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Structural Reliability Assessment of Safety Factors for Unreinforced Masonry Veneer Walls Subjected to Out-of-plane Loading

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Abstract:

Structural safety can be enhanced by the reliability-based calibration of partial safety factors. This paper focuses on the structural reliability-based assessment of unreinforced masonry (URM) veneer wall system with flexible structural backing under uniformly distributed out-of-plane loadings. A stochastic computational model is developed which combines the Finite Element Analysis (FEA) and Monte Carlo simulation to study how the spatial variability of veneer wall material (masonry, wall tie, and timber) properties affects failure progression and system peak load (veneer capacity). Two scenarios, with and without wall tie offset, are considered, where wall tie offset represents the workmanship observed from laboratory testing. Probabilistic characterization of the veneer capacities for these scenarios under inward and outward out-of-plane loading is also reported. The model error statistics are combined with the probabilistic load models to determine the reliability index corresponding to the Australian Standard for Masonry Structures AS 3700. Annual reliabilities are compared to target reliabilities recommended by ISO 2394. It was found that existing levels of reliability exceed target reliabilities for most cases, and changes to the capacity reduction factor is also discussed.

Keywords: Masonry, Spatial variability, Structural reliability, Safety factors, Workmanship, Finite element modeling

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1 Introduction

Generally, a masonry veneer wall is an external wythe of masonry connected to a backup system with different types of ties. In Australia, the internal layer of the masonry veneer wall system is most often composed of timber framing and works as a flexible backup. Masonry is a complex construction material consisting of brick units set in a comparatively flexible mortar mix. Moreover, a high degree of spatial variability in the material properties in unreinforced masonry (URM) compared to other structural materials compounded the uncertainty of load-carrying capacity. Variability can be introduced at different levels, e.g., material properties, geometry, or loads, and the effect is measured by the global or local response of the system. This approach is also known as the Stochastic Finite Element Method, the Random Finite Element Method, or the Probabilistic Finite Element Method. Li et al. (2014) modeled full-size brick masonry walls under uniform pressure loads (in one-way bending) without vertical pre-compression. A stochastic computational model combining the Finite Element Method and Monte Carlo simulation (MCS) was developed to study how the unit-to-unit spatial variability of material properties affects the non-load bearing wall failure progression and wall strength. Using a similar technique, Isfeld et al. (2021) compared spatial stochastic FEA and test results of 2/3 scale brick walls 1, 2, 4 and 10 units long tested in one-way vertical bending. Muhit et al. (2022b) developed the spatial stochastic FEA model of veneer wall system components (masonry, wall tie and timber) subjected to out-of-plane loading (one-way vertical bending) and compared it with test results of 18 full-scale veneer walls under inward and outward lateral out-of-plane loading (Muhit et al. 2022a).

While other international codes have revised and adjusted their factor of safety in order to improve reliability, the load capacity reduction factor (ϕ) of the Australian masonry standards remains mostly unchanged since the 1980s. A reliability-based approach was used by Lawrence and Stewart (2009) for URM walls loaded in compression, who proposed that ϕ can be increased from 0.45 to 0.75 (i.e., a 40% reduction in material usage) and this was incorporated into AS 3700 (2018). Several approaches to calibrating the ϕ for one-way bending in AS 3700 (2018) have been considered. Isfeld et al. (2023) found robust evidence to support an increase of ϕ from 0.60 to 0.65 for single-skin URM walls subject to one-way vertical bending. However, there is no evidence of reliability-based calibrations of the URM veneer wall system under out-of-plane loading (in vertical bending) in the literature.

This paper focuses on a structural reliability-based assessment of the URM veneer wall system subjected to uniformly distributed out-of-plane loads. Stochastic models combining FEA and MCS account for spatial variability of the veneer wall constituent materials when estimating the veneer capacity. The effect of workmanship observed from laboratory testing is considered by offsetting wall ties in the veneer walls and compared with no tie offset scenarios. Model error statistics are then combined with the results of the spatial stochastic FEA and probabilistic load models to determine the reliability index corresponding to the Australian Standard for Masonry Structures AS 3700 (2018) design of veneer walls with flexible structural backing.

2 Structural Reliability

The probability that the load effect exceeds the structural resistance, i.e., probability of failure (p_f) is defined as:

$$p_f = \Pr\left[G(X) \le 0\right] = \Pr\left[R - S \le 0\right] = \Phi(-\beta) \tag{1}$$

$$\beta = -\Phi^{-1}(p_f) \tag{2}$$

where G(X), the limit state function, describes the performance of the structure in terms of variability factors (X). In the simplest case, R is the resistance of the structure and S is the effect of the applied load actions. Conventionally, $G(X) \leq 0$ denotes the failure of the structure. The reliability index (β) is calculated using the inverse of the standard normal distribution function (Φ^{-1}). The limit state function is:

$$G(X) = ME \times R_u - W_p \tag{3}$$

where, ME is the model error, R_u is the resistance determined through spatial stochastic FEA and W_p is the out-of-plane wind loading.

3 Spatial Stochastic Finite Element Modeling

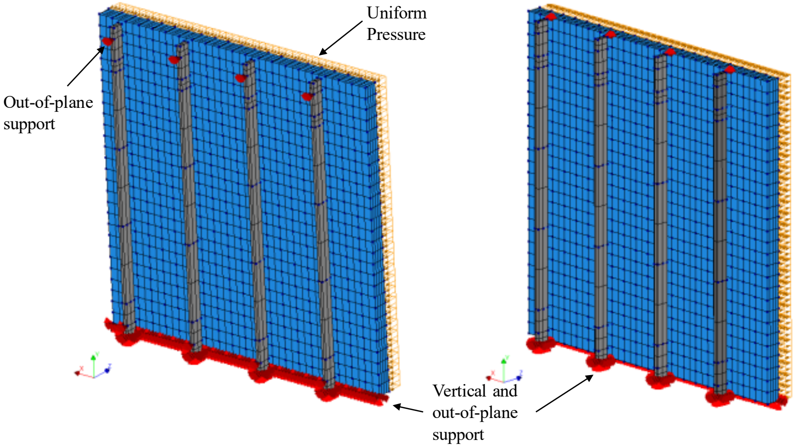
A three-dimensional (3-D) spatial stochastic finite element model for veneer wall of dimensions 2400 mm (height) × 2400 mm (width) × 110 mm (thickness) was modeled using the commercial software package DIANA FEA 10.3 (2019). A simplified micro-modeling strategy (Lourenço et al. 1995) was adopted for the masonry modeling where units are represented by linear elastic continuum elements and the behavior of the mortar joints and the unit/mortar interface is lumped into (a zero-thickness interface) discontinuum elements. The individual brick units were modeled elastically as two halves and potential crack planes were modeled with non-linear behavior using an interface. On the other hand, mortar joints were modeled using a combined cracking-shearing-crushing model (Lourenço and Rots 1997). The spatial stochastic FEA includes unit-to-unit spatial variability of flexural tensile bond strength and a spatial correlation of mortar joint $\rho = 0.4$, established by Heffler et al. (2008), within courses of masonry, and no correlation (statistical independence) was assumed between masonry courses and perpend joints. The wall ties were modeled as 3-D truss elements and the nonlinear behavior of the masonry-tie and the tie-timber interfaces were modeled via the wall tie constitutive law (Muhit et al. 2022c). Material properties were randomly distributed for wall ties and timber stiffness without any consideration of spatial correlation, i.e., statistically independent. The veneer wall flexible backup (timber studs) was considered as a 3-D solid element with a linear elastic material in the FEA as no timber studs were cracked (reached beyond the elastic limit) during any of the full-scale veneer wall tests.

3.1 Stochastic FEA Model Assembly

The boundary conditions are consistent with the experimental setup (Muhit et al. 2022a) to simulate the testing methodology. To represent the inward (ties are in compression) and outward loading (ties are in tension), uniform pressure loading was applied on the wall's exterior skin in two different directions (see Figure 1), and the self-weight of the veneer system is also considered. For inward loading, one edge of the first-course units, adjacent to the cavity, was restrained against translation for all directions. Out-of-plane restraint (roller support) was introduced at the top and bottom of the timber studs, at one brick high distance from the extreme ends, to represent the exact position of the lateral support provided during wall tests. On the other hand, for outward loading, the outer edge (tension side) of the wall was restrained in all directions while the edge adjacent to the cavity is kept free. In addition, the top edge of the timber, closest to the cavity, was supported for lateral direction. Analysis procedures and mesh refinement assessed by Muhit et al. (2022b) are used in all models. The out-of-plane displacement is recorded at the center of the unloaded face (height/2, length/2) for each load step and used to establish the load-displacement behavior of each model.

3.2 Probabilistic Material Properties

The material properties are categorized as deterministic, spatially variable, and spatially dependent. The flexural tensile strength of the unit-mortar interface is treated as spatially variable, varying along the length and height of the masonry wall, and converted to a direct tensile bond strength value using a random variable with a mean of 1.5 and COV of 0.13. Cohesion, fracture energy, and in some cases compressive strength of the masonry are treated as spatially dependent variables, calculated as a function of the direct tensile strength. The remaining material parameters for masonry are considered deterministic based on representative average values as outlined by Muhit et al. (2022b). The masonry prism compression test, triplet shear test, and the bond wrench test were conducted to probabilistically define the material properties in the mortar joint interface elements which are described by Muhit et al. (2022a). Flexural tensile strengths are a mean of 0.40 MPa (COV 0.42) and 0.42 MPa (COV 0.47) for inward and outward loading, respectively, and log-normally distributed for both. Probabilistic material properties of wall ties were obtained from the probabilistic characterization of masonry veneer wall ties described in Muhit et al. (2022c). DIANA FEA needs as input a stress-strain relationship; hence, the tie-constitutive law (as to load-displacement) is converted to the probabilistic stress-strain curve and included in the SFEA.



(a) Inward loading **(b) Outward loading**

Figure 1. FE model of veneer wall under out-of-plane loading

4 Effect of Workmanship

The laboratory wall specimens used to characterize model error were constructed in a manner similar to field conditions, using typical materials and workmanship. AS 3700 (2018) requires using the mean tie strength to design masonry veneer walls which also considers the effect of poor workmanship. Hence, Appendix F of AS 2699.1 (2020) specifies that the mean wall tie capacity should be obtained from testing where the wall tie is installed in between the mortar joint and timber frame with a vertical and horizontal offset (displacement) of 10 mm. However, the stochastic FEA conducted by Muhit et al. (2022b) considered the wall tie as in the 'perfect' (straight) condition; therefore, to make a reasonable comparison between AS 3700 and stochastic FEA, it is essential to modify (reduce) the tie strength in the stochastic FEA to consider the effect of workmanship. Mean tie strength considering the poor workmanship is assumed to be varied between the mean test value (obtained from the couplet test) and the design strength suggested by AS 3700, i.e., a uniform distribution. As mentioned earlier, in DIANA FEA (2019), tie material properties are included as a complete stress-strain relationship, the converted AS 3700 design tie strength (with 10 mm tie offset) would be 43.6 MPa (0.36 kN) and 36.4 MPa (0.30 kN) for compression and tension, respectively for the type of tie used in this study. From the couplet test (Muhit et. al 2022c), mean tie strength was estimated as 126.0 MPa and 160.4 MPa for compression and tension, respectively.

5 Spatial Stochastic FEA Results

Muhit et al. (2022b) conducted the spatial stochastic FEA simulations of the URM veneer wall system under out-of-plane loading where no tie offset (NTO) was considered, i.e., no consideration of the workmanship. The structural resistance (R_u) of the veneer wall for inward and outward loading is 2.71 kPa and 3.55 kPa, respectively with a respective COV of 0.13 and 0.18 (Muhit et al. 2022b). However, the best-fit distributions for each loading were not reported. Hence, in this paper, the spatial stochastic FEA of the NTO scenario is compared to five different distribution types: normal, lognormal, Weibull, Gumbel, and gamma. The Anderson-Darling (A-D) test is applied at the 5% significance level to test the hypothesis that the FEA results are represented by the specified distributions. For all cases, the A-D test failed to reject the null hypothesis for all distributions. The lognormal distribution can be considered the best-fit distribution for both inward and outward loading (see Figures 2 and 3).

By considering the tie offset (TO), a total of 80 spatial stochastic FEA Monte Carlo simulations (MCS) were completed for each loading where convergence for mean and COV were observed, and also to give a sample size sufficient for probabilistic model fitting. Failure was characterized by mid-height cracking, and load-displacement behavior for inward and outward loading is shown in Figure 4.

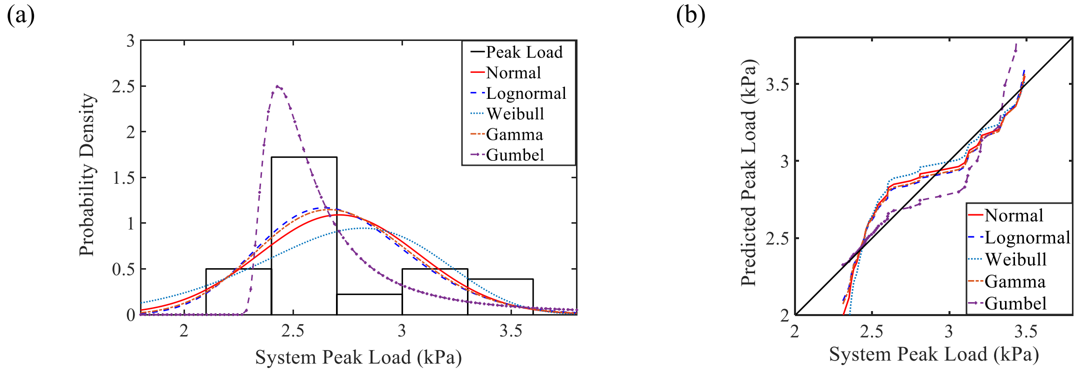


Figure 2. (a) Probability distribution fits and (b) inverse cumulative distribution functions of system peak load for inward loading with NTO

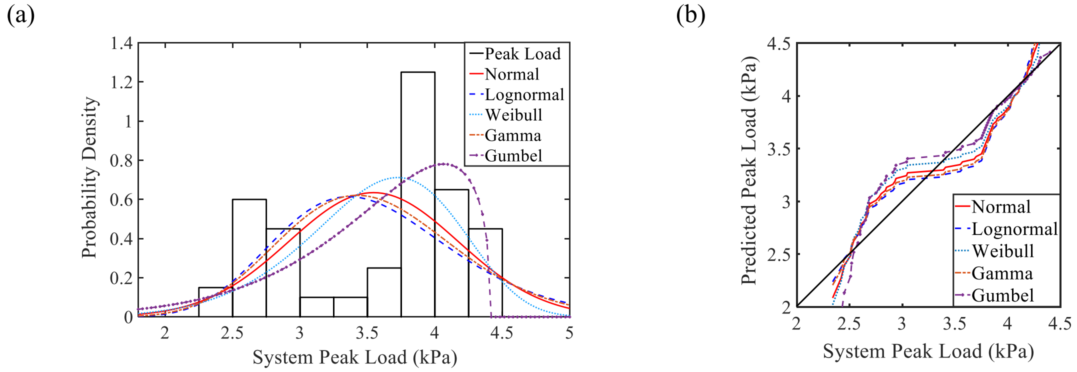


Figure 3. (a) Probability distribution fits and (b) inverse cumulative distribution functions of system peak load for outward loading with NTO

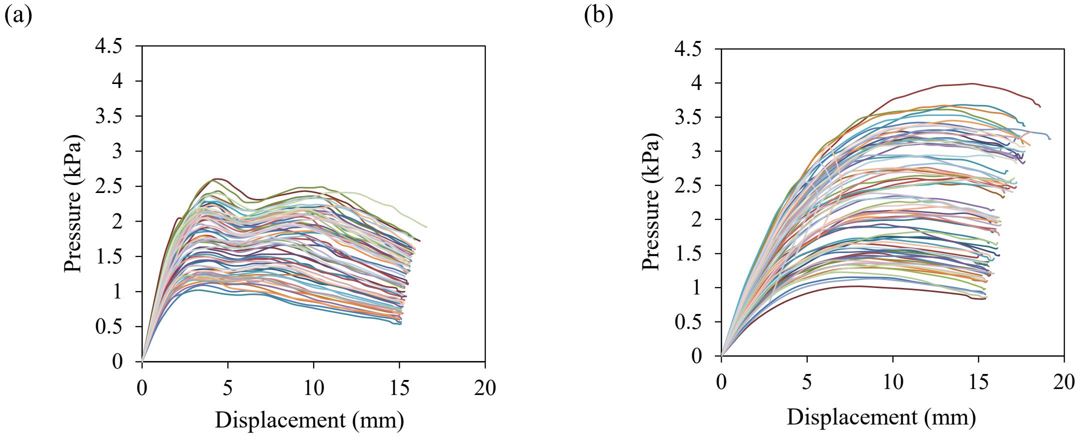


Figure 4. Pressure-deflection plots for 80 MCS under (a) inward and (b) outward loading

The statistics of peak loading (R_u) with TO are shown in Table 1. The mean values of R_u with TO are notably lower than that of NTO which is expected due to the reduced tie strength input for TO. In contrast, COV for the TO is higher than the NTO type due to the inclusion of additional variability caused by tie workmanship. Similar to NTO, a range of probability distributions were fitted to the spatial stochastic FEA results of TO. Based on the A-D test and CDF^{-1} plot, conservatively lognormal distribution can be considered as the best-fit distribution for both inward and outward loading (see Figures 5 and 6).

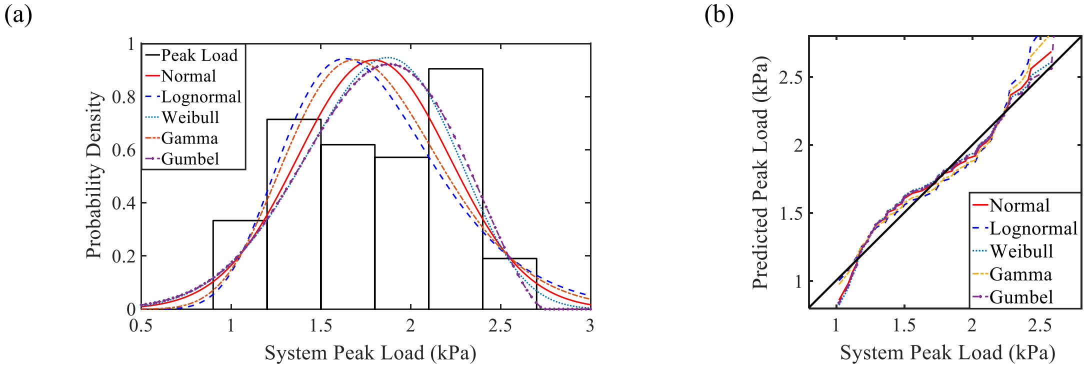


Figure 5. (a) Probability distribution fits and (b) CDF^{-1} of system peak load for inward loading with TO

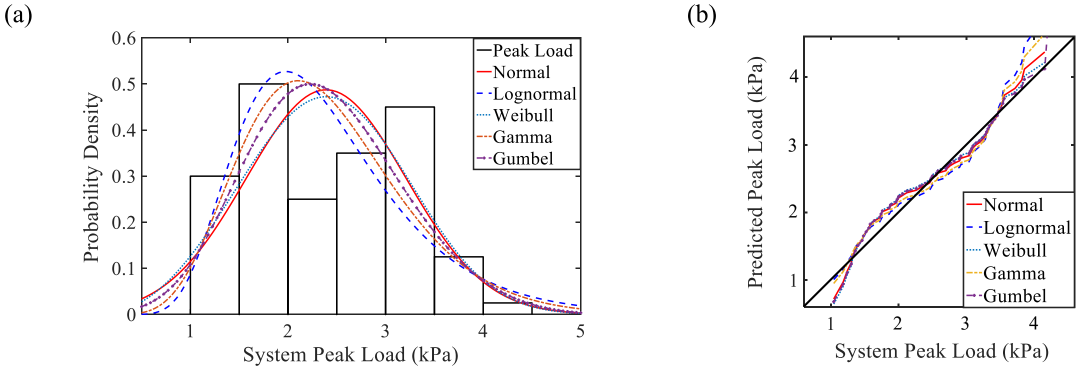


Figure 6. (a) Probability distribution fits and (b) CDF^{-1} of system peak load for outward loading with TO

Table 1. Statistical parameters for reliability analysis

Parameter	Loading	Mean		COV		Distribution	
		NTO	TO	NTO	TO	NTO	TO
Ultimate	Inward	2.71 kPa	1.79 kPa	0.13	0.24	Lognormal	Lognormal
Resistance, R_u	Outward	3.55 kPa	2.39 kPa	0.18	0.34	Lognormal	Lognormal
Model Error, ME*	Inward	1.03		0.0		Lognormal	
	Outward	1.04		0.06		Lognormal	

*source: Muhit et al. (2022b)

6 Structural Reliability Analysis

The failure of the masonry veneer wall, i.e., system peak load is governed by the progressive failure of the wall ties. The AS 3700 (2018) design limit state for the masonry veneer wall with flexible structural backing can be expressed as $F_{td} \leq \phi F_t$, where ϕ is the capacity reduction factor for the wall tie and F_t is the strength of the tie based on its duty rating. According to AS 3700 (2018), for the veneer with flexible structural backing, before and after cracking, the design compressive or tensile tie force (F_{td}) shall be taken as 20% of the total tributary lateral load (W_n) (airbag pressure) on a vertical line of ties between horizontal supports. So, F_{td} can be expressed as:

$$F_{td} = 0.2 \times W_n \times H \times d = \phi\, F_t \tag{4}$$

Therefore, W_n can be calculated as follows:

$$W_n = \frac{\phi . F_t}{0.2 \times H \times d} \tag{5}$$

where, the distance between two vertical lines of ties (d) is 600 mm, the total height (H) of the wall is 2400 mm, and AS 3700 recommended ϕ is 0.95 for wall ties in tension and/or compression. All the veneer walls tested in the laboratory were constructed with two rows of ties at the top to resist the 2 x F_{td} as per AS 3700. The AS3700 (2018) specified tie strength (F_t) for Type A light-duty tie is 0.36 kN and 0.30 kN for compression (inward loading) and tension (outward loading), respectively. The mean-to-nominal statistics for peak annual wind loading for non-cyclonic and cyclonic conditions are based on a recommendation from the Australian Building Codes Board (2019), see Table 2.

Table 2. Statistical parameters W/W_n for peak annual wind loading (ABCB, 2019)

Conditions	Mean	COV	Distribution
Non-cyclonic	0.33	0.49	Lognormal
Cyclonic	0.16	0.71	Lognormal

The wind load statistics are related to nominal resistance as:

$$W_p = W_n \left(\frac{W}{W_n} \right) \tag{6}$$

The probability of failure of the veneer wall can be thus calculated as:

$$p_f = Pr\left[ME \times R_u - W_n \left(\frac{W}{W_n} \right) \right] = Pr\left[ME \times R_u - \frac{\phi . F_t}{0.2 \times H \times d} \times \frac{W}{W_n} \leq 0 \right] \tag{7}$$

where ME, R_u, and W/W_n are modeled as random variables (see Tables 1 and 2), and all other parameters are deterministic.

6.1 Target Reliability

The optimum value of target reliabilities (β_T) is dictated by factors including types of failure, expected costs of failure and costs of increasing existing levels of safety. The type (nature) of the failure is critical in the determination of target reliability, for instance, structural elements that exhibit brittle or sudden failure without pre-warning should be assessed in a higher consequence class. The Australian Standard, AS 5104 (2017) (adopted from ISO 2394 (2015)), provides a basis for target reliabilities based on a one-year reference period and ultimate limit states for economic (cost-benefit) optimization (see Table 4).

The present design situation is a single-skin masonry wall with a flexible structural backing subject to a lateral (wind) load – i.e., there is no vertical pre-compression other than the veneer system's self-weight. In this case, the consequence class is minor (expected number of fatalities fewer than 5, smaller buildings and industrial facilities), however, as the failure mode is brittle without pre-warning the consequence class can be increased to Class 3 (moderate consequences of failure – material losses and functionality losses of societal significance, the expected number of fatalities fewer than 50, most residential buildings) in Table 4. The Joint Committee on Structural Safety Probabilistic Model Code (JCSS 2021) recommends that the relative cost of safety is medium for 'the most common design situation'. Moreover, consideration of a lower reliability class is recommended in the case of higher uncertainty (coefficient of variation more than 40%). As the COV of peak annual wind load reaches 0.49 (see Table 3), for minor consequences Class 2 and medium relative cost of safety measures the annual target reliability index is $\beta_T = 3.7$. Furthermore, veneer wall systems are mostly for the smaller buildings in Australia; hence, a failure consequence greater than Class 2 is not required.

Table 4. Annual target reliabilities (β_T) for economic optimization (adapted from AS 5104, 2015)

Relative Costs of Safety Measures	Consequence of Failure		
	Class 2 (Minor)	Class 3 (Moderate)	Class 4 (Large)
Large	3.1	3.3	3.7
Medium	3.7	4.2	4.4
Small	4.2	4.4	4.7

6.2 Results and Discussions

Structural reliability analyses are conducted for a full-sized veneer wall system under inward and outward out-of-plane loading, for cyclonic and non-cyclonic winds. Reliabilities are calculated using a probabilistic model of resistance based on the effect of (a) wall tie offset (workmanship), TO and (b) no tie offset, NTO. The annual reliabilities are shown in Table 5 for non-cyclonic and cyclonic winds when $\phi = 0.95$.

In the case of NTO, which considered wall tie connection as an ideal one, the annual reliability (β) well exceeded the target reliability $\beta_T = 3.7$ for both wind classifications (non-cyclonic and cyclonic) and for both loading scenarios (inward and outward loadings). On the other hand, when tie offset (TO) is considered to represent the workmanship, the β index fails to meet the β_T for non-cyclonic regions. Although for outward loading β index exceeded β_T, for inward loading it still fails to meet the target index for cyclonic regions, though not by much. It might appear counter-intuitive that reliabilities are mostly lower for non-cyclonic regions. It does not mean that non-cyclonic wind speeds are higher, but rather indicates that the actual mean wind speeds are proportionally higher than the nominal (design) values for non-cyclonic regions (mean $W/W_n = 0.33$) than they are for cyclonic regions (mean $W/W_n = 0.16$). This is offset, in part, by the significantly higher variability of cyclonic winds.

Table 5. Annual structural reliabilities when ϕ = 0.95

Conditions	Annual Reliability Index, β			
	Inward loading		Outward loading	
	NTO	TO	NTO	TO
Non-cyclonic	4.28	3.13	5.02	3.63
Cyclonic	4.42	3.59	5.00	4.02

A reliability-based calibration of AS 3700 (2018) is completed considering the target annual reliability index value of 3.7 (class 2) as mentioned earlier that a failure consequence greater than class 2 is not logical for the veneer wall system. For all NTO scenarios, the calculated ϕ factor is more than 1.0 whereas for inward loading TO scenarios a lower ϕ factor is obtained. However, it is important to appreciate that in this study TO scenarios considered the tie offset (i.e., lower in strength) for all ties in the veneer system which is indeed over-conservative and represents the lower bound of workmanship. Hence, TO may provide an overly-conservative capacity reduction factor estimation. To quantify more realistic ϕ value further studies are needed when only a few of the wall ties have offsets. Alternatively, the minimum mean tie strength (F_t) suggested by AS 3700 can be increased in order to make an economical yet reliable design of veneer wall system. However, more future studies are required where F_t can be considered as a variable, unlike this study, to quantify the percentage increase from AS 3700's current recommendation.

This proof of concept work is preliminary and considered only one particular type (Type-A light-duty) of wall tie. Moreover, model error statistics are assumed as lognormal distribution; as such collection of additional veneer wall test data is needed to better characterize model errors. In addition, the inclusion of representative bond strength statistics, the effect of different wall tie types, and then a sensitivity analysis are required to test the robustness of the results. These are areas for further research that will allow for a more robust reliability-based calibration of the Australian Masonry Code for veneer walls with flexible structural backing. Until this work is completed, and appropriate ϕ and/or F_t for these actions are determined, no recommendations can be made for changes to the current factor and minimum mean tie strength.

7 Conclusions

To estimate the resistance of full-scale URM veneer wall systems under out-of-plane loading, a spatial stochastic FEA model was developed. This model accounts for unit-to-unit spatial variability of veneer wall system constituent material properties, observed in typical masonry construction. The veneer walls are subject to a wind load and self-weight with no vertical pre-compression. To include and compare the effect of poor workmanship, tie offset for all wall ties are considered in the model in addition to perfect (i.e., no tie offset) scenarios. An established method of structural reliability analysis was then applied using the spatial stochastic FEA as a resistance model, considering the random variability of model error and wind load. Annual reliabilities are compared to target reliabilities recommended by AS 5104 (and ISO 2394), and capacity reduction factors are discussed and compared to the Australian Masonry Structures Code AS 3700. It was found that there is some evidence to support increasing the minimum tie strength considered by AS 3700. Areas of further research are proposed to better characterize the veneer walls in bending, as this will then allow for a more robust reliability-based calibration of the Australian Masonry Code.

8 Acknowledgements

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