Finite Element Modelling of Unreinforced Masonry (URM) Wall with Openings: Studies in Australia

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Abstract. Unreinforced Masonry (URM) wall is vulnerable in resisting horizontal load such as wind and seismic loading. It is due to the low tensile strength of masonry, the mortar connection between the brick units. URM structures are still widely used in the world as an infill wall and commonly constructed with door and window openings. This research aimed to investigate the behaviour of URM wall with openings when horizontal load acting on it and developed load-drift relationship of the wall. The finite element (FE) method was chosen to numerically simulate the behaviour of URM with openings. In this research, ABAQUS, commercially available FE software with explicit solver was employed. In order to ensure the numerical model can accurately represent the behaviour of an URM wall, the model was validated for URM wall without openings using available experimental results. Load displacement relationship of numerical model is well agreed with experimental results. Evidence shows the same load displacement curve shape obtained from the FE model. After validating the model, parametric study conducted on URM wall with openings to investigate the influence of area of openings and pre-compressive load on the horizontal load capacity of the wall. The result showed that the increasing of area of openings decrease the capacity of the wall in resisting horizontal loading. It is also well observed from the result that capacity of the wall increased with the increasing of pre-compressive load applied on the top of the walls.
Keywords: URM wall, openings, horizontal load, displacement, ABAQUS.

Introduction

It has been decades that masonry material used for infill walls, retaining walls, monuments and bridges. Although this material has been replaced by steel and concrete in the 20ᵗʰ century, masonry buildings are still mainly used now for residence, educational buildings, and industrial constructions (Hendry, 2001). As a result, it is needed to identify much further behaviour of masonry wall. Masonry is a composite material consists of clay brick or concrete block and mortar. There are many advantages of using it as building materials. They are heat resistant and sound insulation. Masonry wall also has a good behaviour under vertical compression loading. However, despite of those advantages, masonry construction is vulnerable at resisting in-plane lateral loading such as seismic loading which caused by earthquake and wind loading (Zhuge *et al.*, 1998). It is due the weakest element in masonry, the mortar connection between the brick units. Consequently, further research requires investigating the complex behaviour of masonry wall subjected to lateral in-plane loading.

A commonly typical structure of masonry wall is frames with masonry infill wall which is still used around the world even in the highly seismic regions. It is essential to conduct a study of masonry panel itself to investigate the maximum capability of the wall to resist lateral horizontal loading before its failure. This research on masonry panel will be useful to evaluate the seismic vulnerability for the whole buildings or structural frames with masonry infill wall. Furthermore, this study can lead to the development of proper retrofitting measures for masonry buildings and can be applied to new construction to expand design guidelines (Pandey and Meguro, 2004). It became an urgent need as existing masonry structures especially ancient building which collect the cultural heritage located on the seismic region around the world (Giambanco *et al.* 2001).

There has been 40 years ago that many researchers have conducted on study of masonry panels subjected to lateral loading (Basoenondo, 2008), but it is still limited

research on unreinforced masonry (URM) wall with more than one opening. As masonry building typically constructed with door and window openings, it is also need to identified behaviour of the wall between two openings. Therefore, it is necessary to conduct numerical research of identifying behaviour of URM wall with openings under lateral in-plane loads

The aim of this research is to comprehensively investigate the behaviour of URM wall with openings by identification of crack propagation on the wall during the analysis and investigation of load drift relationship of the wall by the following objectives: (1) simulating three dimensional finite element model of URM wall panel with openings using a FE program ABAQUS, (2) developing load and drift relationship, (3) investigating the failure crack pattern of the wall, (4) investigating the influence of opening area and pre-compressive load on URM wall with openings.

Materials and Methods
Modelling condition
A commercially FE software, ABAQUS, was used in this research to develop FE model of URM wall. Generally in FE models, important behaviour of the real structure should be speculated with considering limitation of the applied model created in each numerical research. Therefore, it should be mentioned that there are some limitations applied in modelling URM wall in this research which are: (1) No cracking was allowed in bricks units with the increasing of the loading. Consideration was taken at the uncertainty of cracking location in the unit. Therefore, all units considered as the full continuum bricks and mortar with no crack consider in their meshing. However, the inelastic behaviour of continuum part will be model so that they can absorb some energy from the applied load, that can be seen on their deformed shape. (2) Tension behaviour of mortar is assumed to be zero in this analysis.

Material model
A micro modelling technique proposed by Lourenço (1996) and Lourenço *et al.* (2007) were adopted to model URM walls in this research. Unit of the bricks are expanded in both direction of mortar thickness and are modelled using continuum elements. Whilst, the interaction between the brick were modelled as interface. The adopted strategy can be seen in Figure 1.
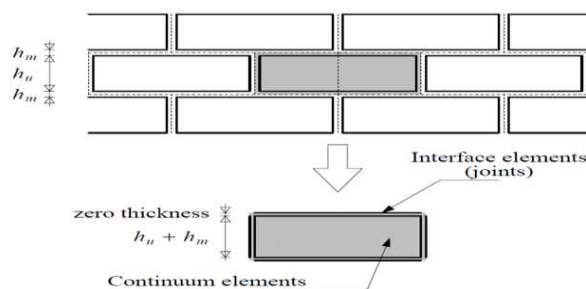

Figure 1. Adopted modelling strategy (Lourenço 1996).

Explicit solver in ABAQUS was chosen to model URM wall. This method is a computationally efficient and capable to simulate quasi static loading which including in this study. Moreover, it can avoid the convergence problem which can be highly occurred in implicit. Bricks and mortar will be modelled using C3D8R element. They were treated as a continuum element and modelled using inelastic constitutive model available in ABAQUS named Drucker Prager plasticity model. This model chosen due to it can be used to model frictional materials, which are typically granular-like soils and rock and exhibit pressure-dependent yield (the material becomes stronger as the pressure increases); to model materials in which the compressive yield strength is greater than the tensile yield strength, such as those commonly found in composite materials; allow a material to harden and/or soften. Normal and tangential behaviour interactions available in interaction module in ABAQUS were used to model the interaction between the bricks. It is assumed that when

two surfaces in contact, they usually transmit shear as well as normal forces across their interface. A general relationship between these two force components is known as friction between the contacting bodies. In this research test data points were chosen as input data for the interaction.

Material properties

Material properties for continuum bricks and mortar both for elastic and inelastic behaviour can be seen in Table 1. Compression hardening masonry used for continuum bricks and mortar can be seen in Figure 2.

Table 1. Material properties for continuum bricks and mortar.

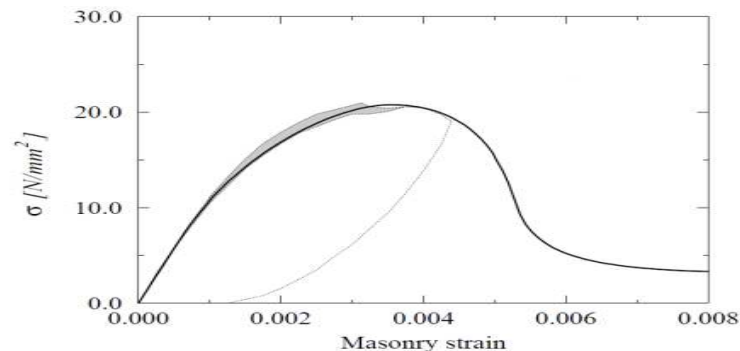| Parameter	Value
Elastic properties:	
- Density (kg/m^3)	2000
- Modulus elasticity (N/m^2)	16700
- Poisson ratio	0.15
Inelastic properties:	
- angle of friction (β)	46°
- flow stress ratio (K)	0.8
- dilatation angle (□)	20°

Figure 2. Compression hardening behaviour of masonry (Lourenço and Rots 1997).

The behaviour of interface interaction between bricks was simulated by normal and tangential behaviour. Friction between contacting bodies was chosen to define the tangential behaviour in this research. Based on Martini (1997) study on finite element model in the out-of-plane failure of unreinforced masonry using ABAQUS, sliding in masonry can be prevented by using higher friction coefficient (10). However in Bekloo study (2008) on numerical analysis of masonry panel using ABAQUS, it was found that friction coefficient of masonry at the value of 5 and 10 did not give any significant differences on the result. Then, it was decided static friction coefficient using in this research is 5. Whilst the chosen kinetic friction coefficient is 0.75 which come from cohesion data available in Lourenço and Rots (1997).

Methods

Validation of FE model of URM solid wall was conducted by comparing load displacement relationship of the wall with available experimental result. The validation model dimension of 800x900 mm^2 was used here. The wall consists of 16 courses high and 4.5 courses long. The dimension of clay bricks is 195x100x45 mm^3 with 10 mm mortar thickness. The geometric of the model and brick dimension can be seen in Figure 3.

There are two kind of loads were applied on the model. The first load is pre-compressive load (σ'_v) of 0.3 N/mm^2 applied on the top of the wall constantly during the analysis. The second load is the horizontal load in term of displacement which applied monotonically from the top side of the wall. The scheme of those two applied load can be seen in Figure 4. Furthermore, during the analysis, the bottom face of the masonry was restraint for all translating DOF's and the top side of wall where the horizontal displacement applied is in the free condition.
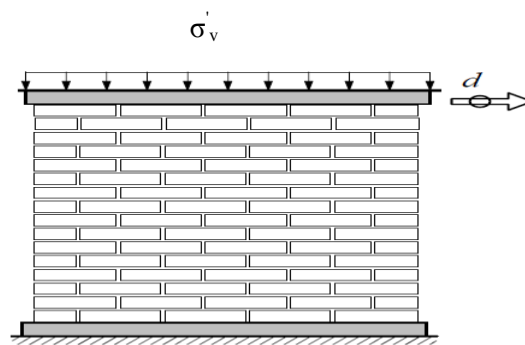
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σ'_v

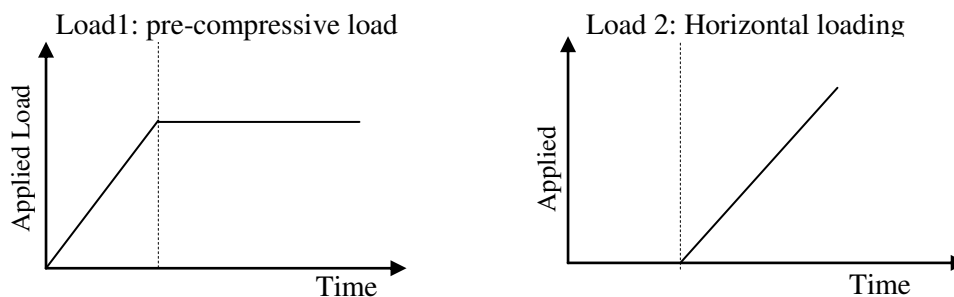Figure 3. Geometry of the adopted URM wall (Lourenço and Rots 1997).

Figure 4. Loading Scheme.

Once the validation model successfully represented the behaviour of URM masonry wall without opening, URM wall with openings model based on the model was developed. Then, the parametric of studies carried out to investigate the influence of area of openings and pre-compressive load applied on the top of the wall. There are three type of opening chosen for parametric studies which can be seen in Table 2. Two value of pre-compressive load of 0.3 N/mm2 and 1.21 N/mm2 applied on the top of the wall to study their influences.

Table 2. Type of URM wall with openings.

Opening Type	Illustration	Opening area
Type I		Window = 0.35 m x 0.3 m Door= 0.65 m x 0.3 m Opening area = 0.3 m^2
Type II		Door = 0.65 m x 0.3 m Opening area = 0.195 m^2
Type III		Window = 0.35 m x 0.3 m Opening area = 0.105 m^2

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Results and Discussion
Influence of Area of Openings

It can be seen in Figure 5 that with the decreasing of opening area, the capacity of the wall to resist the horizontal load is increasing. In observing the crack propagation on URM wall with openings type I with door and window opening, initial diagonal crack appeared from the top and bottom of window openings. Those crack accompanied by sliding of brick components above door opening (see Fig. 6b). With the increasing of the load, diagonal opening appeared at pier 1 and propagated to the support direction (see Fig. 6c). At the end of analysis, another diagonal shear opening formed above door which propagated to the top direction of the wall and accompany by sliding at bottom of pier 3(see Fig 6d). It is likely the final collapse mechanism of the wall is caused by the extension opening of diagonal shear crack at above the window followed by the compressed toe at the bottom side of pier 3 (see Fig. 6a).

Moreover, In Magenes and Calvi (1997) URM wall with failure mechanism of diagonal shear cracking resulted in 0.87 % drift From Figure 5, the drift resulted for URM wall give a good agreement for type I, II and III which are 0.78 %, 1 % and 1.1% respectively. It shows no significant differences of drift between the walls with the same failure mechanism.
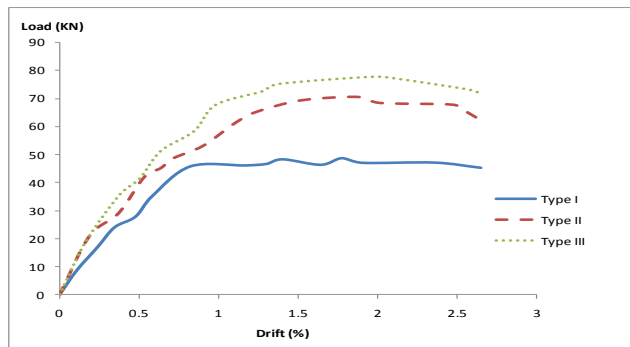

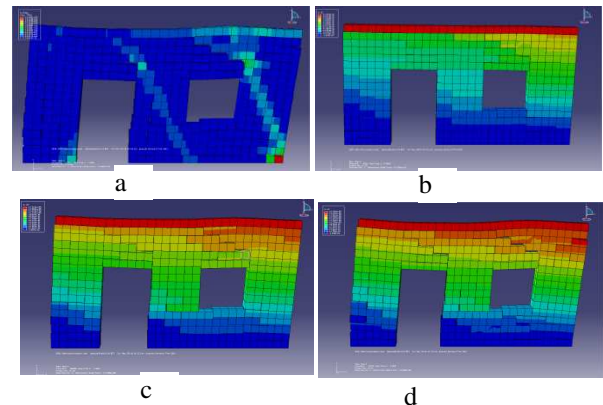Figure 5. Comparison of load-drift relationship of URM wall with various areas

Figure 6. Type I wall at the end of analysis (misses stress), (b) Wall at d= 5 mm, (c) Wall at d= 15 mm), (d) Wall at d= 22 mm).

Influence of Pre-compressive load

In Observing Figure 7a and Figure 7b, it can be concluded that both for URM wall type I and II, with the increasing of pre-compressive load, the capacity of wall in resisting horizontal load will slightly increase.
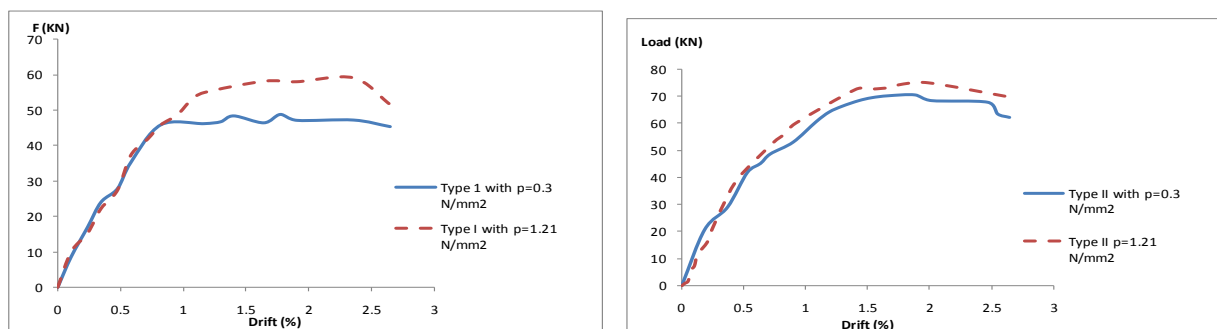

Figure 7. Comparison of load-drift relationship of URM wall Type I with different compressive loading (left), Comparison of load-drift relationship of URM wall Type II with different compressive loading (right).
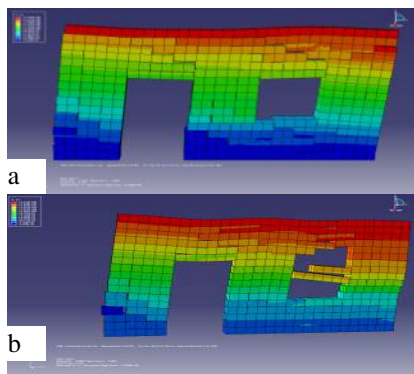
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Figure 8. Crack behaviour of URM wall with opening Type 1 under different pre-compressive load; (a) 0.3 N/mm2, (b) 1.21 N/mm

It also can be observed from Figure 8 for wall type I, evidence shows that with the increasing of pre-compressive loading, reclosing of diagonal crack is founded in observing the crack pattern at the end of analysis. It is also noted that under the same model condition, the response of the wall type I with pre-compressive loading of 1.21 N/mm2 resulted on falling condition of some bricks below the opening. It is likely caused by the modelling condition of the wall which only relies on normal and tangential behaviour of interface interaction between the bricks.

Conclusions

It can be concluded from parametric studies that the capacity of wall with less opening area in resisting horizontal loading are increased. Moreover, higher pre-compressive load applied on the top of the wall resulted on the slightly increasing capacity of the wall. It is also noted that with higher pre-compressive load on the top of the wall resulted on reclosing of diagonal shear crack which is observed from crack pattern at the end of analysis. Moreover, it can be concluded from crack propagation observation on the wall that the collapse mechanism of the wall caused by diagonal shear failures located at piers and the compressed of the toe at the bottom right pier. It shows that this finite model can well capture the behaviour of URM wall with openings.

Acknowledgements

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