loading to design levels and quasi-static pushover tests to determine maximum load capacity and post peak load performance.

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