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INVESTIGATION ON THE EFFECT OF MORTAR QUALITY ON THE OUT-OF-PLANE SEISMIC PERFORMANCE OF UNREINFORCED MASONRY WALLS

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Abstract

Unreinforced masonry (URM) walls are used in a broad range of building-stock worldwide. These walls are susceptible to a loss of functionality, structural damage, or complete collapse during earthquakes. Damage to URM walls due to the out-of-plane loading is usually characterized by weak modes of failure, due to cracking of the mortar joints and crushing failure of the masonry. In addition, historic buildings may present poor mortar quality, degraded and crumbled mortars, and variation of mortar quality through the wall thickness due to the weathering (and later outside repointing), workmanship and aesthetic preferences; this can make the walls more prone to complete collapse during a seismic event.

This study aims to highlight the significance of mortar quality on the seismic performance of URM buildings and the potential need for retrofitting options for buildings with degraded mortar. A validated masonry material model is used to model a 1.4m wide by 2.8m high wall using the LS-DYNA finite element software. Several material parameters (e.g. compressive strength of masonry, tensile strength of bed joints) are varied through the thickness of walls to model the effect non-homogeneous mortar degradation on the out-of-plane performance of walls. These variations are repeated for two types of masonry: calcium silicate and clay walls. Furthermore, a full 3D model of a typical two-story URM building with the timber framing system is analyzed under earthquake conditions to determine the influence of these variations of mortar quality on its seismic performance.

Keywords: Masonry Buildings; Finite Element Analysis; Mortar Quality

1. Introduction

Unreinforced masonry (URM) buildings are classified as those that are constructed from individual bricks, bonded together with mortar, and which do not contain tensile reinforcement. In some countries such as Italy, Mexico, Indonesia and Australia, the URM building inventory accounts for more than 60% of the buildings [7]. These buildings are widely recognized as some of the most seismically vulnerable [15] [4] [9] [11]. As an example, in February 2011 Christchurch earthquake in New Zealand, many of the URM building were damaged due to their brittle nature and inability to dissipate energy, which resulted in 150 casualties.

URM buildings are generally constructed from relatively rigid brick and mortar walls that are attached to light timber floor diaphragms [12]. Due to the high flexibility of floor diaphragms and their inadequate connection to the walls, these masonry walls are very prone to out of plane failure and/or buckling failure mode(s) [1]. Therefore, out-of-plane wall failure is considered as the most hazardous URM failure mode due to falling debris and also potential of catastrophic collapse [3].

There have been many experimental and analytical studies to investigate response of unreinforced masonry walls to out of plane forces. Experimental research by ABK [1] and analytical studies conducted by Priestley [13] have shown that one-way spanning URM walls have significant out-of-plane post-cracking capacity, which improves their seismic behavior. The requirements set in ASCE/SEI 41, for allowable h/t ratio of out-of-plane walls are based on the research by ABK [1]. Doherty [4] studied the behaviour of one-leaf, one-way URM walls, and proposed a formulae for derivation of force-displacement curves that were used in subsequent time history analyses (THA). In a more recent study Sharif et al. (2007) used a rigid body motion method to model the behaviour of cracked URM walls supported by rigid floors. They assumed that a crack had pre-formed at the wall mid-height, and calibrated their model based on a series of shaking table tests performed by Meisl et al. (2007).

In many of the old and historical URM buildings, poor quality non-hydraulic mortars that are susceptible to weathering were used (Fig. 1a). These types of mortars degrade over time and crumble when exposed, which results in missing mortar or partially open joints on the URM walls. Furthermore, re-pointing with good quality mortar was often performed on the external side of these walls after years of mortar deterioration to enhance the strength and aesthetic aspects of these old URM buildings (Fig. 1b). As a result of such a re-pointing on the external face of the URM walls, quality of mortar varies through the wall thickness in these old buildings. As mentioned earlier, the seismic performance of URM buildings is highly dependent on the out-of-plane performance of URM walls. Therefore, a reliable approach that can account for the effect of mortar quality variation through the wall thickness is critical when performing the seismic risk assessment of URM buildings.

(a) (b)

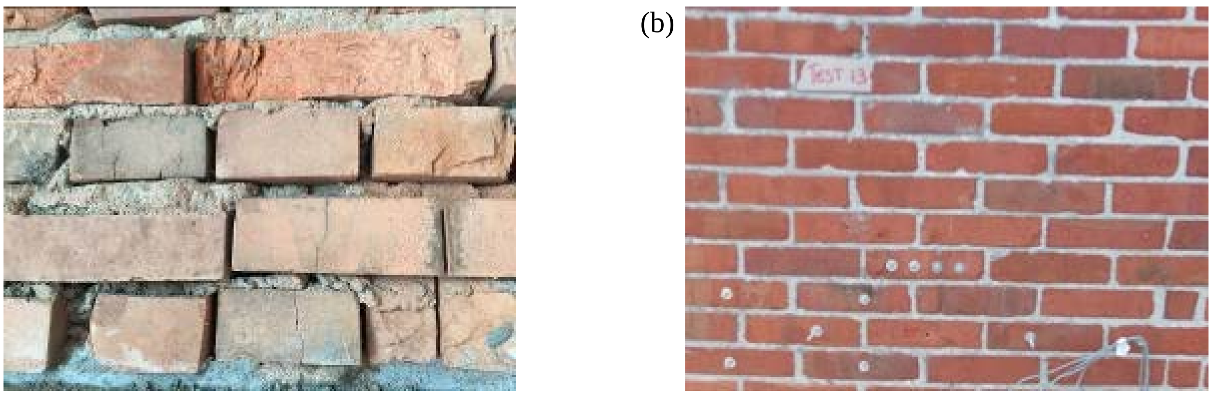

Fig. 1 - (a) Internal and (b) External sides of walls in URM buildings

This paper presents the results of an effort to investigate the effect of mortar quality variation through the wall thickness using a finite element simulation method. The paper begins with the modeling approach that is adopted. Next, a detailed description of one single URM wall and a two-story URM building is presented. All of the cases considered for the sensitivity analysis are then discussed, followed by the results obtained from finite element non-linear response history analysis. Finally, a brief summary and conclusions of this study are provided, comparing the results from all cases against each other.

2. Description of models

In order to investigate the direct effect of mortar quality variation, the seismic response of a single URM wall was considered. Also, to study the effect of such a variation on the overall response of buildings, a typical 2-story URM building was selected. A brief description of each structure is presented below.

2.1. Single URM wall

A single leaf URM wall made from calcium silicate bricks was considered in this study with the overall dimension of 1.4m long, 2.8m high, and 0.1m thick (Fig. 2a). The boundary condition of this wall was assumed to be double-fixed, i.e. no rotation at top or bottoms. Two overburden pressures of 0.3 MPa and 0.1 MPa were considered to represent realistic vertical load for this wall.

2.2. 2-story URM building

The URM building represented a typical 2-storey residential, detached building. It was assumed to be constructed from solid masonry walls, supporting a timber floor at first floor level, and a timber-framed pitched roof. The building has the total height of 7m and plan dimensions of 9m by 8m. Internal and external walls were assumed to be 100mm and 200mm thick, respectively, constructed using clay bricks and cement mortar. The first floor was constructed from 80mm by 180mm timber joints, supporting 25mm by 165mm timber planks. The roof timber members were sized between 50-80mm by 100-180mm rectangular sections.

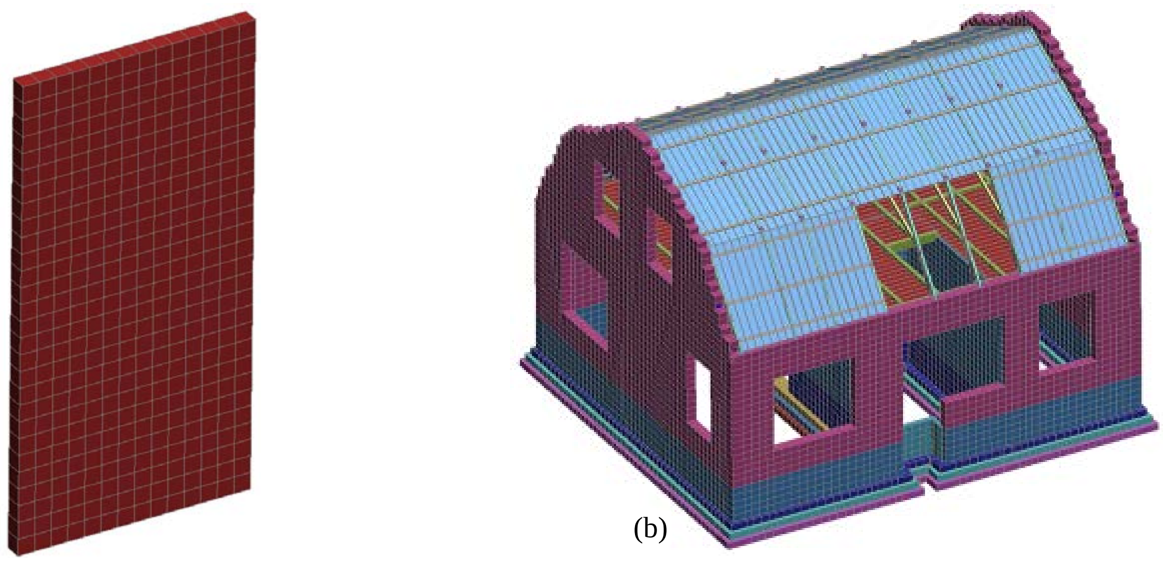

Fig. 2 – (a) Single URM wall and (b) 2-story URM building. Shell elements drawn with their true thickness.

3. Numerical Modelling Approach

The analysis method employed in this study is Non-Linear Time History Analysis (NLTHA) using LS-DYNA [8] together with a “user material model” written by Arup to represent the URM. Specific modelling assumptions are as follows:

3.1. URM walls and footings

The masonry material model used in this study was developed by Arup on behalf of an organization concerned with understanding the seismic performance of URM buildings. The material model is written for shell elements and does not require the individual bricks or the bond pattern to be meshed. The model has a smeared crack formulation, with crack plane directions pre-defined along the mortar joint directions (bed joints and head joints). A fully-integrated shell element formulation was used, which has four integration points in the plane of each element, and a user-selected number of integration points (typically five or more) through the thickness. Collapse of walls and other structural members can be captured by a damage model that deletes elements from the calculation once certain criteria are reached, such as compressive strain (toe-crushing) or accumulated sliding in shear. In this study, the element dimensions were in the range of 100 to 200mm, and a reasonably square aspect ratio is used. In the following sections, the input parameters for masonry material will be presented in more detail.

3.2. Timber framing

Elastic elements with associated cross section properties were used for timber members and planks. Young's moduli of 5000 MPa was used for timber members and planks. Nonlinearity within the timber framing was assumed to be governed by the nailed connections.

Nails are modelled as zero length inelastic ~~e~~elements of 3.15mm diameter. They are assumed to behave elastically in their axial direction, meaning that they cannot be 'pulled out'. They are assumed to behave inelastically in shear, accounting for yielding of the nail and (local) crushing of the timber material [1].

3.3. Connections between timber framing and masonry walls

Various types of connections were used to connect timber framing to the masonry walls depending on the form of detail and location. In general, it was assumed that the strength of anchored connections was governed by the total capacity of the used nails with the hysteretic behavior discussed earlier. Anchored connections are deleted during the analysis if they reach their failure criteria. In addition, any sliding contact conditions within the connections were modelled with an assumed friction coefficient of 0.6.

3.4. Damping ratio

In all the numerical simulations, 2% of critical damping is applied over a frequency range 1-30 Hz to represent the small-strain damping of the masonry. Further damping is of course provided by nonlinear material behavior.

3.5. Analysis procedure

The nonlinear time history analysis starts with applying gravity force and, if applicable, overburden vertical load to the model. After reaching equilibrium under the vertical load, the ground motion time-history is then applied at the bottom of the structure.

4. Numerical Model Validation

The masonry material model used in this study has been extensively validated with available experimental data for different action mechanisms in the masonry components. A summary of two out of plane validation studies are presented here to underpin the outcomes of this paper.

4.1. Quasi static test

Doherty [4] conducted quasi-static out-of-plane pushover tests administered at the University of Adelaide in Austrailia. The specimen (specimen#8) was a 110 mm thick single-wythe wall with aspect ratio of 1.58 constructed of clay brick units. The applied overburden stress was 0.15 MPa. The wall was tested under double clamped boundary conditions. LS-DYNA model of the tested specimen was built and the pushover test was modeled using the masonry material model developed by Arup. Figure 3 compares the total force versus displacement obtained from the test and the finite element model in LS-DYNA. The LS-DYNA results show a good correlation to the test in terms of overall response. The peak strength before the formation of the mid-height crack is, however, slightly higher than the test.

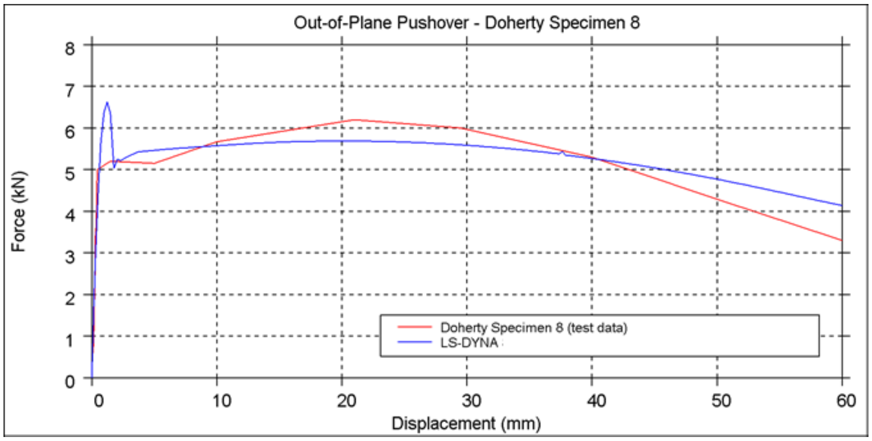

Fig. 3 – Doherty Specimen 8 – Shear force-displacement comparison plot

4.2. Dynamic test

EUC-COMP-4 was a dynamic out-of-plane test administered in the EUCENTRE laboratory at the University of Pavia, Italy [6]. The specimen was a 100 mm thick single-wythe wall with aspect ratio of 2 constructed of calcium-silicate brick units. The applied overburden stress was 0.3 MPa – 0.1 MPa. The wall was tested under double clamped boundary conditions. A series of dynamic load is applied to the specimen by increasing the PGA of the input motion. The maximum mid height displacement of the wall is measured for each PGA.

Figure 4 compares the maximum mid height displacement obtained from the test and the finite element model in LS-DYNA. The LS-DYNA shell model of EUC-COMP-4 predicts dynamic out-of-plane rocking behaviour and associated tensile bed joint failures at the top and bottom of the specimen as well as mid-height displacement.

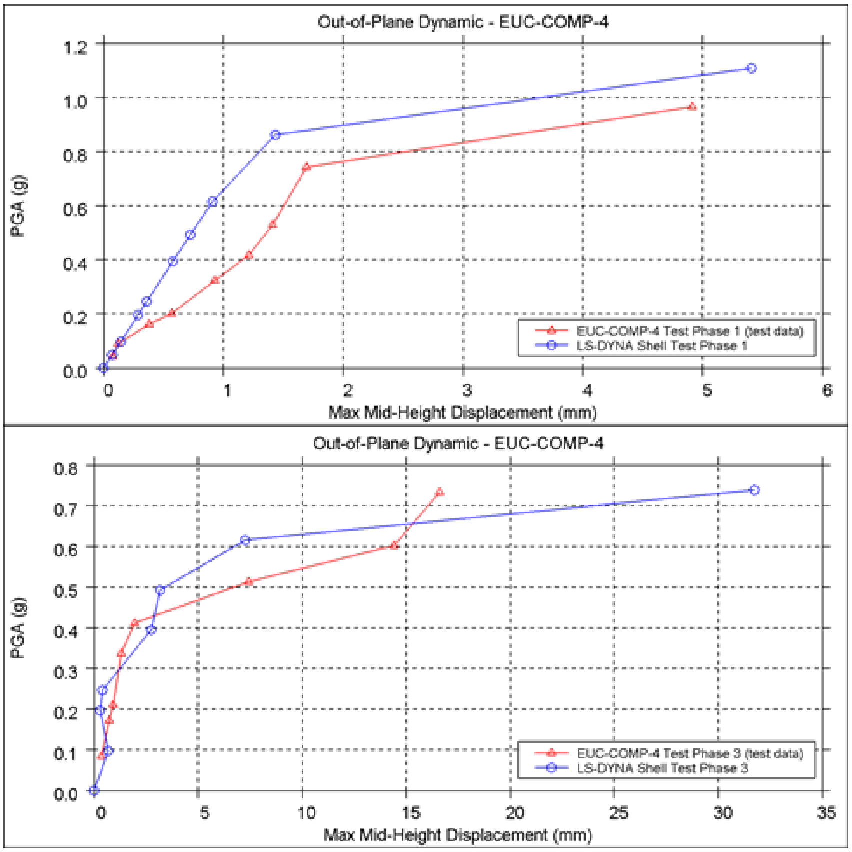

Fig. 4 – EUC-COMP-4 – Maximum mid-height displacement vs PGA plots comparison plot

5. Scenarios for Case studies

In order to investigate the effect of various scenarios of mortar quality through the thickness, five different mortar strength profiles were considered. These were generated by defining five integration points through the thickness of the wall with different material properties for each. According to earlier discussion, the best quality mortar was assigned to the outer layer, while the worst material property were assigned to the inner layer. Properties for the lower quality mortar were derived by scaling the strength parameters by 1%, 25%, 50%, or 75%. Table 1 shows the compresive strength and Young's modulus used for the masonry material with the best quality.

Table 1 – Masonry material parameters with the best quality mortar. Units (MN, m)

Symbol	**Material Property**	**Single URM wall**	**2-Story URM building**
f'm	Masonry compressive strength	6.3	7.5
Em	Masonry Young's modulus	4200	3500

Table 2 shows the quality variation through the wall section from inner layer to the outer layer in different models considered in this study. Such a variation was implemented by scaling the material parameters such as compressive strength, shear and tensile strengths, diagonal tension strength, Young's modulus and energy release rates both in tension and and shear.

To obtain the compressive behavior of lower quality masonry material, the compressive stress-strain curve of the material with the best quality was scaled down in two different ways: 1- Only strength of masonry material was scaled down; 2- Both strength and strain were scaled down. Fig. 5 shows the considered variations for compressive behavior of masonry material.

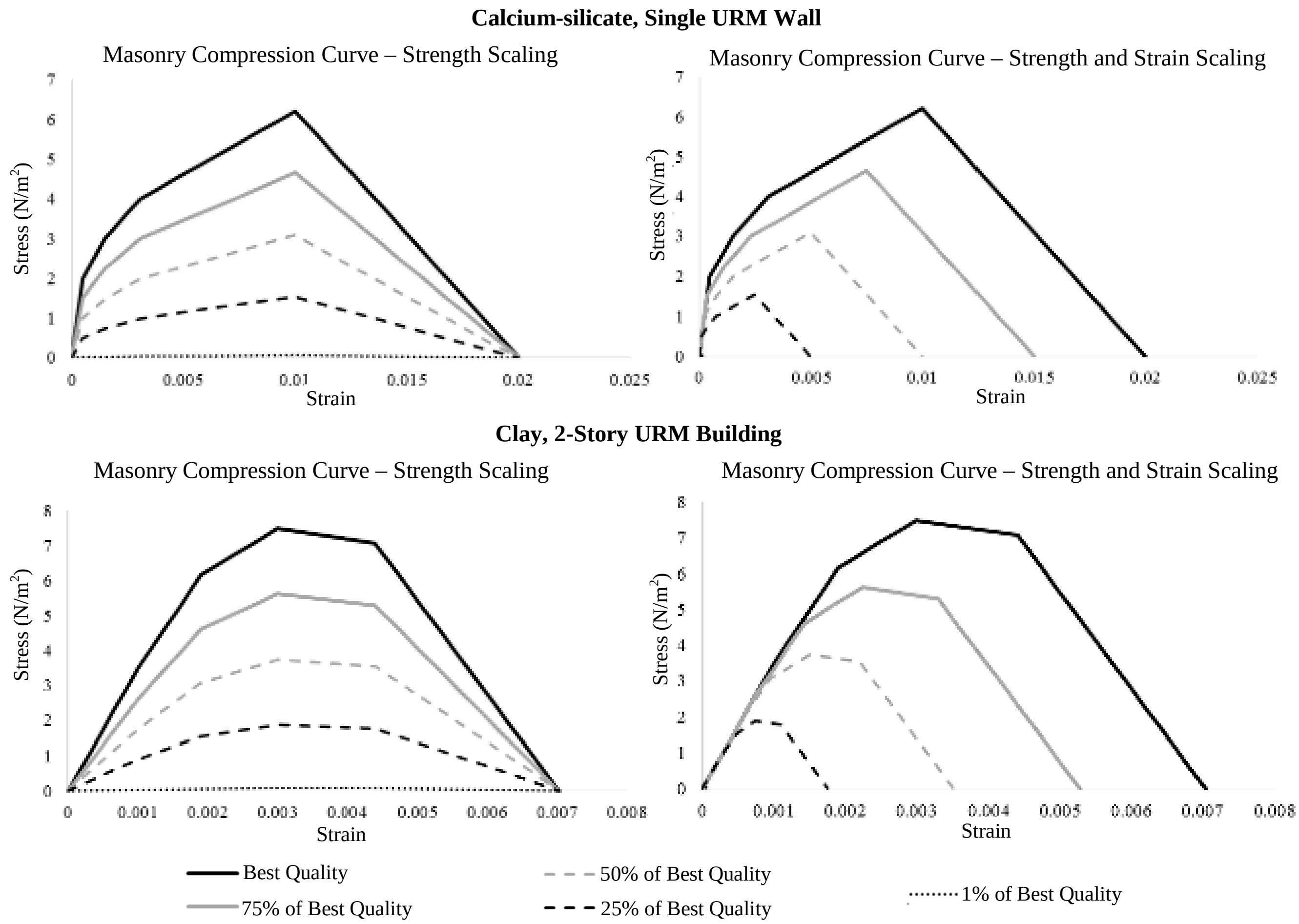

Fig. 5 – Compressive stress-strain curve of masonry material

Table 2 – Models with layers composed from materials with different Quality ratios (%) with respect to the best condition

Models #	Inner	2	3	4	Outer
Model 1:	100	100	100	100	100
Model 2:	50	50	50	100	100
Model 3:	25	25	50	100	100
Model 4:	1	25	50	75	100
Model 5:	1	1	50	100	100

In order to study the effect of motion variations on the performance of these walls, two types of historical motions with peak ground acceleration (PGA) of 0.247g and 0.383g, at their 100% intensity measure, were applied to the single URM wall. These two motions were repeated with increasing scale factors until the complete failure of the single wall model. It should be noted that two values of 0.3 MPa and 0.1Mpa overburden pressure were considered for this wall model (see Fig. 6). One tri-axial motion with horizontal PGA of 0.34g was applied to the 2-story URM building (see Fig. 6).

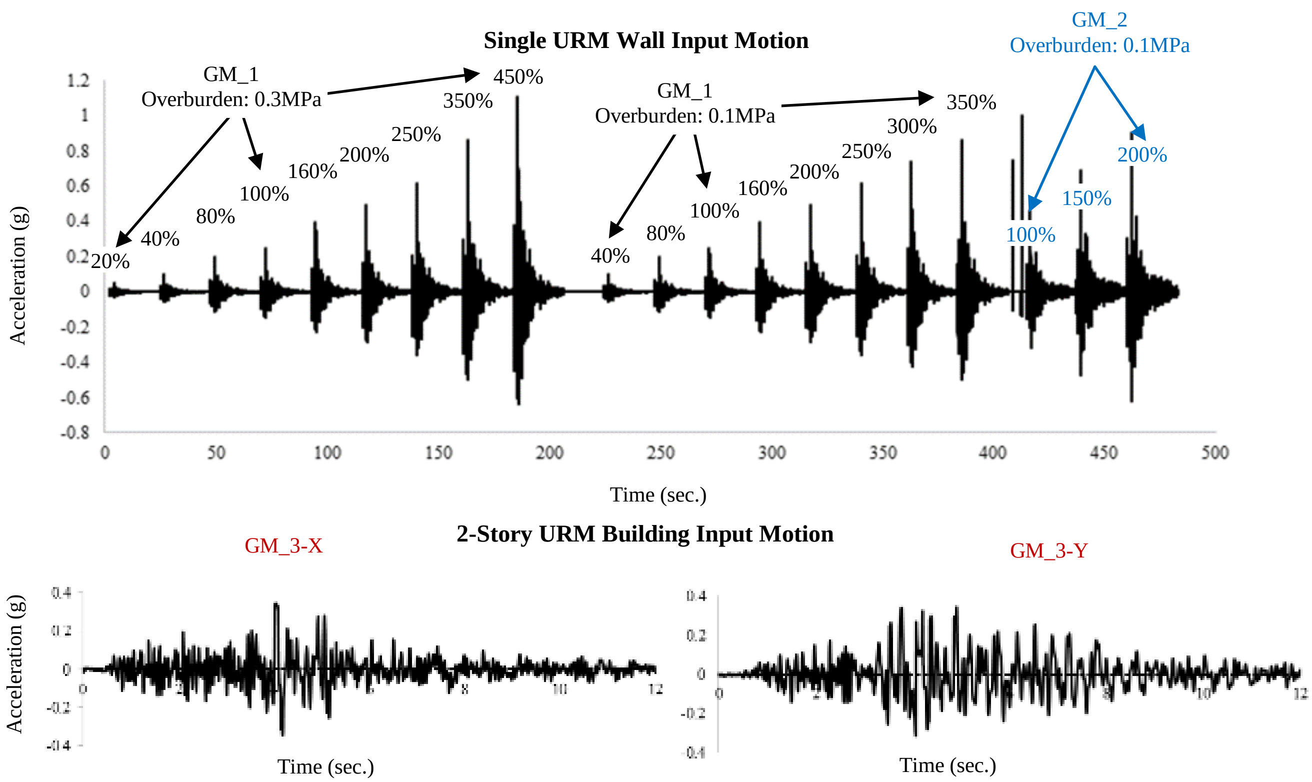

Fig. 6 – Two input motions for the single wall and one tri-axial (horizontal component shown only) motion for the building

6. Results

The five variants of the wall model were each subject to a ground motion that was repeated with increasing scale factor until the point of complete collapse. Fig. 7 shows the maximum crack opening of five wall model variants at the time when Model5 (the variant with the worst mortar condition) collapses. At this time, there was negligible damage in the wall with best mortar quality (model1) (no crack opening shown in Fig. 7). Also the collapse time of each wall specimen is presented in Fig. 8, which clearly shows that wall models with the best mortar quality tolerated more motion cycles. Results from this study shows that walls with best mortar quality were able to tolerate maximum PGAs of 0.96g and 0.51g under 0.3MPa and 0.1MPa, respectively, while walls with the worst mortar condition were only tolerated maximum PGA of 0.53g under 0.3MPa overburden pressure.

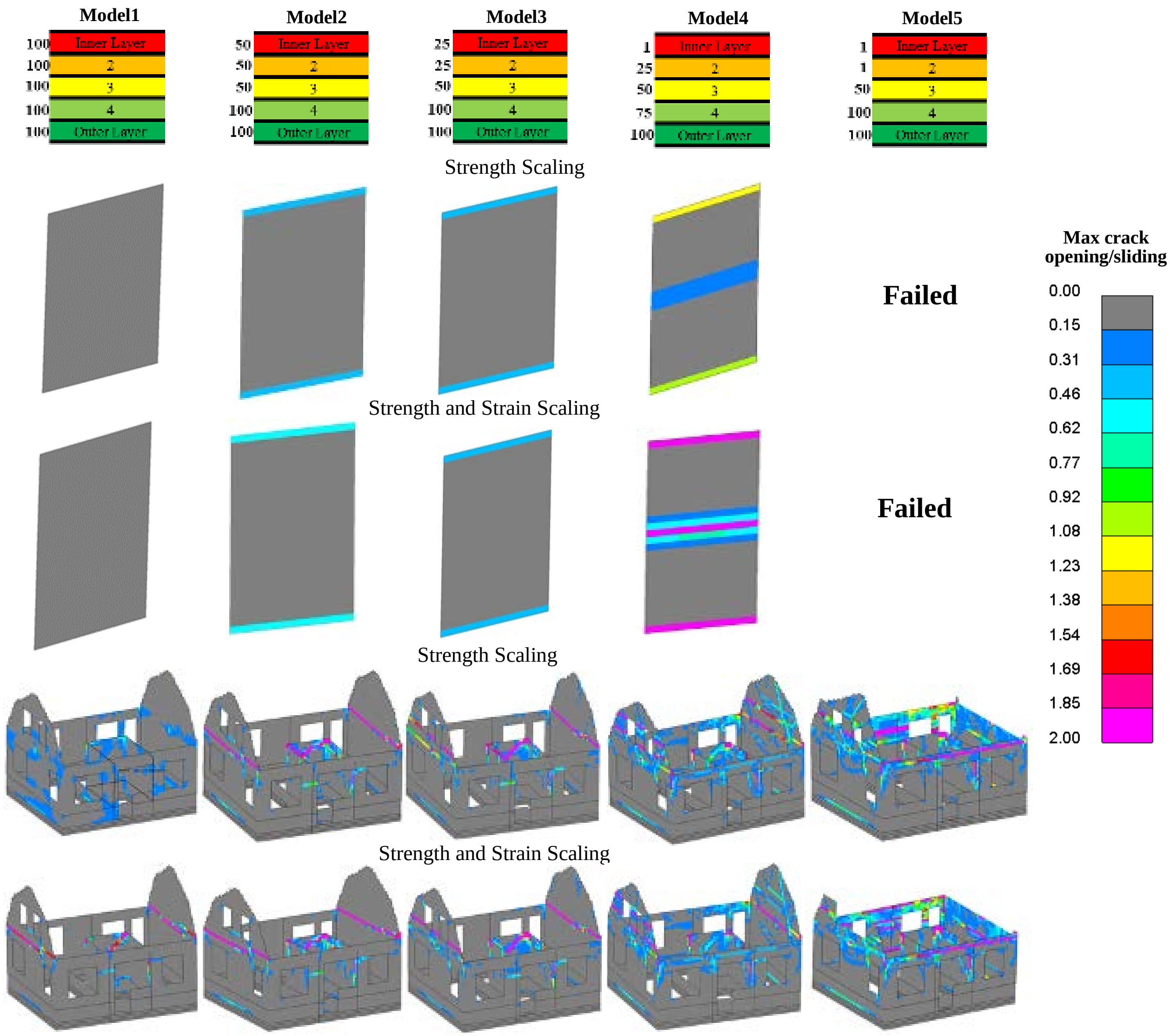

Fig. 7 – Maximum crack opening/sliding (max contour 2mm) within the models with different masonry parameters

The results demonstrate that out-of-plane failure of URM walls is very sensitive to mortar quality. In the case of the wall models, there was little sensitivity to the scaling method used for the compressive stress-strain behavior.

The five URM building model variants with different mortar quality were each subjected to the same ground motion. The resulting damage is compared in Fig. 7. As shown, results are quite sensitive to the variation of mortar quality through the section. In this building, while the model with the best mortar quality (model1) showed minimal damage, complete collapse was observed in the model with the worst mortar quality (model5).

In the case of the building model, the damage is slightly greater in the models in which mortar deterioration was represented by scaling both the stress and the strain.

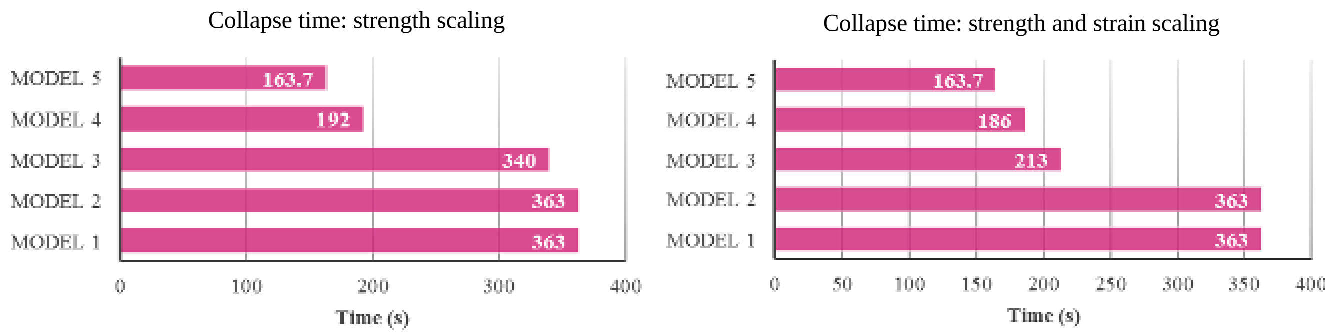

Fig. 8 – Collapse time of single URM wall

7. Summary and Conclusions

A single URM masonry wall and a 2-story building were modeled in this study using the LS-DYNA finite element software and a purpose-written user-defined material model to represent unreinforced masonry. Variations of mortar quality were represented by modifying the input material parameters. In total ten different cross sections were considered for these to models. Results suggest that variation of mortar quality can significantly affect the out-of-plane response and failure of masonry buildings. The results of this study shows that the performance of URM structures highly depends on the variation of mortar quality through the thickness. Therefore, in many of the old and historical masonry buildings that deterioration of mortar material and re-pointing of outer side of walls exist, special attention to the modelling of their material properties through the wall sections.

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