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EXPERIMENTAL INVESTIGATION OF UNREINFORCED MASONRY VENEER WALL SYSTEM UNDER OUT-OF-PLANE LOADING

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ABSTRACT

Unreinforced masonry veneer walls are susceptible to extreme damage and possible collapse under wind and earthquake loading. The behaviour is complex due to the interaction of the masonry veneer, the timber support frame and the wall ties which connect them. The behaviour is further complicated due to spatial variability in the properties of constituent materials. In this paper, the outcome of full-scale testing of masonry veneer systems under out-of-plane loading, which includes multiple repeat specimens, is reported. These masonry veneer wall systems represent contemporary construction practices in Australia according to AS 3700. A total of ten masonry veneer assemblies, dimensions of 2398 mm (height) × 2390 mm (length) × 110 mm (thickness), supported via wall ties to a four-stud timber frame, and theoretically identical properties, were tested to predict the stochastic (probabilistic) strength of veneer walls. Out-of-plane loading (airbag pressure) was applied on the wall's external surface, which induced compression in the wall ties. The flexural bond strength of the brick-mortar joints was estimated by the bond-wrench test, conducted in parallel with wall testing throughout the experimental program. The typical trend of the pressure-displacement behaviour was, veneer cracking at a mean load of 1.84 kPa followed by a slight decrease in pressure. Then, the pressure climbed until it reached the veneer system peak load where randomly different rows of the wall ties were buckled or nail pulled out from the timber studs. The test was continued beyond the peak load to observe the veneer system behaviour. The coefficient of variation of peak load was found to be 11%. The nature of the veneer cracking and tie failures are reported and discussed at the end of this paper.

KEYWORDS: *bond strength, lateral pressure, tie failure, unreinforced masonry, variability*

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INTRODUCTION

A masonry veneer wall consists of an exterior masonry cladding separated from the flexible structural backing frame by an air cavity, designed to form the skin of the structure. The structural backing system varies according to the traditional construction technology being mostly timber, or light steel stud frames or structural masonry in United States, Australia and New Zealand [1, 2] and reinforced concrete masonry infilled frames in Europe. In Australia, the internal layer of the masonry veneer wall system is most often composed of timber framing (see Figure 1) and provides lateral support via wall ties attached to the external leaf of masonry. The ties are fabricated from galvanised or stainless steel, and exhibit axial stiffness and strength in tension and compression, however negligible shear resistance. Wall ties perform three primary functions, namely: (1) provide a connection/support to the masonry veneer; (2) transfer lateral loads incident on the veneer to the supporting frame; (3) allow in-plane movement to accommodate differential displacements. The structural behaviour of the veneer walls depends on support conditions, the relative stiffnesses of the masonry veneer and backup frame and the tie characteristics. Therefore, individual tie forces are not merely a function of their nominal tributary loaded area, but the outcome of these various factors' interaction. Several recommendations for the design and detailing of wall ties are available in different codes. However, because of the lack of a rational method for the design of wall ties, masonry codes often contain deemed-to-satisfy requirements rather than systematic procedures for the design of wall ties.

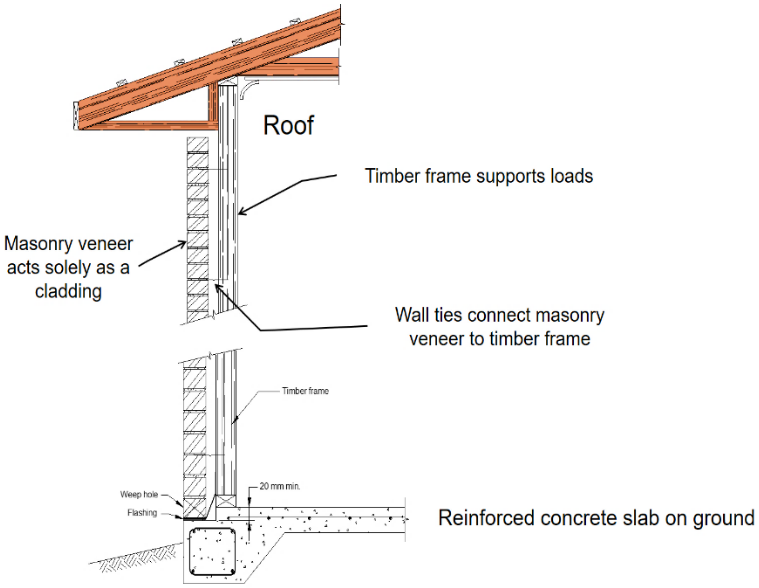


Figure 1: Typical Masonry Veneer Wall System Details (Think Brick Australia)

The experimental characterisation of brick masonry veneer walls has necessarily considered the system composed of the brick masonry veneer, the backup wall or frame and the ties connecting the two. Some experimental investigations have focused on the static in-plane and out-of-plane (OOP) behaviour of the brick masonry veneer systems. Some of these works have also focused on the dynamic shaking table tests of both brick veneer elements [3 – 6] or full scale or reduced scale buildings with attached brick veneer walls [7 – 9]. Based on some of the earlier studies of commercial brick veneer walls, Page et al. [8, 9] conducted a preliminary experimental study in which the emphasis was on developing an effective means of measuring the in-situ tie forces. The tie force distribution on a vertically spanning cavity brick masonry wall was studied by measuring the individual tie displacements in-situ as the walling system was subjected to a uniform lateral pressure load and inferring the tie forces from accompanying load versus displacement tests of individual ties. Cavity walls (two leaves of masonry separated by a cavity) and veneer walls were tested under lateral loading using an airbag. Based on the literature available, it has been observed that the OOP seismic performance of residential anchored brick veneer walls is generally governed by: (1) the tensile and compression strength and stiffness of the tie connections; (2) tie installation details (screwed or nailed); (3) spacing of the ties, especially for ties along the edges of openings and at the upper regions of walls; (4) wall dimensions and configurations.

The research work reported in this paper is a part of a broader project which is in progress at The University of Newcastle, Australia. The project aims to develop an improved understanding of the behaviour of unreinforced masonry (URM) veneer and cavity wall systems through extensive experimental and numerical studies when subjected to wind and seismic hazards considering the spatial variability of the material properties. In this study, 'Monte-Carlo lab testing' of full-scale masonry veneer facade systems subjected to OOP loading, including multiple repeat specimens, are reported to deduce probabilistic distributions of collapse loads. The masonry veneer wall systems tested in this study are relevant to Australian contemporary masonry building typologies and materials.

MONTE-CARLO VENEER WALL SYSTEM TEST

Wall Specimens and Test Setup

Figure 2 depicts the schematic diagram of the complete test setup used in this study. A total of ten theoretically identical masonry veneer assemblies, dimensions of 2398 mm (height) × 2390 mm (length) × 110 mm (thickness) were fabricated for testing. The dimensions of the wall were selected in a way that wall cracking and distinct failure modes can be observed within the chosen wall geometry. Typical Australian brick size of 76 mm (height) × 230 mm (length) × 76 mm (thickness) with 10 mm mortar joints was used to build the URM wall of chosen geometry. Mixing ratio for the mortar was 1:1:6 (cement: lime: sand by volume). Light-duty' Type A' (non-seismic areas) veneer ties were installed at a spacing of 600 mm in the horizontal and vertical direction along with the double rows of the ties at the top, and nail fastened (side-fixed) to the timber studs by maintaining 50 mm cavity width as per AS 3700 [10]. The timber stud frame dimension was 90 mm × 35 mm, representing the typical Australian timber-framed construction as per AS 1684.4 [11]. At the mid-height of the wall, horizontal noggings were added to the timber frame which is standard construction practice to prevent lateral torsional buckling of studs under bending. Moreover, a damp-proof course (DPC) of 110 mm breadth (across the thickness of the masonry veneer) was installed between wall base and concrete footing to replicate the realistic construction practice. Professional masons were commissioned to fabricate the walls and each wall was cured for at least 14 days prior to testing. For each batch of mortar mixed, two x 6 unit high masonry piers were constructed for bond wrench testing at the same age as the associated wall constructed, using that mortar. It should be noted that due to availability of masons, it was not the same individual mason who constructed all walls.

An airbag loading system was used to apply uniformly distributed pressure to the external surface of the masonry veneer; therefore, ties in the cavity would be in compression. The boundary conditions of the wall were as follows, (a) top of the veneer wall system was free, (b) top of the timber restrained for lateral movement, (c) bottom of the timber restrained for all movement and (d) no additional in-plane support. Linear variable differential transformers, LVDTs (referred to as potentiometers onwards) were used to measure and monitor the displacements at different locations on the wall specimen, as shown in Figures 2 and 3. In additional to the potentiometers shown in Figure 2, a potentiometer was located beside every tie to record the change in cavity width during testing, as shown in Figure 3.

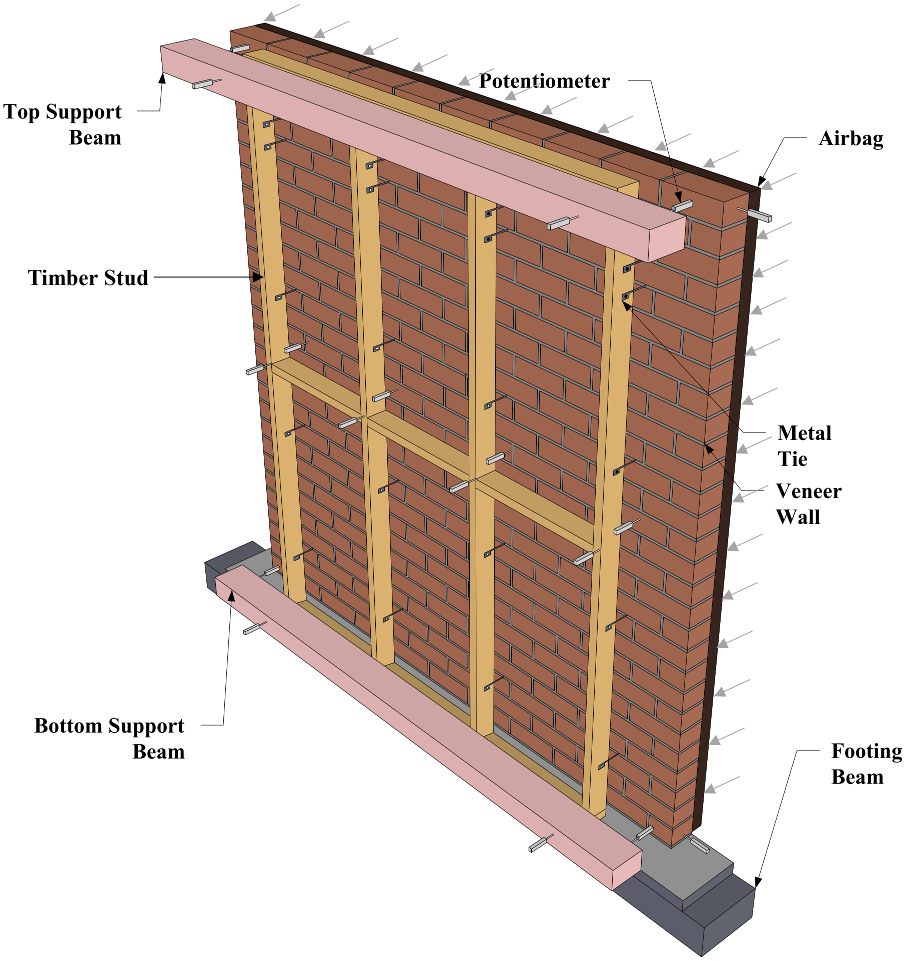
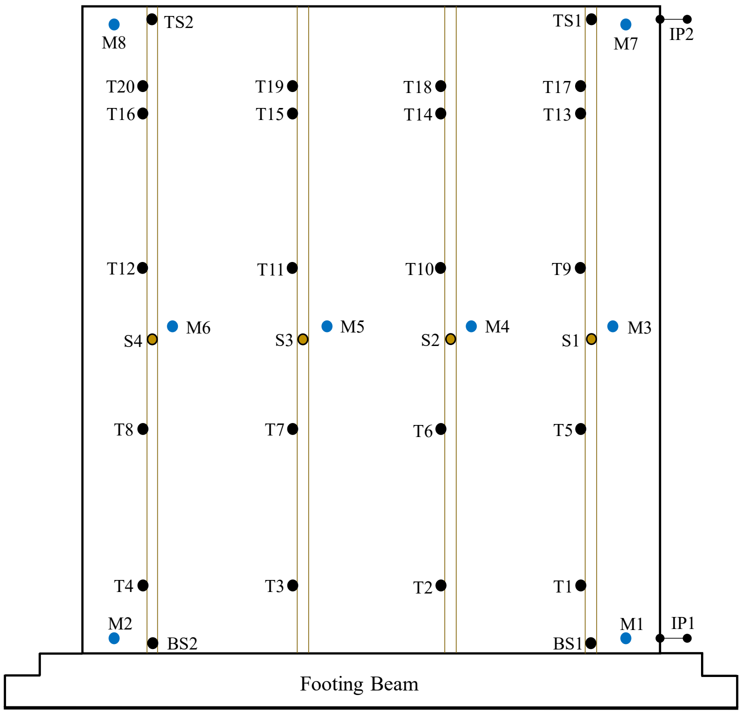


Figure 2: Schematic Diagram of the Test Setup Under Lateral Out-of-plane Loading



Note: T = Ties; M = Masonry; S = Studs; TS = Top-support; BS = Bottom-support; IP = In-plane

Figure 3: Instrumentation (Potentiometers Position) of the Veneer Wall for OOP Test

Veneer Wall Testing

Uniformly distributed pressure loading was applied slowly via the airbag system. For nine out of ten walls, the pressure was applied montonically and was continued beyond collapse (peak) load. For the last specimen, the pressure was applied in cycles of loading and unloading as shown in Figure 4. Each test was terminated when the post-peak lateral pressure dropped by at least 20% of the peak load.

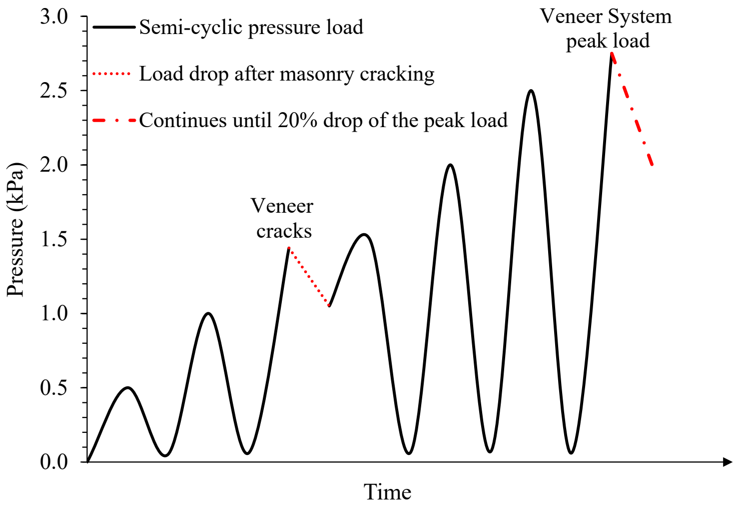


Figure 4: Semi-Cyclic Pressure Loading History for VWI-10 Specimen

EXPERIMENTAL RESULTS AND DISCUSSION

During each test, the following observations were recorded: applied pressure, including the wall's load-carrying capacity (wall collapse load), out-of-plane displacements of the masonry veneer, individual tie deformations, and bending deflections of the timber framing studs. The typical trend of the pressure versus wall mid-height displacement curve was, veneer cracking at a mean load of 1.84 kPa, followed by a sudden small pressure drop, then increasing pressure until veneer system peak load was achieved, where randomly different rows of the wall ties buckled or nails pulled out (in the direction of force) from the timber studs. Examples of this response can be seen in Figures 5 to 7. Table 1 summarises the key results (masonry cracking and veneer system peak load and associated displacements) for all wall specimens with mean and COV values.

Compared to all other specimens, VW-1 exhibited considerably higher masonry cracking (P_{cr}) and system peak load (P_{max}). This is believed to be the result of VW-1 having stronger masonry (higher flexural bond strength) as a result of the increased curing time leading up to this first test. The higher cracking resistance for VW-1 resulted in buckling of some of the ties before masonry cracking, unlike the remaining specimens, for which veneer cracking occurred prior to any significant non-linear behaviour in the ties. Figures 5 to 7 show the load versus veneer mid-height displacement behaviour for three of the walls, VW-1: higher cracking load than any specimens, VW-2: representative of the remaining eight monotonically tested specimens and VW-10: subjected to semi-cyclic loading. From the mean-envelope curve of Figure 6, it can be said that the monotonic response envelopes the cyclic response quite closely. However, due to the cyclic nature of the loading, the system's displacement capacity increased significantly (38.78 mm). The COV for overall veneer system peak load was considerably less (0.12) than the COV of masonry cracking load (0.21), which indicates the higher variability in masonry strength properties compared to other materials (ties) in the wall system.

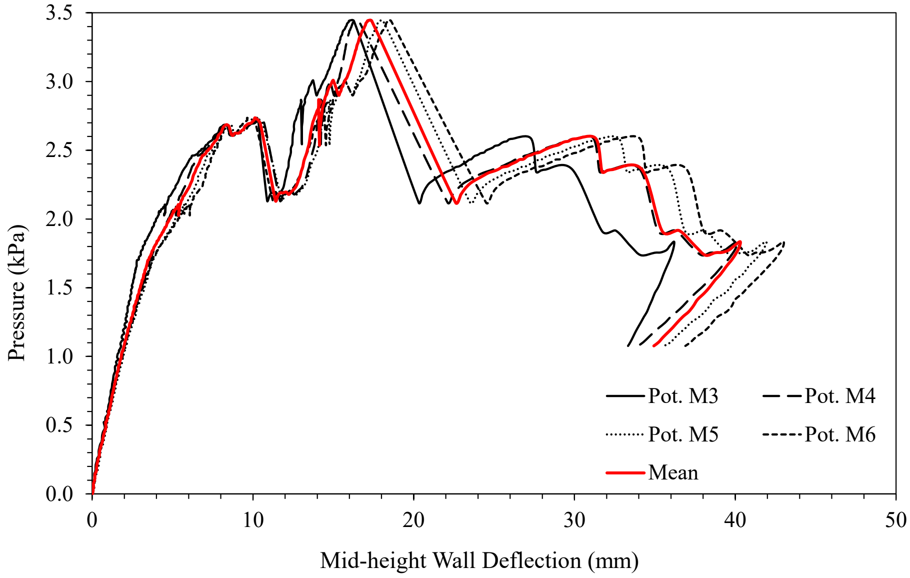


Figure 5: Pressure vs. Mid-height Wall Deflection of VW-1 Wall Specimen

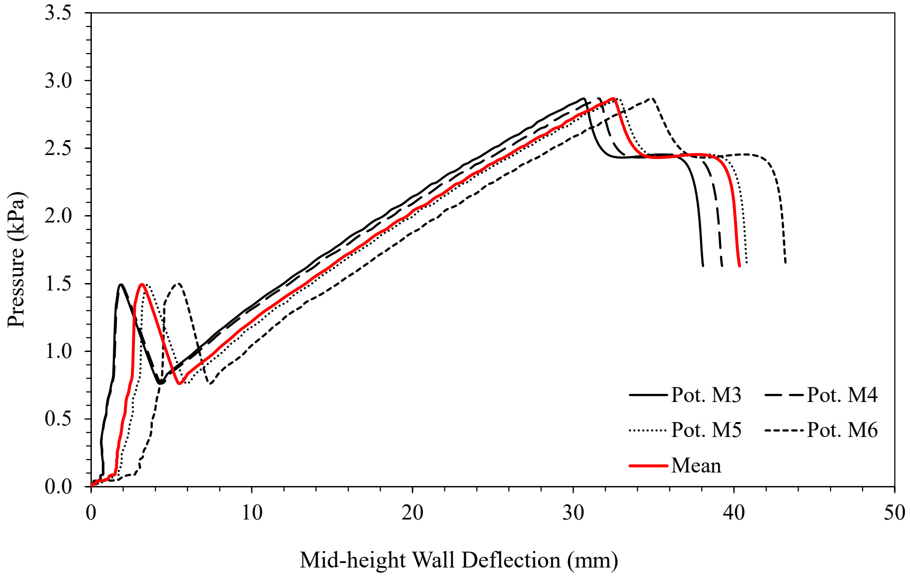


Figure 6: Pressure vs. Mid-height Wall Deflection of VW-2 Wall Specimen

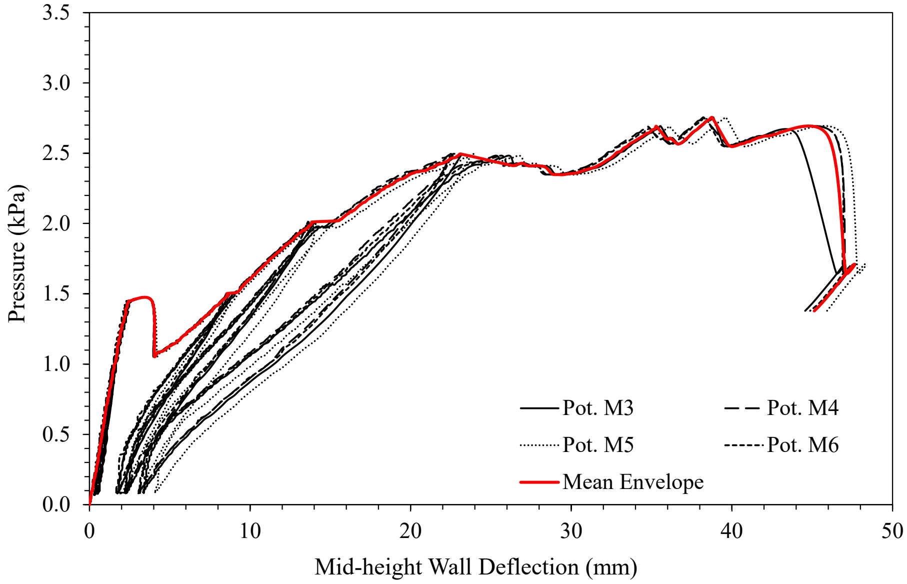


Figure 7: Pressure vs. Mid-height Wall Deflection of VW-10 Wall Specimen

Eight out of ten walls exhibited a single horizontal layer of the crack through the brick-mortar interface. The lowest crack level was observed at courses between 11 and 12 (from bottom) and the highest in between 15 and 16 (see Table 1). The position of cracking depends upon the maximum flexural tensile stress induced by the applied out-of-plane pressure loading and the presence of a weak joint in the masonry. Therefore, spatial variability in masonry joint strengths plays a significant role in defining the location of veneer cracking. Figure 8 shows the typical horizontal crack across the wall length observed in the test. The deflected shape of the wall following the development of the veneer crack is shown in Figure 9.

When the veneer was subjected to OOP loading, prior to veneer cracking the maximum tie forces were experienced by the top two rows of ties. Upon veneer cracking, the load was redistributed to the two rows of ties on either side of wall mid-height. Tie displacement histories for all specimens were recorded and analysed to understand the tie failure progression and quantify the tie force. However, tie displacement histories for only one wall (VW-2) are reported in this paper (see Figure 10) to keep the discussion brief.

Table 1: Masonry Cracking and Veneer System Peak Load from Inward Loading Test

Wall ID	**Test Age (days)**	**Masonry Cracking Load, P_{cr} (kPa)**	**Displacement at P_{cr} (mm)**	**Veneer System Peak Load, P_{max} (kPa)**	**Displacement at P_{max} (mm)**	**Position of Veneer Cracking (between courses from bottom)**
VW-1	47	2.74	10.15	3.44	17.14	14-15
VW-2	20	1.48	3.29	2.70	32.57	14-15
VW-3	14	1.72	1.93	2.67	27.61	11-12
VW-4	16	1.79	2.26	2.77	19.42	11-12 & 12-13
VW-5	26	1.98	4.41	2.55	21.63	10-11 & 11-12
VW-6	16	1.59	2.52	2.62	21.52	12-13
VW-7	20	1.55	2.95	2.28	30.62	15-16
VW-8	16	2.14	3.25	2.80	27.10	15-16
VW-9	17	1.95	3.47	2.61	24.98	12-13
VW-10	15	1.45	2.44	2.75	38.78	11-12
Mean	-	1.84	3.79	2.86	26.14	-
COV	-	0.21	0.61	0.12	0.25	-

Figure 8: Brick Veneer Cracking Under Out-of-plane Loading

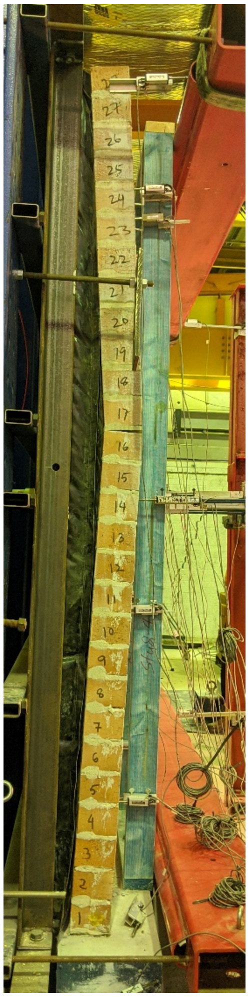


Figure 9: Deflected Shape of the Wall After Veneer Cracking

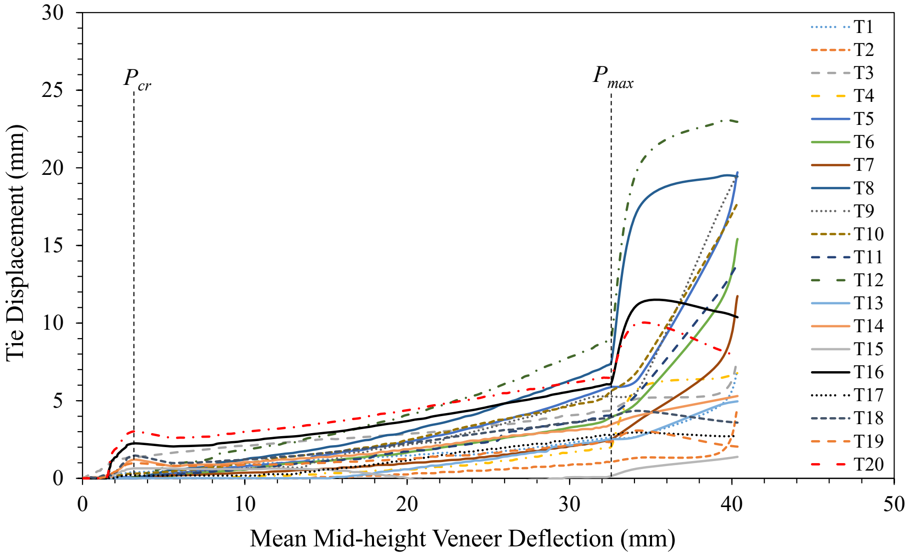


Figure 10: Tie Displacement with Masonry Veneer Wall Deflection of VW-2

The most common tie failure mode observed in the wall testing was the buckling of the tie at 90° across the cavity (see Figure 11), although a few of the ties failed via nail pull out from the timber. It is worth mentioning that a larger number of ties failed via nail pull out for semi-cyclic loading, compared to the monotonic loading. For nail-pull out failure, ties were failed at the tie-nail-timber connection (in the direction of applied pressure) instead of tie bending at the middle, as shown in Figure 12. On the other hand, no timber studs failed during wall tests, which can be interpreted as linear elastic behaviour of the stud.

Figure 11: Typical (Buckling) Tie Failure Observed in Veneer Wall Tests

Figure 12: Nail Pull Out Tie Failure Observed in Veneer Wall Tests

CONCLUSIONS

In this Monte-Carlo lab testing study, ten veneer wall systems were tested under later OOP loading to infer the probabilistic failure of the masonry and whole system. Bond wrench tests were conducted in parallel for each batch of the mortar used to prepare the veneer walls to know the mortar joint's flexural tensile strength. The OOP loading test's overall behaviour was somewhat similar in terms of veneer failure progression, tie yielding and failure, and timber studs deflection except for the first wall (VWI-1). When flexural tensile strength of the mortar is comparatively higher (VW-1), the top two rows of ties failed before masonry cracking; otherwise tie buckling occurred after the veneer cracks somewhere near mid-height. The load-deflection response of monotonic testing enveloped closely the semi-cyclic testing behaviour, which validates the efficacy of the monotonic loading test to identify the system peak load. Tie failure and tie deflection histories are observed throughout the test program and reported in this paper. The typical tie failure was buckling of the tie at a right angle; nonetheless, a substantial number of ties failed by nail pulling out of the timber for the semi-cyclic scenario.

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REFERENCES

[1] Paton-Cole, V. P., Gad, E. F., Clifton, C., Lam, N. T. K., Davies, C., and Hicks, S. (2012). "Out-of-plane performance of a brick veneer steel-framed house subjected to seismic loads," *Construction and Building Materials,* 28(1), 779-790.

[2] Reneckis, D., LaFave, J. M., and Clarke, W. M. (2004). "Out-of-plane performance of brick veneer walls on wood frame construction," *Engineering Structures,* 26(8), 1027-1042.

[3] Jo, S. (2010). Seismic Behavior and Design of Low-rise Reinforced Concrete Masonry with Clay Masonry Veneer, PhD Thesis*, The University of Texas at Austin*.

[4] McGinley, W. and Hamoush, S. (2008). "Seismic Masonry Veneer: Quazi-Static Testing of Wood Stud Backed Clay Masonry Veneer Walls". *Proc., Structures Congress*, Vancouver, BC, Canada.

[5] Okail, H. (2010). Experimental and Analytical Investigation of the Seismic Performance of Low-Rise Masonry Veneer Buildings, Ph.D. Thesis*, University of California, San Diego*.

[6] Reneckis, D. and LaFave, J. M. (2010). "Out-of-plane seismic performance and detailing of Brick Veneer walls," *Journal of Structural Engineering,* 136(7), 781–793.

[7] Okail, H. O., Shing, P. B., McGinley, W. M., Klingner, R. E., Jo, S., and McLean, D. I. (2011). "Shaking table tests of a full-scale single-story masonry veneer wood-frame structure," *Earthq. Eng. Struct. Dyn.,* 40, 509-530.

[8] Page, A. W., G., S., and Masia, M. J. (2007). "Wall tie behaviour in cavity and veneer wall systems (A preliminary investigation)". *Proc., 10th North American Masonry Conference* St. Louis, Missouri, USA.

[9] Page, A. W., Simundic, G., and Masia, M. (2009). "A Study of Wall Tie Force Distribution in Veneer Wall Systems (Stage 1)". *Proc., 11th Canadian Masonry Symposium*, Toronto, Ontario, Canada.

[10] Standards Australia. (2018). Masonry Structures *(AS 3700)*. Standards Australia Limited, Australia.

[11] Standards Australia. (2010). Residential Timber-framed Construction, Part 4: Simplified – Non-Cyclonic Areas *(AS 1684.4)*. Standards Australia Limited, Australia.