Seismic Performance of a Brick Veneer Steel-Framed House

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Abstract

The use of high-strength, cold-formed steel frames in residential construction is steadily increasing in both Australia and New Zealand. One common form of this construction uses brick veneer as a cladding, where non-structural brick walls are attached to the structural frame via brick ties. Under earthquake loading there is a complex interaction between the frame and veneer walls. While there is a standard component test method for assessing the seismic capacity of brick ties, this method has been developed around brick veneer on timber studs and its application to the very different steel stud characteristics is inappropriate. In order to realistically assess the overall performance of brick veneer construction with steel framing, a full scale one-room test structure "Test House" was tested on a shaking table. The Test House incorporated veneer walls with different geometries. It was subjected to varying levels of the El Centro earthquake ranging from moderate serviceability limit state ground motion to well beyond the design maximum considered earthquake for New Zealand. These levels of shaking were selected in order to ascertain the response for specific limit states to the Australasian Loadings Standard and to compare against minimum performance requirements. Comprehensive measurements on the frame and veneer walls were taken including acceleration, drift and differential movements between the frame and veneer. The Test House performed very well, with no brick loss up to 2.6 times El Centro (ElC) earthquake which is well in excess of all performance requirements.

Keywords: Steel-framed, test house, brick veneer, shaking table, brick ties.

1 Introduction

Brick veneer is a popular form of cladding for low-rise residential construction in Australia and New Zealand. The use of high-strength cold-formed steel frames with brick veneer cladding is steadily increasing in both Australia and New Zealand. In this form of construction, veneer walls are attached to the structural C section studs via metal brick ties. The high strength (G550) and thin walled steel studs used in New Zealand and Australia are unique to these two countries. The brick ties are normally connected to the flanges of the steel studs at one end and are embedded into the veneer mortar at their other end. In assessing the seismic performance of brick veneer houses, understanding the interaction between the frame and veneer via the ties is critical. There has generally been very little research into the performance of brick veneer structures and even less into that of steel-framed brick veneer houses. Recent studies on the seismic performance of brick veneer structures in New Zealand have focussed on timber framed houses (Thurston and Beattie, 2008a, 2008b & 2009). The results provided in this paper attempt to fill research gaps related to the overall performance of brick-veneer steel-framed houses subjected to large magnitude earthquakes.

In collaboration between Melbourne University, Auckland University, Building Research Association of New Zealand (BRANZ), National Association of Steel-Framed Housing in New Zealand (NASH-NZ) and NASH-Australia, a typical test structure known as the "Test House" was designed for a comprehensive seismic test program. A comprehensive series of tests were performed using a bi-directional shaking table. The main aim of the test program was to assess the performance of brick veneer walls when subjected to out-of-plane earthquake loading, having been previously subjected to in-plane loading which has the potential to weaken the veneer/tie/stud system for subsequent loading in the out-of-plane direction. This paper reports the overall performance of the Test House having been subjected to increasingly severe levels of shaking intensity induced in two orthogonal horizontal directions.

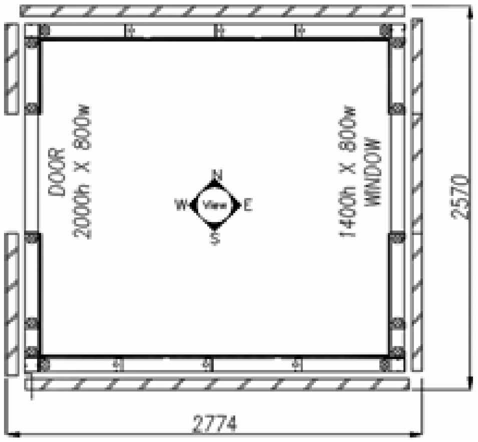
2 Test House Configuration

The Test House measured approximately 2.6m x 2.8m x 2.4m high and was built on an earthquake simulator (shaker table). It comprised of a steel frame with brick veneer cladding and plasterboard lining completely constructed using typical full scale components. All framing and bracing members were made of galvanised 0.75mm G550 steel. The top and bottom plates were made of 90 x 50mm plain C sections. Wall studs were lipped C sections (90 x 40mm) spaced at a nominal spacing of 600mm. The bottom plates were bolted to the shaker table with M12 bolts coupled with 5mm thick hold-down washers. Wall bracing was provided by 90mm x 40mm diagonal channels. All the framing connections between plates, studs, noggings and bracing were screwed connections.

The Test House was designed such that it encompassed a range of typical geometric features in the veneer walls in two different directions. It had two brick veneer walls without openings in one direction and in the orthogonal direction it had one wall with a window opening and the other wall with a door opening. Since the primary objective of the test was to examine the out-of-plane performance of the brick veneer walls, the brick walls were not connected at the four corners of the Test House. This was to ensure that the ultimate inertia load effect of the out-of-plane walls would be fully imposed on the ties. As testing was performed in both directions, each veneer wall could be treated as one specimen, and the geometric configurations would be equivalent to testing three (3) different cases: walls with no opening, wall with a window opening and a wall with a door opening. A plan of the Test House is shown in Figure 1a and Figure 1b shows the completed Test House.

A roof slab weighing 1500kg was placed on top of the Test House and supported by the frame to simulate the equivalent mass from a house roof. The roof mass was supported on the East and

West walls. With this roof mass combined with the designed frame wall bracing, the Test House was deemed to exhibit the same dynamic characteristics as those of a typical full scale single storey brick veneer house.



(a) Plan of Test House

(b) Completed Test specimen

Figure 1.Test House geometry

2.1 Construction details

The brick veneer walls were constructed using standard 70 series clay unit bricks measuring 230mm x 70 mm x 76 mm high with five core holes. All brick walls had 26 courses of bricks and spaced from the steel frame to form a cavity of 50mm. The bricks were bedded with 10mm thick mortar joints horizontally and vertically. The specified mortar mix composition was 1:0.5:4.5 (Cement: Hydrated Lime: Mortar sand) and mixed to a workable consistency.

Type B Eagle brick ties were used for connecting the veneer walls to the light steel framing using 12g Type 17 hex head screws, drilled through 40mm wide x 10 mm thick polystyrene thermal break strips which were glued to the external flange of each stud. The ties were installed using the “wet-bedding” technique as used in New Zealand. Ties were placed on the walls at every fourth course starting at the second base course while those around the edges and openings were at every second course.

The brick veneer walls were prevented from sliding along the bottom (interface with the table) by placing angle stoppers at the edges and door opening. These eliminated the possibility of a sliding failure at the brick-shaking table interface. The East and West walls were restrained by steel angle sections at the top which restricted their movement while shaking in the North-South direction. These top angle restraints were removed during shaking in the East-West direction.

Walls and ceiling were lined with 10mm thick plasterboard secured in position with 6mm self tapping screws and drywall adhesive. The vertical and horizontal joints between plasterboard sheets were finished with paper tape and cement compound. These details are in accordance with standard construction for New Zealand.

3 Experimental setup

The instrumentation and testing protocol for both directions are outlined below.

3.1 Test house instrumentation

Displacements and accelerations were measured at numerous locations on the Test House. Horizontal accelerations of the table, top of frame, in-plane and out-of-plane (at top and mid height) veneer walls were measured using uniaxial accelerometers. Linear Voltage Displacement Transducers (LVDTs) were used to measure the absolute displacement of the shaker table and top of Test House, and relative movement between the frame and veneer walls in both out-of plane and in-plane directions. Permanent accelerometers were provided at general locations on the Test House irrespective of the shaking direction while some instrumentation was repositioned when changing direction of shaking from East-West to North-South and vice-versa. In total 18 transducers and 26 accelerometers were used and all their data were recorded using a high speed data acquisition system. Additionally, strain gauges were installed on specific brick ties to monitor the load in the ties due to out-of-plane veneer deformation. Webcams were installed at strategic locations to monitor the relative movement between the frame and veneer through the cavity. Video recording for the various tests were also taken.

3.2 Input motions and testing protocols

To assess the performance of the Test House against specific design performance criteria, a design earthquake was selected as input excitation to the table. The selected excitation was the 1940 El-Centro earthquake. This earthquake is compliant with the New Zealand Earthquake loading Standard NZS 1170.5 (2004) and is widely used for benchmark testing. The specific levels of excitation which were targeted are listed in Table 1. The acceleration time history of the selected excitation was double integrated to obtain the corresponding displacement-time history and scaled in magnitude (refer Figure 2) for each earthquake design level and then used as input to the shaking table. This ensured that the frequency content was preserved for the various levels of shaking. The corresponding earthquake design levels were compared by a response spectrum analysis based upon a single degree-of-freedom system (refer Figure 2). A low pass filter of 0.8Hz was applied to the table input to eliminate displacements associated with such low frequencies likely exceeding the table displacement capacity (100mm) and which in reality would not produce dynamic response of any seismic significance.

Table 1: Earthquake levels adopted for testing and corresponding performance criteria

Earthquake design level	Scale relative to El-Centro	Required performance limits
Serviceability Limit State (SLS)	0.89 El-Centro	Localised hairline cracking of veneer and lining at most vulnerable locations. No post earthquake remedial work required.
Ultimate Limit State (ULS)	1.28 El-Centro	Noticeable cracking of veneer and linings, brick loss limited to < 5% of bricks or the top two rows above the top row of ties. Visible damage to frame expected but not to be significant and not to reduce ability of frame to support house.
Maximum Considered Earthquake (MCE)	1.72 El-Centro	Significant linings and framing damage but no collapse of framing. Significant brick loss.

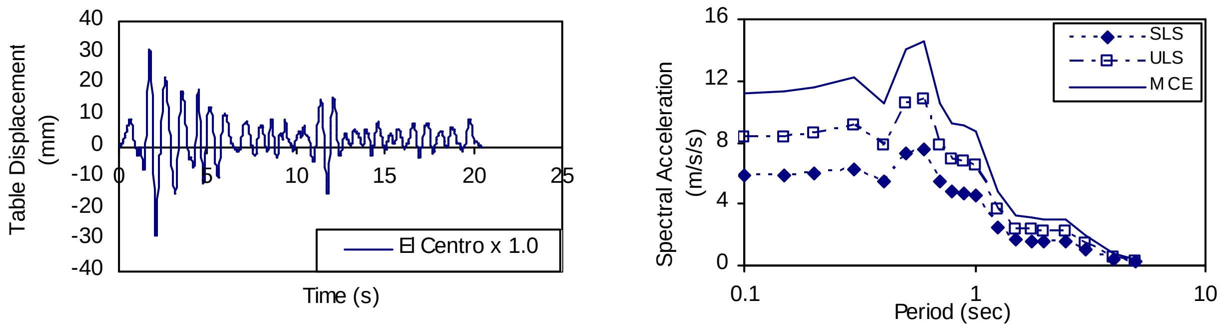


Figure 2: Selected input excitation: (a) El-Centro displacement-time history and (b) Response spectra for design earthquakes

While the main direction of interest prior to testing was excitation in the North-South direction, the Test House was subjected to excitations in each direction up to MCE level or greater. The testing schedule adopted is presented alongside observations made during the test in Table 3. The rationale for undertaking the prescribed testing sequence as outlined was to examine possible deterioration through in-plane loading effects prior to applying out-of-plane loading, since the test program's primary objective was to assess the performance of the brick veneer walls when subjected to out-of-plane earthquake loading. Once MCE had been applied in each direction with negligible damage it was considered likely that the N-S walls would be weaker than the E-W walls, due to a lower density of ties, and so further testing to try and initiate an out-of-plane failure was conducted on the N-S walls.

Intermittently before and after each shaking table test, low level pulse and swept-sine inputs were used to characterise the dynamic properties of the Test House. Pulses of 5 - 20Hz and swept-sine input with a frequency range of 0.5-30Hz were imposed on the Test House using the shaking table. These were used to provide the basis for the evaluation of the modal parameters of the Test House. Prior to the earthquake shaking, it was found that the Test House had a natural frequency of approximately 6Hz, which lies within the high energy content of the El-Centro earthquake as shown in Figure 2b. It could therefore be concluded that the selected record was appropriate for the testing schedule.

4 Experimental results

4.1 Dynamic characteristics

Modal testing was performed in each direction and used to evaluate the dynamic modal parameters of the Test House. The modal parameters include the natural frequencies, mode shapes and the damping ratios of each mode that influence the response of the Test House in the frequency range of interest. For both directions of shaking, three distinct modes were picked up. Typically, the first mode was a lateral sway (racking) mode of the entire Test House where the frame and the veneer walls moved back and forth together, the second mode was a sway mode of the out-of-plane walls only, while the third mode was the flexural response of the brick veneer walls in the out-of-plane direction. Table 2 presents a summary of the natural frequencies at which these distinct modes were picked for both directions of shaking.

Table2: Dynamic properties of Test House

Modal parameter	North-South direction	East-West direction
	Natural Frequency (Hz)	Natural Frequency (Hz)
First mode	5.8	5.5
Second mode	13.5	13.3
Third mode	26.8	24.7

The first natural frequencies of the Test House in the North-South and East-West directions are consistent with those expected in single storey houses. Hence the dynamic response for the Test House would be representative of a typical full scale house. Further, the Test House was expected to experience severe shaking using the selected test earthquake.

4.2 Test House performance

The Test House was subjected to progressively increasing excitation until failure was observed. A summary of the testing sequence and observations made after each test are presented in Table 3. The Test House performed very well in both directions of shaking. After performing shaking levels at SLS in each direction, ULS in the North-South direction and MCE in each direction, the observed damage was minor. Limited hairline cracking in the veneer was observed along with minor cracking of the plasterboard at the openings. This is considered to be an exceptionally good performance at this severity of shaking in comparison to the performance criteria as outlined in Table 1.

Table 3: Summary of tests performed and observations made

Test No	Earthquake level and direction		Observations
	N-S[1]	E-W[2]	
1	SLS		No damage observable whatsoever.
2	ULS		Minimal hairline cracks in the plasterboard lining at window top corners. Very limited hairline cracks at locations in brick veneer adjacent to opening. No damage to any brick ties, the screws or the thermal break.
3		SLS	No increase in damage from test 2.
4	MCE		Minor increase in cracking of internal plasterboard at window corners. No increase in cracking in brick veneer. No visible damage to any ties.
5		MCE	No increase in damage from test 4.
6	1.16MCE (2.0 El-Centro)		Noticeable rocking of wall brick piers at base of window. Hairline cracks post test extending right across pier base. No bricks lost. No visible damage to any ties. No visible damage to steel framing. Plasterboard cracks in window top corners now remaining open approx 1mm after test.
7	1.34MCE (2.3 El-Centro)		Increased rocking and cracking during test. No new cracks. No bricks lost. No visible damage to brick ties but in plane twisting for the East and West walls. No evidence of pullout of any ties. No visible damage to steel frame.
8	1.51MCE (2.6El-Centro)		Partial failure of connection between the top of diagonal brace and top plate for East and West walls. No bricks lost. No tie pullout from frame or veneer.
9	1.57MCE (2.7El-Centro)		Failure of connection of diagonal brace to top plate in East and West walls. Top 2 rows of bricks lost in East and West walls. No bricks lost from the North and South walls. Minimal to no damage to ties in the North and South walls. No tie pullout from studs in any location.

1. For shaking in the North-South direction, the North and South veneer walls were subjected to out-of plane loading.
2. For shaking in the East-West direction, the East and West veneer walls were subjected to out-of plane loading.

Given the outstanding level of performance of the Test House up to MCE earthquakes (refer Table 3) it was further subjected to even more severe shaking. The Test House did not suffer serious damage up to 2.6 times El-Centro (approximately 1.51 MCE or Modified Mercalli Magnitude 11). It should be noted that damage to the lining at 1.34 MCE would have caused more load to shed to the bracing system in subsequent tests. This in turn led to partial failure of the bracing system commencing at 1.51 MCE as noted in Table 3. Up to 2.6 El-Centro no bricks were lost or any significant damage occurred to the out-of-plane brick veneer walls. This is extremely good performance given the fact that the Test House had already been subjected to 7 high level earthquakes prior 2.6 El-Centro. It is considered impossible for a single house to experience this number and severity of earthquakes during its design life. The excellent performance of the NASH Test House is similar to that observed in a test structure using light steel framing with brick veneer, which was evaluated ten years ago (Gad et al., 1999).

4.3 Ultimate failure mode

Despite the very large racking displacement of the frame, the brick ties did not separate from the studs or the veneer in the out-of-plane direction. The brick ties were able to transmit the forces imposed on the out-of-plane veneer by the frame and vice-versa. At the end of 2.6 times El-Centro, a partial failure of the connection between the top diagonal brace and top plate for the East and West walls was noticed but no bricks loss or tie pullout from frame or veneer was observed. At the end of the test at 2.7 times El-Centro, which is the upper limit of the shaking table capacity for this test setup, a complete connection failure occurred at the ends of the top diagonal bracing on both in-plane walls (East and West walls). Based on visual observations, the connectivity between the veneer walls and the frame were maintained throughout the test with no ties disengaging except at the maximum level of shaking at 2.7 times El-Centro when the top two courses of bricks along the in-plane walls fell off. This was due to failure at the connections of the diagonal bracing and excessive twisting of the ties on the in-plane walls.

4.4 Assessment of measured accelerations and displacements

A summary of the measured responses obtained in both directions of testing are presented in Tables 4 and 5. These tables list the maximum accelerations, absolute and relative displacements for all tests. The table and top of frame displacements are the absolute displacements reached at the table or top of Test House respectively. The drift is based on the peak relative response between the top of the Test House and the shaking table. These results show that the brick veneer walls experienced rather large peak accelerations. Despite the high out-of-plane accelerations in the North-South direction, the out-of-plane brick veneer walls did not peel off from the frame.

Table 4: Summary of test results for earthquake testing (North-South shaking)

Test No.	Magni-tude	Table displace-ment (mm)	Top of frame displace-ment (mm)	Drift (%)	Out-of-plane veneer acceleration (m/s^2)		Relative out-of-plane veneer displacement (mm)			
					North Wall	South Wall	Top of frame: North Wall	Top of frame: South Wall	Mid-height: North Wall	Mid-height: South Wall
1	SLS (0.89ElC)	28.1	30.9	0.12	9.4	9.3	2.7	2.6	0.91	1.53
2	ULS (1.28ElC)	40.2	46.0	0.25	15.9	13.2	5.1	4.5	1.6	4.7
4	MCE (1.72ElC)	51.0	61.1	0.42	19.6	19.5	7.1	7.1	2.4	7.9
6	1.16MCE (2.0 ElC)	53.4	74.4	0.87	21.1	25.9	8.4	9.7	3.6	6.9
7	1.34MCE (2.3ElC)	70.6	94.6	1.00	25.4	29.8	8.3	13.6	6.8	6.5
8	1.51MCE (2.6ElC)	80.6	119.3	1.61	24.5	33.9	9.8	16.1	8.4	9.9
9	1.57MCE (2.7ElC)	86.4	154.1	2.82	22.6	32.9	12.1	12.8	9.6	17.1

At 2.6 El-Centro earthquake intensity of shaking in the North-South direction, the maximum relative displacement between the frame and the out-of-plane veneer was approximately 16mm. Despite this very large magnitude earthquake and the fact that the Test House had already been subjected to severe shaking in both directions (Tests 1-7), the out-of-plane veneer did not fail. This reflects the rather high degree of resistance and robustness of the connections of the ties at both the stud end as well as the veneer end. At the MCE level earthquake intensity of shaking in

Table 5: Summary of test results for earthquake testing (East-West shaking)

Test No	Magnitude	Table displace-ment (mm)	Top of frame displace-ment (mm)	Drift (%)	Out-of-plane veneer acceleration (m/s^2)		Relative out-of-plane veneer displacement (mm)		Maximum in-plane veneer relative displacement (mm)
					East Wall	West Wall	East Wall	West Wall	
3	SLS 0.89(ElC)	23.4	25.8	0.10	6.6	11.7	1.0	0.9	2.6
5	MCE 1.72(ElC)	43.9	49.6	0.24	12.3	14.4	8.0	5.2	3.4

the East-West direction, the maximum relative displacement between the frame and in-plane walls was only 3.4mm (refer to Table 4). This is significantly smaller than the relative displacement of ±24mm which is imposed by the tie standard AS/NZS 2699.1 (2000) as part of the tie testing procedure. This suggests that the tie test procedure is too conservative.

The maximum relative displacement between the frame and the out-of-plane veneer for the MCE earthquake was about 8mm in both the North-South and the East-West directions. At this level of relative displacement there were no visible signs of damage to the veneer walls. Most of these relative displacements would have been accommodated by: (i) flexibility in the flange of the stud; (ii) compressibility of the thermal break and (iii) bending and distortion of the ties. The bending of the ties results from the fact that the line of force along the tie does not coincide with its connection to the stud.

5 Conclusions

A Test House constructed of high-strength cold-formed steel frame with brick veneer cladding and plasterboard lining was tested under earthquake loads to assess the performance of out-of-plane veneer walls when subjected to design earthquakes. The Test House was subjected to increasing levels of the 1940 El-Centro North South earthquake record. This earthquake was scaled to specific levels to match certain seismic demands specified in NZS 1170.5 (2004) in order that the performance of the Test House could be directly related to specific design limit states.

Up to the Maximum Considered Earthquake (MCE) (1.72 El-Centro earthquake), when major brick losses but no collapse of the frame would be considered acceptable, the observed damage to the Test House was minor. Limited hairline cracking in the veneer was observed along with minor cracking of the plasterboard at the openings. At this intensity of shaking, a maximum relative displacement between the frame and out-of-plane veneer of about 8mm was obtained.

With the exceptional performance up to the MCE intensity, additional excitation tests (2 ElC, 2.3 ElC and 2.6 ElC) were imposed to establish the ultimate performance level of the Test House. The Test House survived all of these three severe earthquakes with no loss of bricks. After the 2.6 El-Centro earthquake, damage to the frame’s diagonal bracing was observed. Finally, the Test House was subjected to 1.57 MCE (2.7 El-Centro) earthquake in the North-South direction, which led to failure of the connections of the diagonal frame bracing and in turn loss of bricks in the in-plane walls. A racking displacement of about 70mm (2.8% drift) was measured at the 2.7 El-Centro intensity of shaking. The maximum relative displacement between the frame and out-of-plane veneer measured was approximately 16mm. Despite the very large racking displacement of the frame and relative movement between the frame and out-of-plane veneer walls, the brick ties in the out-of-plane direction did not separate from the studs or the veneer. The brick ties were able to transmit the forces imposed on the out-of-plane veneer to the frame and vice-versa.

Given that the Test House was designed using conventional methods, constructed from typical components and built using standard techniques it would be considered to be representative of brick-veneer light steel framed construction. With its excellent performance under an extremely onerous earthquake testing program, it can be concluded that such a form of construction would be expected to perform very well in areas of high seismicity. The results also show that a revision of the loading regime for brick tie component testing (AS/NZS 2699) should be undertaken.

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