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Nonlinear Finite Element Analysis of Unreinforced Masonry Veneer Wall Systems Under Out-of-Plane Loading

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ABSTRACT

This paper presents part of a research project that aims to develop an improved understanding of the structural behavior of unreinforced masonry (URM) veneer and facade systems considering the variability of strength and stiffness of the brick, mortar, and wall ties. It is imperative to develop a deterministic nonlinear FEA model prior to establishing a stochastic nonlinear FEA model of veneer walls with flexible backup systems. In this paper, a nonlinear FEA model is developed for a full-sized single-story non-loadbearing veneer wall with ties and flexible timber stud framing as a structural backup. The brick URM wall has dimensions of 2400 mm (h) × 2400 mm (w) × 110 mm (t) with the inclusion of four vertical lines of ties, and four timber studs as an internal layer of the wall system, spaced as per Australian standards. Both inward and outward acting uniform out-of-plane pressure, which represents earthquake and windstorm loadings, are applied to the masonry veneer wall system. The structural response along with tie force distributions are explicated for both uncracked and cracked veneer. Additionally, the load transfer mechanism for a multistory veneer is also analyzed, and tie force distributions across the height are quantified.

KEYWORDS: unreinforced masonry (URM), masonry veneer, nonlinear numerical modeling, wall ties, out-of-plane loading, tie-force

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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, and light steel stud walls or structural masonry in 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 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 galvanized or stainless steel and exhibit adequate axial stiffness and strength in tension and compression, however negligible shear capacity. Usually, wall ties perform three primary functions, namely: (1) provide a connection; (2) transfer lateral loads; (3) allow in-plane movement to accommodate differential displacements. The structural behavior 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.

Recognizing that the tie connections play a crucial role on in-plane and out-of-plane performance of the masonry veneer system under seismic actions, some researchers carried out investigations aimed at assessing the behavior of the tie connections under shear, tension and compression (Choi and LaFave, 2004; Mertens et al., 2014; Page et al., 2009; Reneckis, 2009; Ribeiro et al., 2014; Zisi and Bennett, 2011). Choi and 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. An extension of this study was demonstrated by Zisi and Bennett (2011), who investigated the local behavior of brick-tie-timber subassemblies with variable features under cyclic shear. Reneckis (2009) also conducted subassembly tests akin to Choi and LaFave (2004) to explore tie connection behavior further, primarily when loaded in tension, for various code compliant and non-compliant tie installation methods. The experimental characterization of brick masonry veneers has necessarily considered the system composed of the brick masonry veneer, the backup wall or frame and the ties connecting the masonry veneer and the backup wall or frame. Some experimental investigations have focused on the static in-plane and out-of-plane behavior of the brick masonry veneer systems. Some of these works have also focused on the dynamic shaking table tests of both brick veneer elements (Jo 2010, McGinley and Hamoush 2008, Memari et al. 2002, Okail 2010, Okail et al. 2010, Reneckis 2009, Reneckis and LaFave 2010, Reneckis et al. 2004) or full scale or reduced scale buildings with attached brick veneer walls (Beattie and Thurston 2008, Okail 2010, Okail et al. 2011, Page et al. 2007, Page et al. 2009, Paton-Cole et al. 2012, Reneckis 2009, Reneckis and LaFave 2012). Based on some of the earlier studies of commercial brick veneer walls, Page et al. (2007) and Page et al. (2009) conducted a preliminary experimental study in which the emphasis was on the development of 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 forces in-situ as the walling system was subjected to a uniform lateral pressure load. 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 out-of-plane 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.

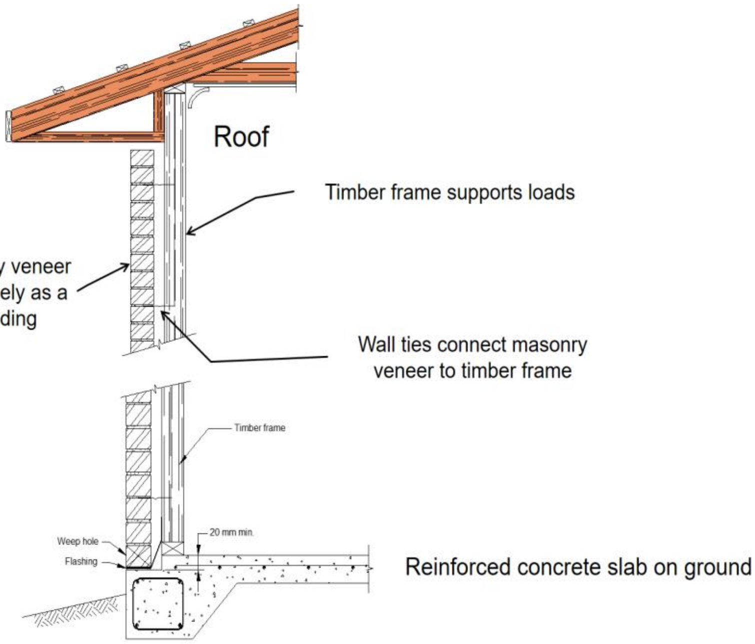


Figure 1. Typical masonry veneer wall system details (Think Brick Australia)

The research work reported in this paper is a part of the broader project which is in progress at The University of Newcastle, Australia to develop an improved understanding of the behavior of masonry 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. The project will consider the structural reliability of new construction as well as investigate the levels of safety amongst older existing construction. In this study, FEA analysis is performed using the commercial software package DIANA FEA 10.2 (DIANA FEA BV 2017) to simulate the behavior of the whole veneer wall system and to understand the load transfer mechanism of the veneer wall through the ties to the backup frame. This deterministic model will be refined by future experimental program and will be used to conduct stochastic analyses in the upcoming stages of the research by considering the spatial variability of the material properties.

FINITE ELEMENT ANALYSIS

To accurately model the behavior of a URM veneer wall system, the structural response and failure modes of the masonry, tie force distribution and failure, and unit to unit variability of material properties need to be considered. To simulate the behavior of the whole veneer wall system, a deterministic model is generated before developing the non-spatial and spatial probabilistic analysis models. Due to the large sections of masonry being considered, the need to include wall ties and structural backup, and the need to consider nonlinear material behavior, a finite element macro-modeling technique was adopted so that the computational demand is manageable. In the macro-modeling approach, the complete masonry assemblage (brick units, mortar joints, and unit/mortar interface) are smeared into a homogeneous continuum element. The FE analysis study commenced with the modeling of a 2-D nonlinear masonry wall model with ties and backup frames to corroborate the numerical accuracy of the FEA package with linear/elastic theory. Using this theory, the load at which the peak stress at the extreme fiber on the tension side of the wall at the location of maximum bending moment equaled the bond strength of the interface element at that location is calculated. For simplicity, self-weight is not included in the model and hand calculation. While the 2D FEA model assisted model development and validation, it is essential to develop a 3-D nonlinear URM wall model with ties and timber studs to allow the inclusion of spatial variability which is the principal purpose of this project. In this study, a 3-D nonlinear veneer brick URM wall system is modeled deterministically and verified against the results obtained using the 2-D model.

Deterministic Modeling of the URM Veneer Wall System

The dimensions chosen for the URM wall model are 2400 mm (height) × 2400 mm (width) × 110 mm (thickness), and the masonry units are considered solid. A masonry veneer wall system with vertically spanning timber frame members is essentially a one way vertically spanning system and could be modeled deterministically using a single timber stud with the appropriate tributary length of the masonry wall. However, a wall length of 2400 mm was chosen here so that the future stochastic modeling to be conducted using the same model will allow for the potentially higher chance of a weak joint in the wall at which cracking could initiate, compared to a wall with a shorter length. AS3700 (Standards Australia 2018) requires that wall ties are spaced no greater than 600 mm apart in both vertical and horizontal directions. In addition, the first row of ties must be located no more than 300 mm from the bottom of the wall, and the last row of ties no more than 300 mm from the top of the wall. Therefore, for the 2400 mm x 2400 mm wall, the backup frame consists of four wall studs, with four vertical lines of ties spaced at 600 mm in the horizontal and vertical direction, in accordance with AS3700 (Standards Australia 2018). Each timber frame member (wall stud) has the cross-section of 90 mm × 35 mm, with the 90 mm dimension aligned perpendicular to the wall. Each tie is 4.27 mm in diameter, and side fixed from the masonry wall to timber with a 50 mm cavity width. The complete assemblage of the 3D model is shown in Figure 2.

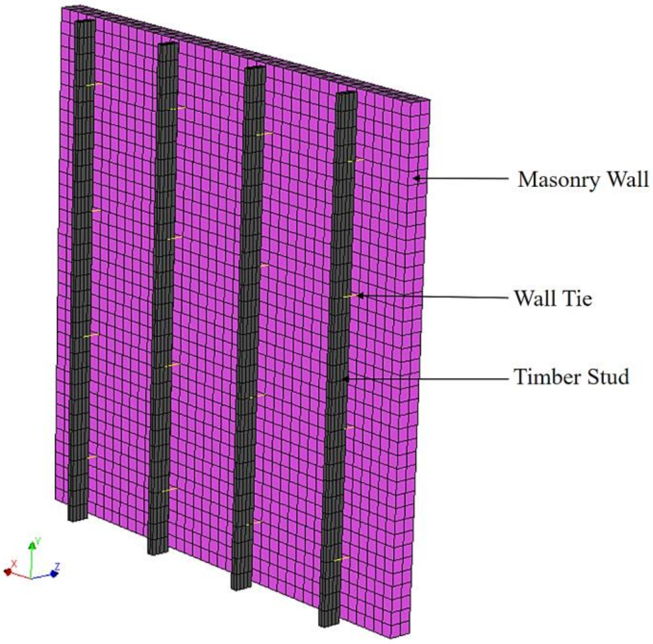


Figure 2. The 3D model of the veneer wall system assembly

The structural configuration considered here is a non-loadbearing masonry wall with no support at the top edge and simply supported at the bottom edge, i.e., the masonry wall can move laterally (out-of-plane) and is held only by the wall ties connected to the timber backup frame, but is restrained horizontally (x-axis) and vertically (y-axis) along its bottom edge. The top and bottom of the flexible timber studs are restrained against out-of-plane displacement (z-axis) and horizontal displacement (x-axis), and the bottom of the studs are also restrained against vertical displacement (y-axis). The studs are restrained in the x-axis direction at several locations along their height to represent the effects of nogging members in real construction. No part of the veneer system (masonry or timber studs) is rotationally restrained. The complete boundary conditions for the whole veneer wall system are shown in Figure 3. Both inward (ties are in compression) and outward (ties are in tension) uniform out-of-plane lateral pressure load is applied over the full face of the wall.

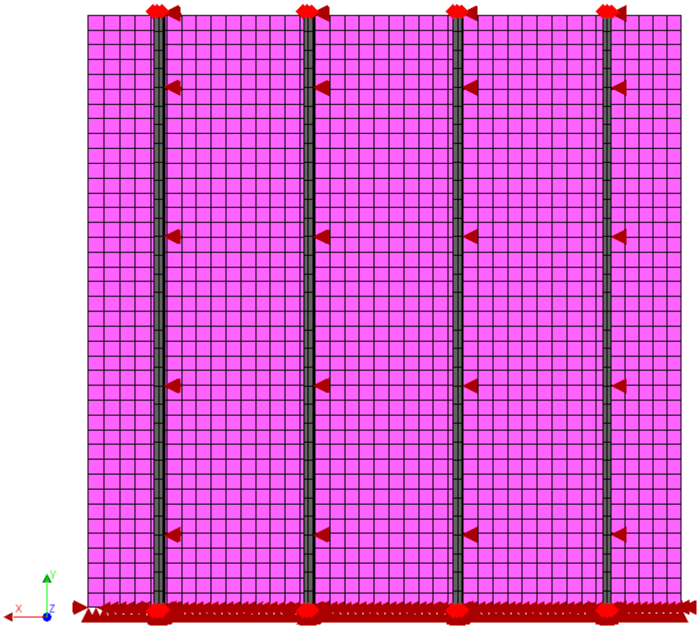


Figure 3. Boundary conditions of the veneer wall system

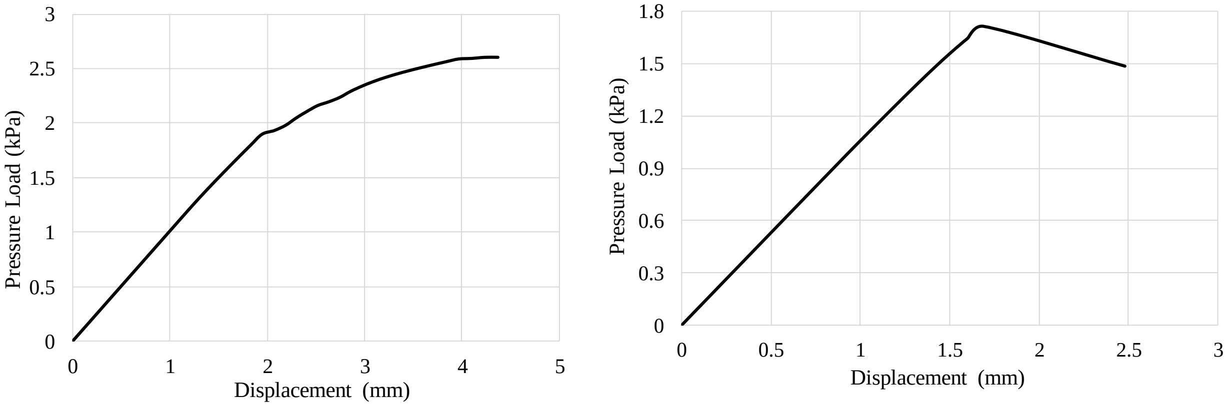
Masonry is modeled as continuum elements (element type HE20 CHX60, a twenty-node 3-D isoparametric solid brick element based on quadratic interpolation and Gauss integration), the ties are modeled as beam elements (BE2 L12BE, a two-node class-I beam based on constant strains along the center line of the beam) and the timber studs are modeled as solid brick elements (HE8 HX24L, an eight-node solid element), respectively. A constitutive model based on total strain, named 'Total strain-based crack model' (Selby and Vecchio 1993, Vecchio and Collins 1986) is used to simulate the nonlinear behavior of the masonry, which describes the tensile and compressive behavior of a material with one stress-strain relation. Like the multi-directional fixed crack model, the total strain-based crack models follow a smeared approach for the fracture energy. This model is appropriate to simulate the cracking and crushing behavior of the material with a nonlinear elasticity relation. The plasticity behavior of the ties is modeled as a bilinear elastic-plastic model (Von-Mises plasticity model) whereas the flexible timber backup is modeled as linear elastic isotropic. Material property input parameters for the macro-models are determined based on the measured material properties by other researchers and standards. A summary of the key input parameters for modeling are presented in Table 1.

RESULTS AND DISCUSSION

Figure 4(a) shows numerically generated curves of displacement in the middle (mid-height and mid-length) of the masonry veneer versus inward pressure load (that is, load directed in the negative z-direction, for directions as defined in Figure 2). Cracking initiated in the masonry veneer at a pressure load just under 2 kPa and is fully developed at 2.61 kPa with 4.37 mm lateral displacement. The crack pattern and failure mode of the URM wall (rear side) in the form of strain contour is shown in Figure 5. The maximum strain occurs from near the mid-height of the URM wall to the area of the second row of ties (from top).

Table 1. Summary of Key Material Parameters for Finite Element Macro-Model

Parameter	Adopted Value	Data source
Elastic modulus of masonry, E_m	9573 MPa	Allen et al. (2017)
Poisson's ratio of masonry, ν	0.15	Assumed
Mass density of Masonry, ρ_m	$1.92 \times 10\text{-}9$ T/mm^3	Assumed
Tensile strength of masonry, f_{tm}	0.48 MPa	Lourenco (2008)
Tensile fracture energy of masonry, G_{ft}	0.052 N/mm	Lourenco (2008)
Compressive strength of masonry, f_{cm}	9.64 MPa	Allen et al. (2017)
Compressive fracture energy of masonry, G_{fc}	15.42 N/mm	Lourenco (2008)
Shear retention factor of masonry, β	0.01	Assumed
Elastic modulus of tie, E_s	200000 MPa	Abey Australia (1990)
Poisson's ratio of tie, ν_s	0.3	Assumed
Mass density of tie, ρ_m	8×10^{-9} T/mm^3	Assumed
Yield stress of tie	206 MPa	Abey Australia (1990)
Elastic modulus of timber, E_t	6900 MPa	AS1720.1:2010 (Standards Australia, 2010)
Poisson's ratio of timber, ν_t	0.4	Assumed



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

Figure 4. Pressure load-displacement relationship

To observe the behavior under outward (tension) load (loading in the positive z-direction), another simulation was conducted, and the load-deflection response is depicted in Figure 4(b). It can be deduced that outward collapse load is significantly lower than that of the inward load. This is because, in the inward (compression) load case, tie buckling may occur which provides significant strength to the system compared to tension. However, tie rupture or pull-out of the tie from the mortar would govern the failure under the tension load. It should be noted that AS3700 sets a serviceability limit state (under wind loading) on backup frame deflection of span/300, which for the 2400 mm span considered here is 8 mm. As shown in Figure 4, the veneer will crack well before reaching this limit for both inward and outward loading.

For a flexible backup (timber stud) both cracked and uncracked veneer must be considered to analyze the vertically spanning masonry veneer system. The veneer could be cracked either from the previous loading or have cracked prematurely during loading because of low bond strength. It can be seen from Figure 5 that cracking occurred in a horizontal bed joint near the mid-height (1200 mm from the top) of the wall where lateral bending effects are most significant.

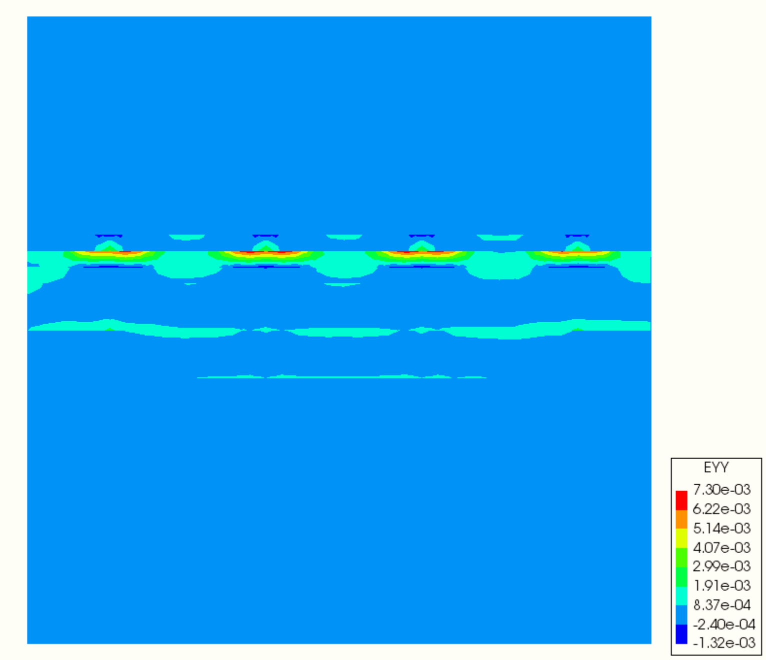


Figure 5. Strain contours of masonry wall (rear side) for inward loading

Uncracked Brick Veneer

When the backup is flexible, the largest tie forces are generated in the top and bottom row of ties (Page et al. 1996, Yi et al. 2003). As the backup wall deflects, the veneer tends to span from its bottom support to the point of support of the backup via the top row of ties. The forces in the ties for the whole specimen are given in Table 2 based on ties numbered in Figure 6. As indicated in the table maximum forces in the ties occur at the top and the bottom, and the forces in the intermediate ties are much lower and sometimes in tension, even under inward loading on the veneer. It can be deduced that the magnitude of the tie forces and the nature (compression or tension force) in a single row of ties are almost identical across the row. The average tie force distributions for single story veneer wall systems along the height of the wall is depicted in Figure 7(a) where a positive value represents tension in the tie, and a negative value represents compression. The distribution profile of the tie forces in the model matches profiles observed experimentally (McGinley et al. 1986) and numerically (Yi et al. 2003). The equilibrium of the structure is checked by comparing the total applied load (on the face of the wall) and total exerted forces of ties. The deflected shapes are continuous smooth curves for both veneer and timber stud before the veneer cracks. There is a difference in the deflections of the veneer and the studs, however, because of the vast difference between their flexural stiffnesses. According to (Page et al. 1996), vertical tensile stress in the masonry is relatively large, and it is entirely conceivable that the veneer could crack along a bed joint near mid-height sometime in its design life. This cracking completely changes the distribution of tie forces as discussed in the next section.

Cracked Brick Veneer

Under higher wind load, the peak vertical tensile stresses in the brick veneer on the side closest to the studs (i.e., the tension side of the veneer under inward loading) will be higher than the typical tensile strengths of clay masonry. Therefore cracking can be expected. After the veneer is cracked, the forces in the ties alter. Results from the model are given in Table 2. When the veneer cracks at, or near, mid-height, a hinge will form at this location. The exact location will depend upon the maximum vertical tensile stress induced in the masonry, the possible presence of a weak joint and the level of pre-compression on the joint due to the wall self-weight (Page et al. 1996). The masonry will then span as an upper and lower segment; one from the base to the hinge, the other from the hinge to the top row of ties opposite the support to the backup. The redistribution of tie forces upon cracking of the veneer will cause an increase in the deflection of the backup frame. This large backup deflection will cause the crack in the veneer to increase in size, which may have serviceability implications regarding water penetration and possibly aesthetics. The veneer deflection (and the crack size) will also increase by any take up in the tying system itself due to mechanical movement between its components. The distribution of the average tie force for the same veneer cracked is shown in Figure 7(b). This force distribution profile matches well with McGinley et al. (1986) and Yi et al. (2003). The deflected shape remains a continuous smooth curve for the timber stud but becomes two approximately straight lines for the veneer.

With regard to design provisions, it is conspicuous that both the uncracked and cracked veneer cases must be included, with the tie design being based on the worst of both cases.

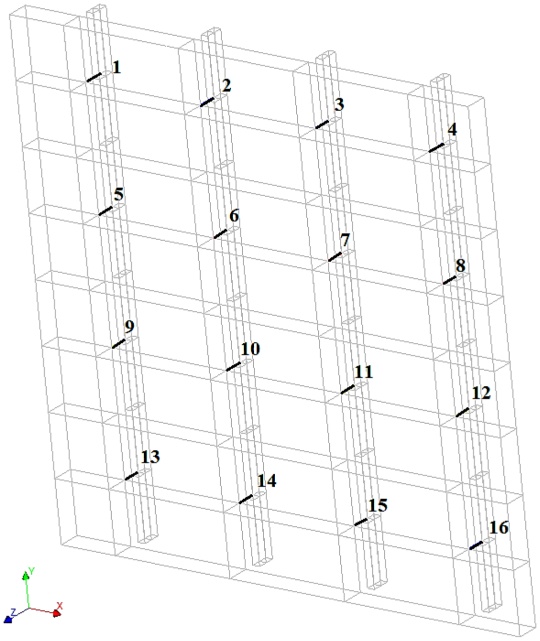
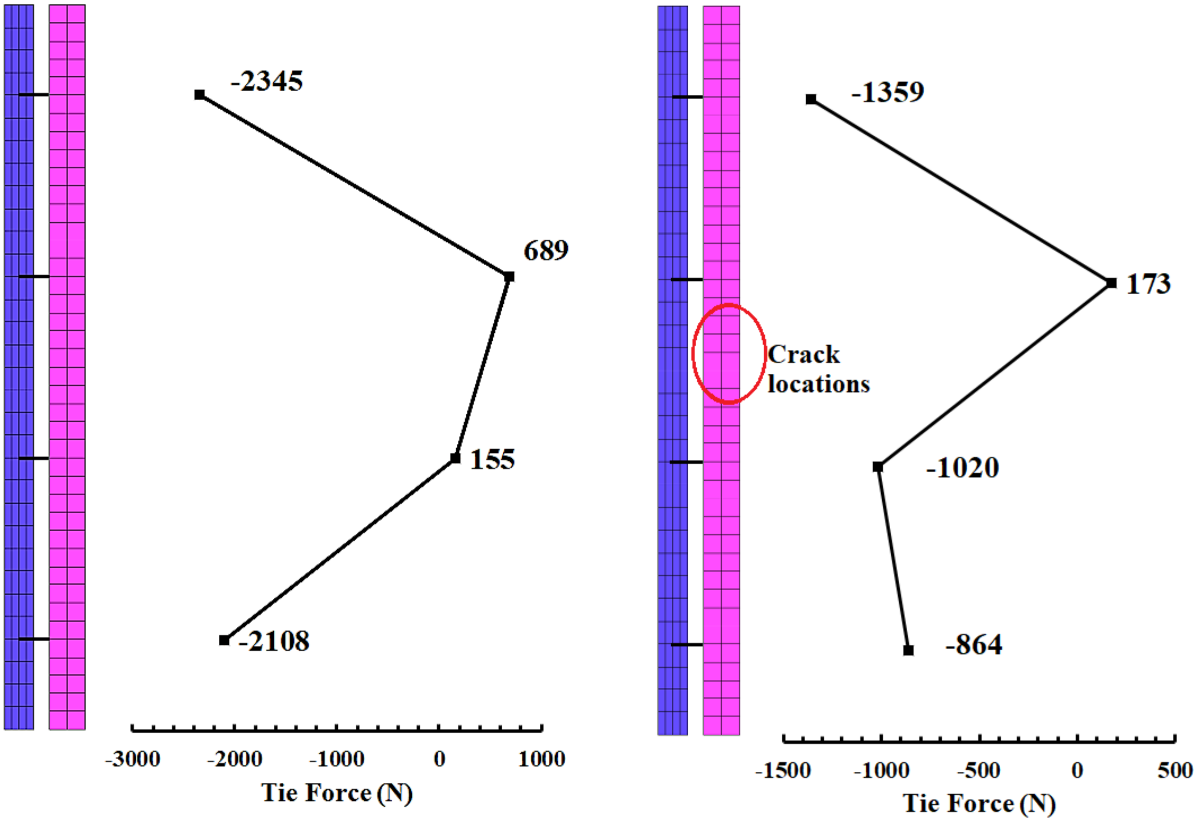


Figure 6. Tie position in the masonry veneer wall system

Table 2. Forces in ties in single story uncracked and cracked veneer wall subject to inward loading

Tie No.	Uncracked		Cracked	
	Forces (N)	Comments	Forces (N)	Comments
1	-2355	All ties are in compression	-1361	All ties are in compression
2	-2328		-1343	
3	-2327		-1335	
4	-2370		-1376	
5	690	All ties are in tension	168	All ties are in tension
6	676		156	
7	678		184	
8	711		187	
9	151	All ties are in tension	-998	All ties are in compression
10	145		-1025	
11	151		-1010	
12	171		-1046	
13	-2148	All ties are in compression	-887	All ties are in compression
14	-2051		-814	
15	-2047		-835	
16	-2186		-920	

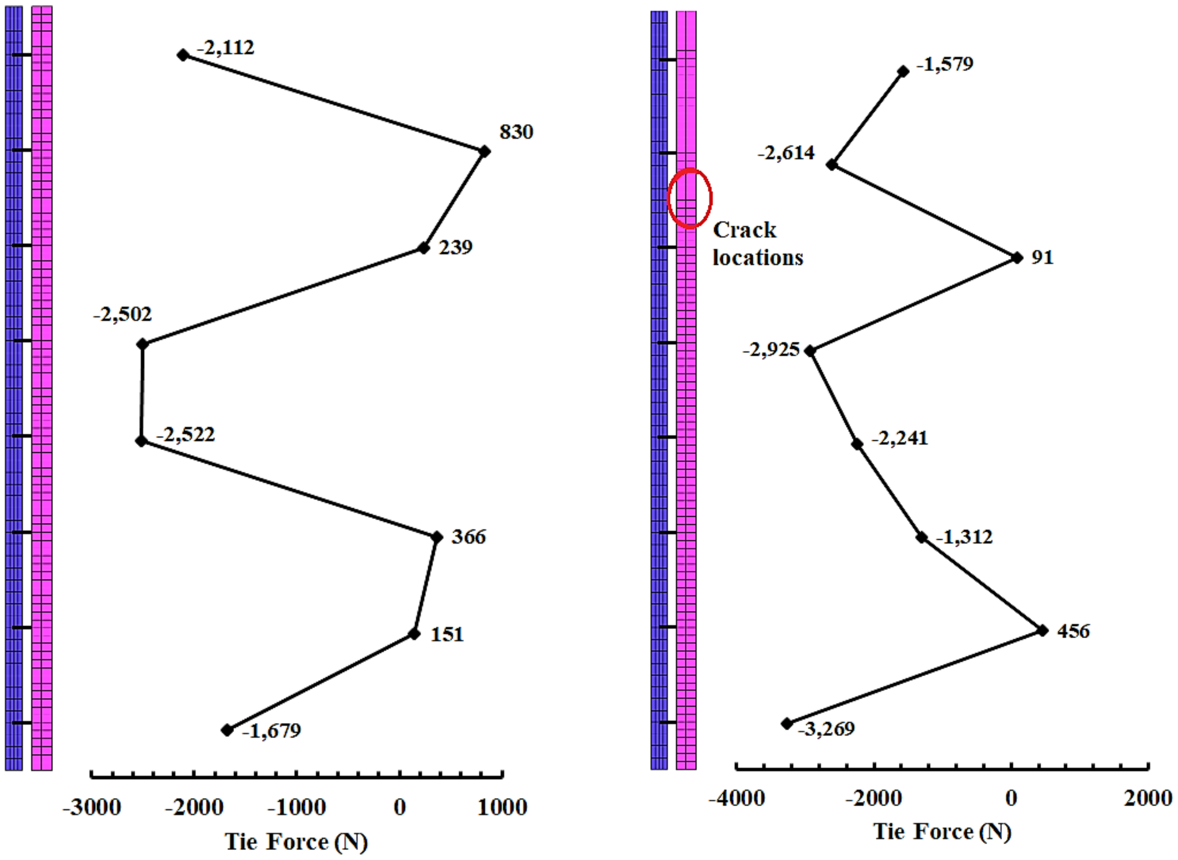


(a) Uncracked veneer **(b)** Cracked veneer

Figure 7. Tie force distribution across the height of the wall for single story system under inward loading

Multistory Veneer

Multistory veneer is used as a cladding in high rise framed construction as well as in housing. A two-story brick veneer wall system (4800 mm high × 1200 mm long × 110 mm thick) is modeled with two vertical timber studs (flexible backup) connected via ties to represent the mechanism of load transfer in multistory veneer system. The boundary conditions are the same as for the single-story model, with additional lateral restraint in the out-of-plane (z-axis) direction (to represent a floor diaphragm) for timber studs at mid-height. The average tie force distributions along the vertical location of the wall are shown in Figure 8(a) and Figure 8(b) for uncracked and cracked veneer, respectively. From the analysis, it can be inferred that the mechanism of load transfer through the ties, in this case, is similar to that for single story veneer, although the distribution of load in the ties is influenced by wall continuity and support conditions at mid-height. When a veneer continues past a horizontal support such as a floor system, and the veneer is uncracked, high tie forces are induced in the ties at both the top and bottom of the wall at each floor level due to the deflection of the flexible backup. This is why high compression force is visible at mid height (first-floor diaphragm) of the double story veneer system. The observed force distributions for multi-story veneer system are as expected based on findings reported by Page et al. (1996). However, if the veneer is discontinuous at a floor level (i.e., supported on a shelf angle), the distribution of loads in ties within each story will be similar to the single-story case.



(a) Uncracked veneer

(b) Cracked veneer

Figure 8. Tie force distribution across the height of the wall with for double story system under inward loading

CONCLUSIONS

A numerical study of the behavior of masonry veneer wall systems subjected to out-of-plane (lateral) loads and associated tie force distributions has been described for single and multi-story veneer wall systems. From the analyses performed, it is discerned that when the veneer is uncracked, the deflection of the flexible backup induces maximum tie forces in the top and bottom row of ties with lower tie forces in the intermediate ties. All the tie forces are nearly identical across a single row of ties. Moreover, the tie force behavior of the multi-story veneer is akin to the single story with additional high tie forces near the top and base of the wall at each story. It also becomes apparent that the veneer cracks horizontally along a bed joint near mid-height which is an expected phenomenon. However, this cracking of the veneer changes the distribution of tie forces drastically, with the rows of ties near mid-height now being critically loaded and causing an increase in the deflection of the backup frame. Therefore, the design procedures of the wall ties should consider the ultimate strength checks of both the uncracked and cracked conditions of the veneer wall.

ACKNOWLEDGMENTS

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