Experimental Evaluation and Probabilistic Analysis of the Masonry Veneer Wall Tie Characteristics

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ABSTRACT: Wall tie strengths and stiffnesses are not constant for all ties in a masonry veneer wall system. This paper uses an Australian standard tie calibration experimental approach to delve into wall-tie probabilistic characterisation by estimating the mean, variance, and characteristic axial tensile and compressive strengths and how they influence failure behaviour. A total of 50 veneer brick-tie-timber subassemblies are tested using an Instron testing machine, 25 samples in compression and 25 samples in tension. Both cross head displacement and displacement across the cavity is recorded along with the complete load versus displacement response, which allows determination of elastic stiffness, peak strength and displacement capacity. Using the maximum likelihood method, a range of probability distributions are fitted to tie strength and corresponding displacement histogram data sets, and a best-fitted probability distribution is selected for each case. A Cumulative Distribution Function plot was also used along with the Anderson-Darling test to infer a goodness-of-fit for the probabilistic models.

1 INTRODUCTION

Brick masonry walls are used as external cladding in both residential and commercial construction in many countries including Australia. Masonry veneer walls comprise of exterior masonry cladding and a flexible structural backing partitioned by an air cavity. The structural backing system varies according to the construction practice being mostly timber, and light steel stud walls or structural masonry in the United States, Australia and New Zealand (Paton-Cole et al. 2012, Reneckis et al. 2004) and reinforced concrete masonry infilled frames in Europe. In Australia, the internal layer of the masonry veneer wall system is composed of timber framing mostly, and provides lateral support by wall ties attached to the external leaf of masonry.

The ties are galvanised or stainless steel depending on the geo-environmental requirement, and typically have axial stiffness and strength in tension and compression, but negligible shear capacity. The out-of-plane mechanisms represent the primary cause of structural failure in unreinforced masonry (URM) buildings under seismic and wind loading, explicitly caused by poor tie connections and strengths. This is because, the ties are responsible for transferring the lateral loads from exterior wall to the backup and allowing in-plane movement to accommodate differential movements, therefore, the properties of the ties have an important role to play in the structural performance of veneer wall system.

Recognizing that tie connections play a crucial role for in-plane and out-of-plane performance of the masonry veneer system under seismic actions, some researchers carried out investigations aimed at assessing the behaviour of the tie connections under shear, tension and compression (Choi & LaFave 2004, Mertens et al. 2014, Page et al. 2009, Reneckis 2009, Ribeiro et al. 2014, Zisi & Bennett 2011). Choi & LaFave (2004) experimented with brick-tie-timber subassemblies for varying tie thickness, initial offset displacement, method of attachment of ties to timber studs, and type of loading (including cyclic), subjected to lateral loads in the in-plane and out-of-plane directions. Reneckis (2009) also conducted subassembly tests akin to Choi & LaFave (2004) to explore tie connection behavior further, primarily when loaded in tension, for various code compliant and non-compliant tie installation methods. As a part of the large-scale testing program carried out at Delft University of Technology to characterise the behaviour of the terraced house typology, characterisation of wall tie connection in cavity walls was reported by Skroumpelou et al. (2018). When the wall system is subjected to a lateral load, the distribution of forces in the ties will be influenced by the deflection of the backup, and maximum forces are experienced by the top and the bottom rows of the ties (Muhit et al. 2019).

Wall tie strengths and stiffnesses are not constant for all ties in a masonry veneer wall system. While an assumption of deterministic material strength properties may be considered in the majority of the masonry design, there is growing realisation that material variability needs to be considered when assessing structural safety. Therefore, it is pivotal to develop probabilistic material models of wall tie strengths and stiffnesses from an ample number of brick-tie-timber subassembly tests. This paper describes an extensive experimental study of the brick-tie-timber subassembly under axial compression and tension loading, considering one of the leaves (brick) is fixed and the relative motion of the free leaf (timber) occur in the perpendicular direction. A range of probability distributions are fitted to tie strength histogram data sets, and a best-fitted probability distribution is selected. The study reported herein is a part of the broader project which is in progress at The University of Newcastle, Australia. The outcome of this paper serves as the basis for performance evaluations of brick masonry veneer wall systems subjected to wind and seismic hazards considering the spatial and random variability of the constituent material properties.

2 EXPERIMENTAL EVALUATION OF TIE CHARACTERISTICS

2.1 *Material selection and test specimens*

Wall ties in Australia are available in a number of sizes and shapes and are usually made from galvanised mild steel or stainless steel in areas of high corrosion risk. Both face-fixed ties and side-fixed ties are commonly used for veneer wall construction. These veneer ties are often strip ties nailed or screwed to the timber or steel back-up frame. However, side-fixing corrugated sheet metal tie with timber as backup is customary Australian practice and is selected accordingly for this study. The testing of brick-tie-timber subassemblies (alluded to as ‘the couplet’ onwards) is more realistic and rational than just testing the ties in isolation to characterise the local behaviour of a wall system. Hence, the couplets were constructed with two perforated clay bricks (230 mm long × 110 mm wide × 76 mm high), one machine graded pine (MGP10 grade) timber stud (150 mm in length and 90 mm × 35 mm in cross-section), one corrugated Type-A light-duty side-fixing stainless steel R4 tie (tie dimensions are given in mm in Figure 1), and general purpose M3 mortar (1: 1: 6) (cement: lime: sand by volume). Wall ties were embedded at least 50 mm into the mortar as per AS 4773.2 (Standards Australia, 2015). These ties are side fixed to the timber stud with the supplied nail and a strictly maintained 50 mm cavity width. The complete couplet assemblage is shown in Figure 2. A total of 50 couplet specimens were prepared and left undisturbed for 7 days. Then specimens were randomly divided into two groups (25 specimens each) to be tested for compression and tension, respectively.

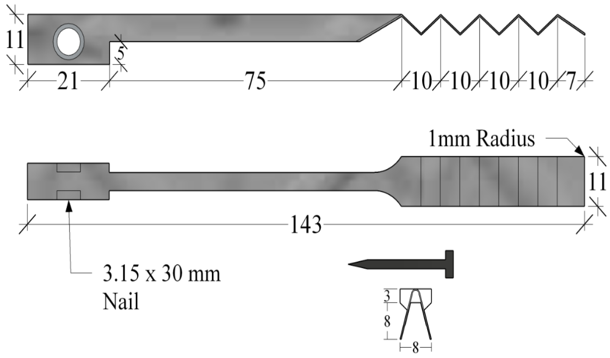


Figure 1. Side-fixed veneer tie details (dimensions are in mm)

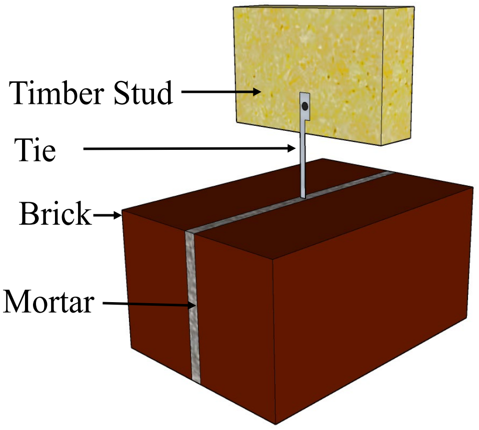


Figure 2. Brick-tie-timber subassembly specimen

2.2 *Testing setup and procedure*

All tests were performed using a displacement control Instron electromechanical testing system for compression and tension loading at least 7 days after specimen construction in accordance with the test method suggested in AS/NZS 2699.1 (Standards Australia/Standards New Zealand, 2000). The specimen was rotated into a vertical position and clamped in the machine as illustrated in Figure 3. A monotonic compressive load was then induced through a constant displacement of the machine cross head. The load cell in the testing frame was connected to the controller computer to measure and control the load and actuator displacement. In addition to this cross-head displacement, one displacement transducer was attached to measure the displacement of the brick-timber cavity. The actuator displacement was controlled at a rate of 1mm/min for both compression and tension loading. Figures 3(a) and 3(b) shows the setup for compression and tension testing, respectively.

Figure 3. Couplet testing setup for (a) compression and (b) tension loading

2.3 *Test Results*

2.3.1 *Compression Tests*

A total of 25 specimens were tested in compression, and failure modes slightly varied. Almost all (23 specimens) specimens failed by axial buckling of the tie, and only 2 specimens failed by the combination of tie buckling and pull-out of nail from timber. Each tie started to bend at a 90 degree angle at 20 mm to 30 mm from the nail-tie-timber connection, and scratched the timber surface along its bending path (see Figure 4). After buckling, load was decreased significantly up to 7mm displacement, followed by load fluctuations to a lesser extent. Mean buckling load and corresponding displacement was 1.04 kN and 3.08 mm, respectively. All load-displacement curves, along with an average multilinear ideal curve for compression specimens are shown in Figure 5. This ideal curve was generated based on the average of all actual load-displacement relationships. This idealisation of the curve facilitates to input average stiffness data into numerical models of overall brick veneer wall system behaviour. This curve comprises four zones, (a) a line from origin to the inflection point (at 1 mm displacement), (b) an intermediate stage from inflection point to the mean buckling load, (c) a decreasing stage from mean buckling load to 7 mm displacement, and (d) slightly decreasing stage from 7 mm displacement to 25 mm displacement (which represents the half of the air cavity distance). The elastic stiffness was calculated as 0.66 kN/mm from the ideal curve.

Figure 4. Tie buckling and failure for compression loading

2.3.2 *Tension Tests*

Similar to the compression tests, 25 specimens were tested in tension. The failure mode was identical (ductile nail pull-out from the timber stud) for all of the specimens as shown in Figure 6. No pull-out of tie from mortar joint or tie hole yielding were observed. However, in some cases timber was cracked at the nail joint at peak load. The load decreases as the nail started to be pulled out from the timber stud, which represents a ductile failure mode. The variation of peak load and post peak behaviours are notably higher compared to the compression behaviour. Mean peak load and associated displacement was 1.32 kN and 7.36 mm, respectively. All load-displacement curves along with an ideal multilinear curve (akin to compression tests) for tension tests are presented in Figure 7. To capture most of the elastic and peak load behaviour, two intermediate points (at 1 mm and 3 mm) were selected in between the origin and peak load for the ideal curve. Moreover, decreasing stage (from peak load to mean load at 25 mm displacement) represents the post peak behaviour. The elastic stiffness was calculated as 0.45 kN/mm from the ideal curve.

3 PROBABILISTIC MODEL OF WALL TIE CONNECTION PERFORMANCE

3.1 *Wall tie connection strength*

In a finite element model of a masonry veneer wall system, these behaviours of ties under compression and tension loading would be included with mean and coefficient of variation to represent the stochas-

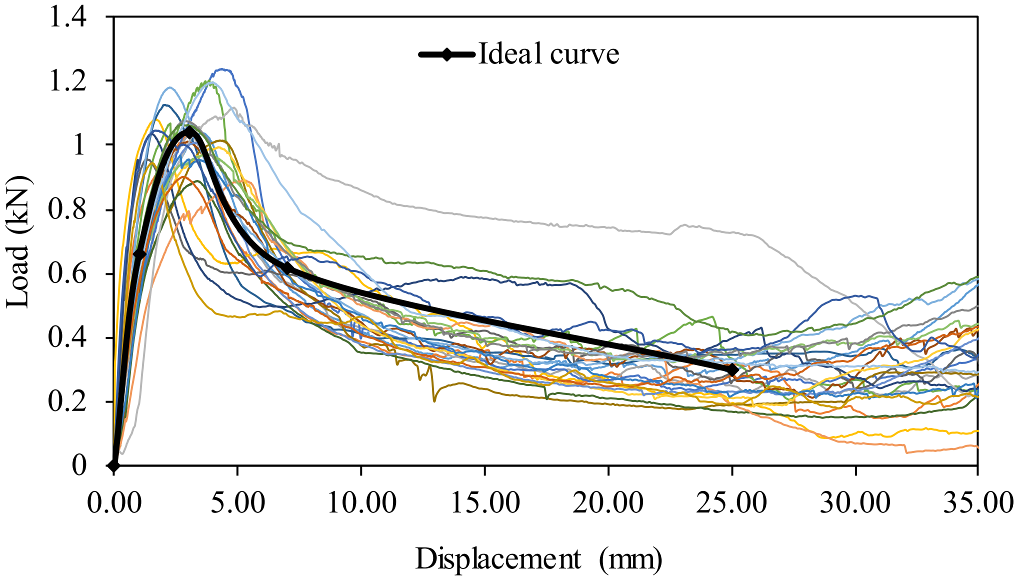


Figure 5. Load-displacement curves with ideal curve for compression loading

Figure 6. Nail pull-out from timber in tension specimens

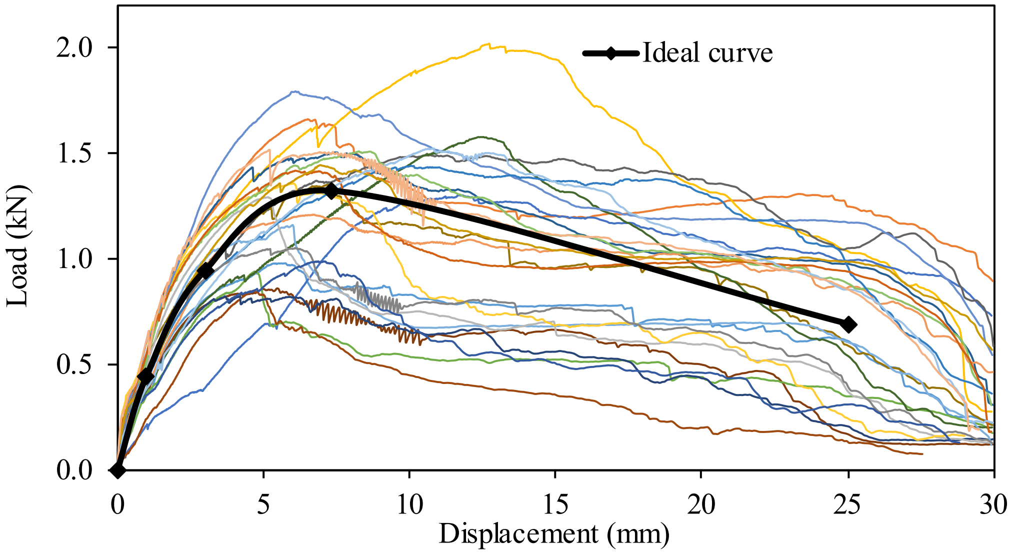


Figure 7. Load-displacement curves with ideal curve for tension loading

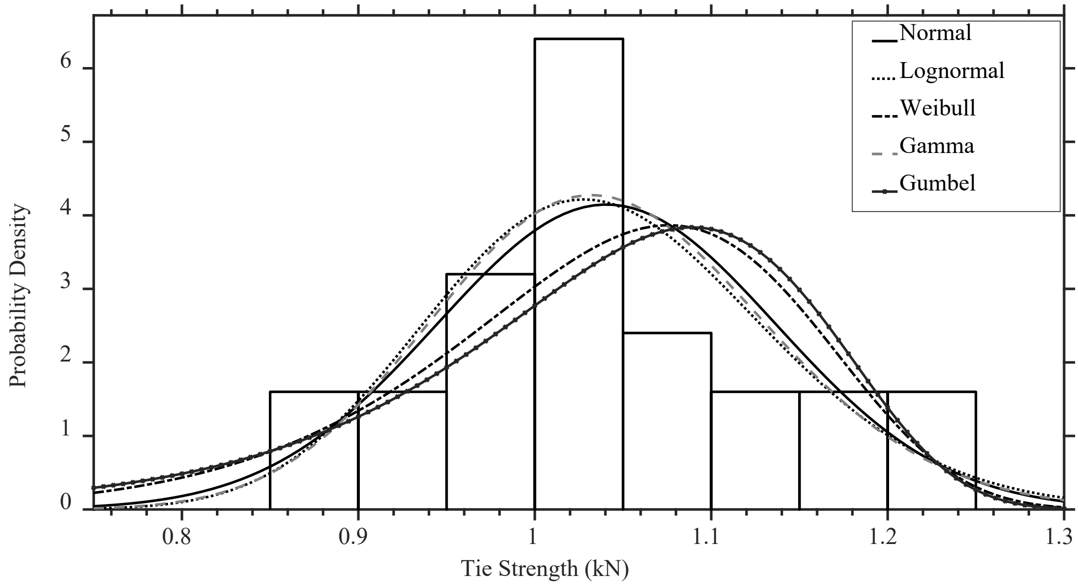


Figure 8. Probability distribution fits of tie connection strength under compression loading

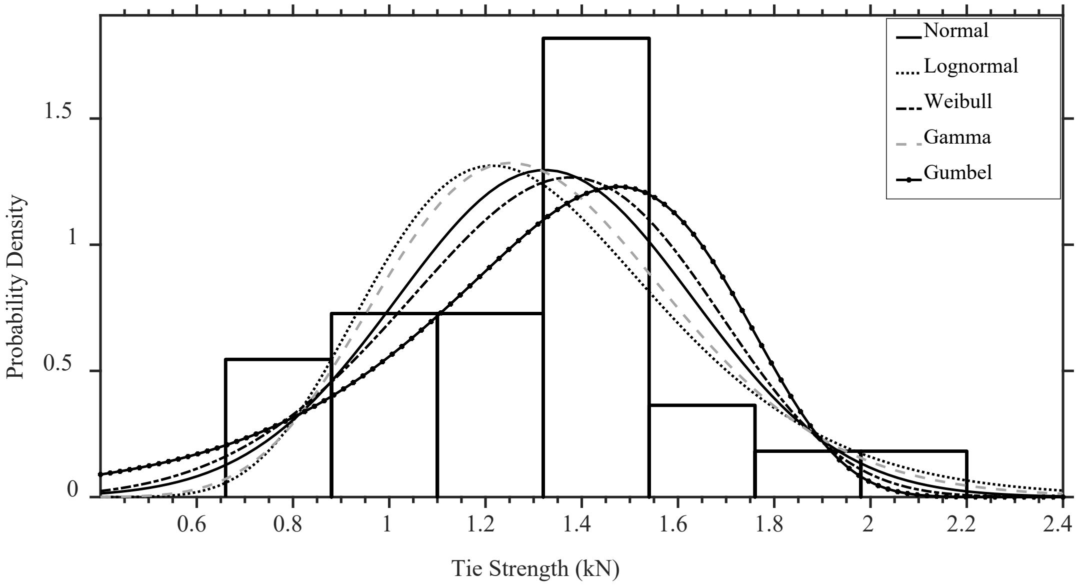


Figure 9. Probability distribution fits of tie connection strength under tension loading

tic nature of the ties. Using the maximum likelihood method, a range of probability distributions were fitted to tie strength (peak load) data sets under compression and tension loading. The tie strength histograms and fitted probability distributions (normal, lognormal, Weibull, gamma and Gumbel distributions) for compression and tension shown in Figure 8 and Figure 9, respectively. The Anderson-Darling (A-D) test at the 5% significance level was performed to check the goodness-of-fit as the lower tail of the distribution has more importance to wall failure progression compared to the whole distribution.

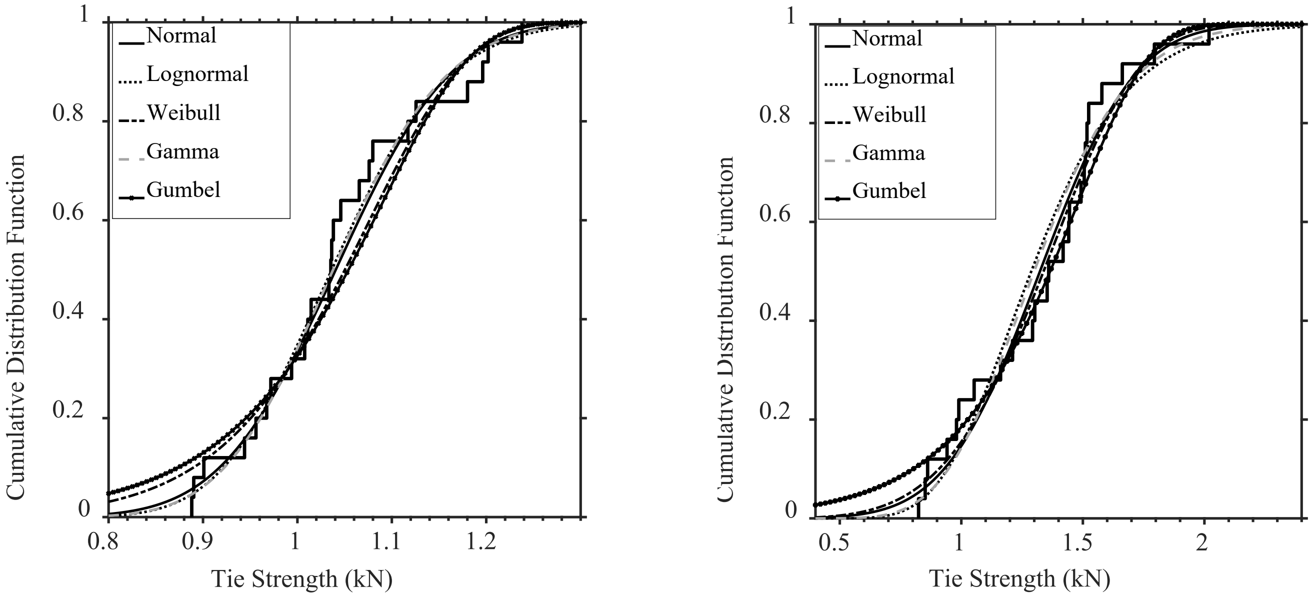
For compression loaded specimens ‘lognormal’ ranked highest according to A-D test, whereas ‘normal’ distribution shows the better fit for tension specimens. Moreover, a visual comparison of CDFs (cumulative distribution functions) with derived data for wall tie connection load capacity (both compression and tension cases) are shown in Figure 10 to infer a goodness-of- fit for the probabilistic models. Statistical parameters for both compression and tension specimens are summarised in Table 1.

3.2 *Wall tie connection displacement at peak load*

Lastly, probability distribution parameters were estimated for tie connection displacement at peak load (connection capacity) using the maximum likelihood method. Figure 11 illustrates the resulting CDFs to infer a goodness-of-fit for the distribution models.

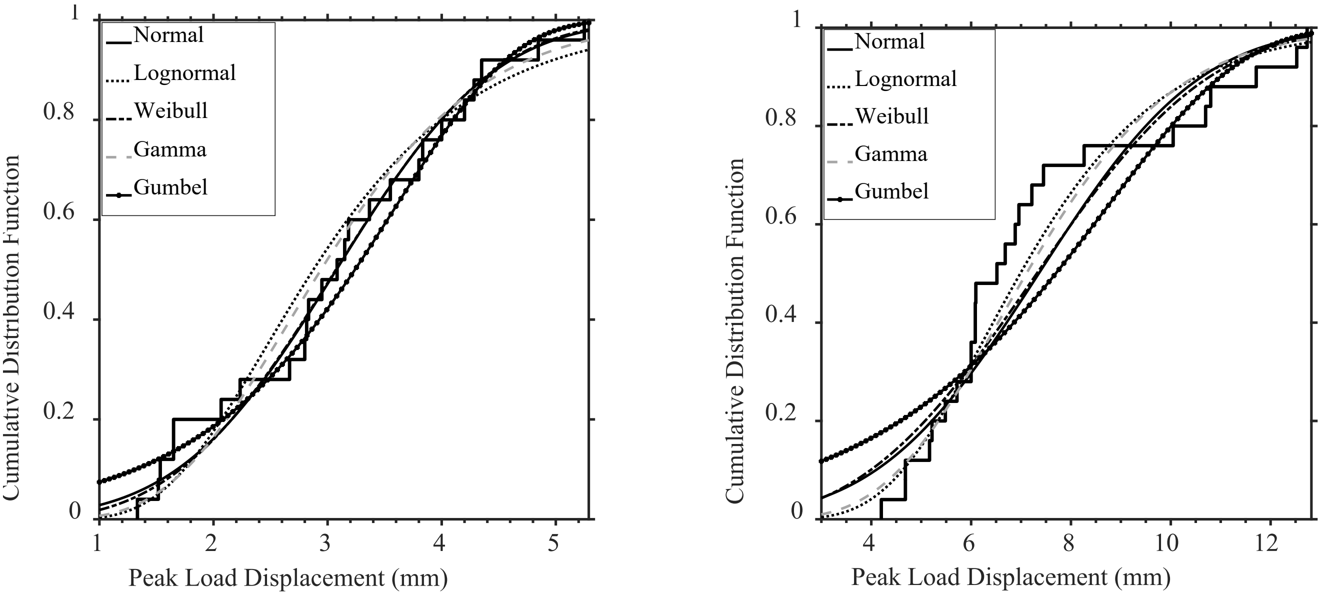
Table 1. Statistical parameters for tie strength (peak load)

Sample type	Sample size	Distribution	Mean tie strength	Coefficient of variation (COV)
Compression	25	Lognormal	1.04 kN	0.09
Tension	25	Normal	1.32 kN	0.23



(a) (b)

Figure 10. Comparison of the CDFs and derived data for tie load capacity for (a) compression loading and (b) tension loading



(a) (b)

Figure 11. Comparison of the CDFs and derived data for tie displacement at peak load for (a) compression loading and (b) tension loading

Table 2. Statistical parameters for tie displacement (at peak load)

Sample type	Sample size	Distribution	Mean tie displacement at peak load	Coefficient of variation (COV)
Compression	25	Normal	3.08 mm	0.35
Tension	25	Lognormal	7.36 mm	0.33

According to A-D test, normal and lognormal distribution best fits the displacement histograms for compression and tension loading, respectively. Table 2 summarises the statistical parameters for tie connection displacement at peak load.

It is evident from the statistical parameters that the variation of the tie properties under tension loading is significantly higher compared to compression. This may happen due to the failure pattern of the tie under tension, which is nail pull-out from the timber. Timber is an extremely variable material, and nail pull-out patterns were different from each other, i.e., in some cases, nails were pulled out by creating a wide hole in the timber, while in other cases timbers were cracked, etc. These variable features of failure pattern govern the COV in a significant manner.

4 CONCLUSIONS AND FUTURE WORK

This paper has described part of an on-going investigation into the stochastic behaviour and design of veneer wall systems under out of plane loading. Results and observations are reported in this paper for brick-tie-timber subassemblies under compression and tension loading. Axial buckling of the tie and ductile nail pull-out from the timber stud are the governing failure mode for compression and tension specimens, respectively. For both cases average multi-linear ideal curves were generated to input different parameters for a related finite element model. However, in order to include the variability of the tie strength and stiffness under compression and tension loading a range of probability distributions were fitted to tie strength (peak load) and associated displacement data sets using maximum likelihood method. The study found that, (a) for compression, the tie connection capacity (strength) best fits the lognormal probability distribution whereas corresponding displacement fits normal distribution; (b) for tension, the tie strength best fits the normal probability distribution and corresponding displacement fits lognormal distribution. The mean and COV was calculated for each case and will be included in numerical finite element modelling work along with post peak softening behaviour. Future work will focus on correlation between each of the stages of the load-displacement response. Moreover, using this probabilistic model damage fragility curves will be developed for the tie connections by implementing them in brick veneer walls that are characteristic of buildings located in Australia.

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