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# LS-DYNA NUMERICAL SIMULATION OF MASONRY GABLES OUT-OF-PLANE RESPONSE TESTED DYNAMICALLY

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**Abstract**

*Past earthquake events show that unreinforced masonry buildings are vulnerable to seismic loading. The assessment of masonry structures presents significant challenges due to the complexity of accurately reproducing the material response. In an effort to advance the understanding and predictive capabilities in this field, ERIES SUPREME organized a blind prediction contest focused on predicting the out-of-plane response of masonry gable walls. The organization asked participants to predict the response of two different experiments: one representing a gable wall connected to a stiff roof and the other to a flexible roof. Experiments were conducted on a shake table with increasing signal intensity until the collapse of the gables.*
*This study was conducted to participate in the contest, employing non-linear time history analysis to capture the dynamic response of the gables. The modeling approach adopted utilized LS-DYNA, a highly sophisticated finite element analysis software. This paper describes the modeling techniques and discusses the relevant parameters critical to the prediction. The results highlight the effectiveness of the chosen methods and provide insights into the behavior of masonry structures under dynamic loading conditions. The relevant parameters to the prediction are discussed, offering valuable guidance for future assessments and mitigation strategies for masonry structures.*

**Keywords:** URM, Masonry, LS-DYNA, Numerical Simulation, Shake table, Seismic


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# 1 INTRODUCTION

Unreinforced masonry buildings constitute a large part of the existing building stock worldwide, including in seismic areas. When subjected to lateral loading, masonry structures have demonstrated many vulnerabilities and failure mechanisms in past earthquakes, with out-of-plane failure mechanisms often being the most common type of failure and local collapse [1].

The heterogeneity of masonry as a material, along with its brittle and non-linear behavior, presents challenges in accurately predicting the response of masonry structures. This leads to conservative assumptions and simplified methodologies for assessing masonry buildings, necessitating the design of invasive and extensive retrofits.

# 2 ERIES SUPREME BLIND PREDICTION

The ERIES SUPREME blind prediction contest aims to improve the safety and seismic resilience of low-rise masonry buildings in Europe. These buildings are characterized by their unreinforced masonry (URM) walls and diverse pitched roofs, supported by masonry gables (Figure 1).

Figure 1: Typical modern masonry building with gable walls.

A series of dynamic tests were conducted by ERIES SUPREME to advance the understanding of the seismic out-of-plane response of masonry gables. The tests were performed at the EUCENTRE in Pavia, using the 9DLAB shake table facility, which was able to represent different restraint conditions on the gable during the dynamic testing [2].

## 2.1 Gable specimens

Two gable specimens were built and tested, representing gable walls supporting laterally flexible roofs and roofs that can perform rigidly with small relative in-plane deformation of the roof. Modern masonry with a single leaf of clay bricks and mortar was used to construct the gables. Material characterization was conducted to identify the average properties of the masonry as described in Table 1.

The 100x200 mm C24 grade timber joists were connected to the masonry gable by a pocket on one end. The other end of the joists connected via a hinge to the UPN140 back posts, which spanned between platforms.

| Material | Mechanical Properties | Mean Value |
|---|---|---|
| Mortar | Compressive Strength | 0.70 MPa |
| Mortar | Flexural Strength | 0.20 MPa |
| Bricks | Compressive Strength | 42.6 MPa |
| Masonry | Compressive strength | 7.44 MPa |
| Masonry | Young’s modulus | 4072 MPa |
| Masonry | Bond strength | 0.27 MPa |
| Masonry | Cohesion | 0.21 MPa |

Table 1: Masonry material characterization.

## 2.2 Test setup

The different restraint conditions of the gable provided by the roof were simulated by applying motions to two different platforms, above and below the gable, as shown in Figure 2. For the gable supporting a rigid roof, the same ground motion sequence was applied to the bottom and top platforms. For the gable supporting a flexible roof, a different record was used in the sequence between the bottom and top platforms, as schematically shown in Figure 2.

Joists connecting to the gable were spring-loaded with an approximately constant imposed force of 4 kN at the location of each pocket.

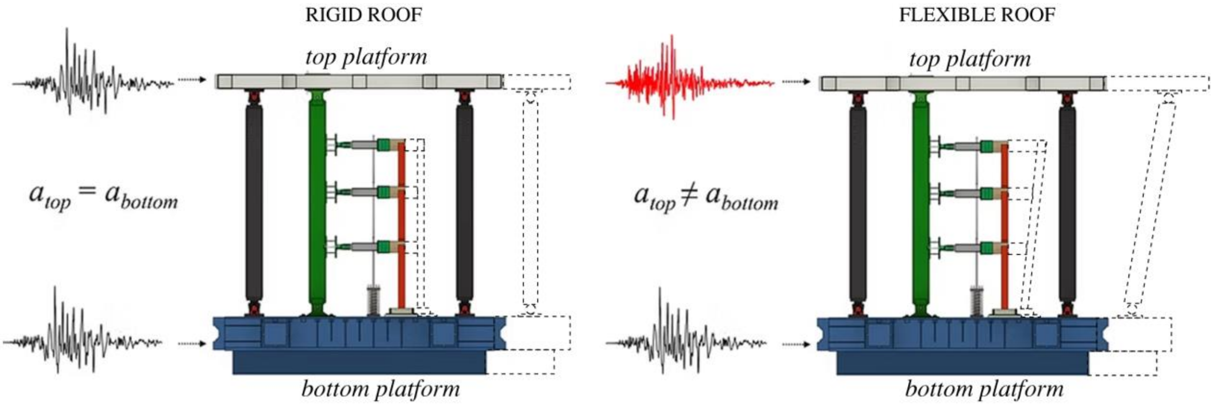


Figure 2: Testing configurations for the two gables (Modified after [2]). Dashed lines represent the conceptual deformations of the specimens and platforms.

A sequence of motions at increasing discrete intensities, with a rest phase in between each increment, was applied to the platforms until gable collapse. The applied sequence included two different motion sets, shown in Figure 3: one based on an induced seismicity record and another based on a natural tectonic seismicity record. The first applied record had a peak acceleration at the bottom platform (PBA) of 0.018g (i.e., EQ1@10%) and was incremented in 5 steps to 100%. The second record was applied, starting with a PBA of 0.28g (i.e., EQ2@50%), with an increment of 25% for the next intensity up to 200%, and then incremented by 50% until collapse.

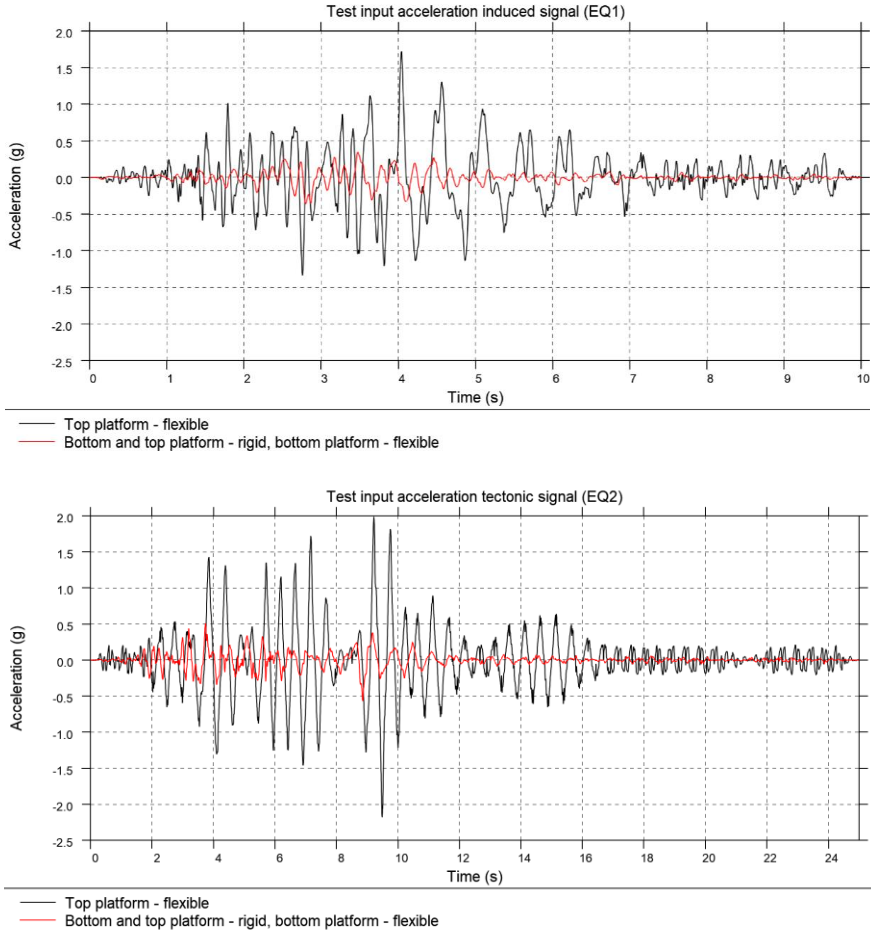


Figure 3: EQ1 and EQ2 acceleration time histories at 100% scaling.

## 3 PROPOSED MODELLING APPROACH

### 3.1 LS-DYNA FE model

The proposed modelling approach to predict the out-of-plane response of the masonry gables was through non-linear dynamic modelling with an explicit time-integration scheme. The software used for the analysis was Ansys LS-DYNA® [3], a multi-purpose nonlinear finite element program, that can be used to model complex problems with the possibility of parallelizing the analysis on multi-processor computers [4]. The software has been applied to a variety of projects in the seismic assessment of historical buildings using Non-Linear Time History Analysis [5].

The model generated to replicate the response of the gables is shown in Figure 4. A squared mesh of 10 cm shell elements was used to model the masonry gable.

The timber joists were modelled as elastic beam elements. They were connected to the gable via one-dimensional elements with frictional resistance to replicate the joist pocket connection. A coefficient of friction equal to 0.6 was considered. Frictional sliding was possible along the axial direction of the joists. No initial bond was modelled. Steel beams on one end of the joists were modelled as elastic beam elements and pinned on the side attached to the steel posts.

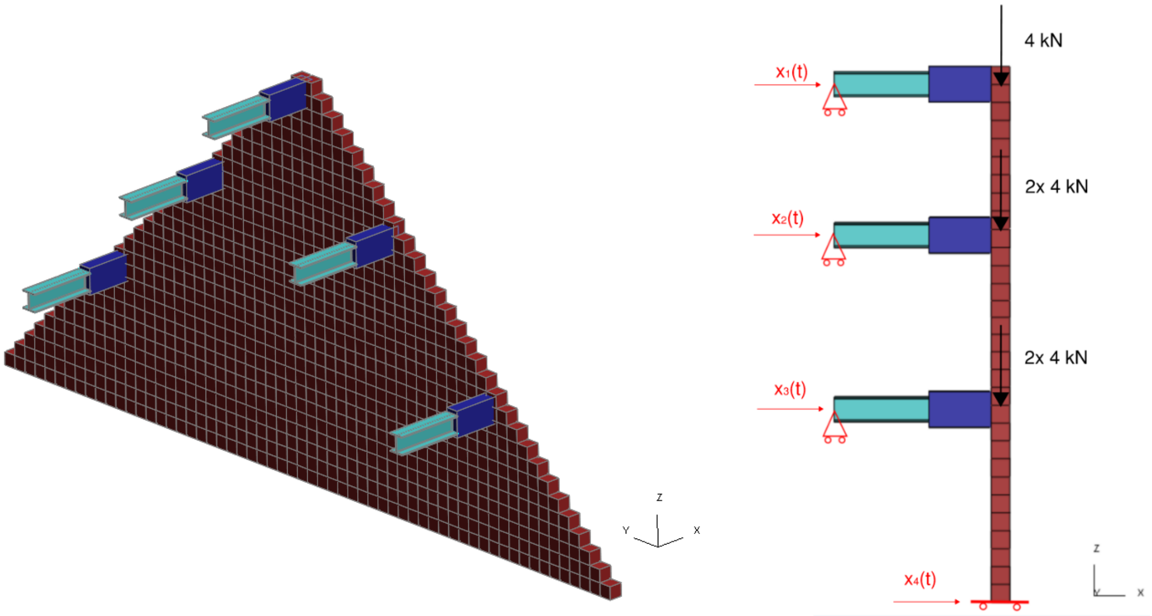


Figure 4: LS-DYNA model, loads and boundaries, with element cross-sections flashed out.

Input accelerations were applied at the base of the gable nodes and at the back of the steel beams where these connect with the vertical steel posts. The accelerations applied to the base and top platforms were provided directly by ERIES SUPREME. Linear interpolation from those two records was used to derive the accelerations to be applied over the height. This modelling approach considers the response of the back posts as sufficiently stiff to be neglected in the response of the masonry gable.

The base of the gable is considered fixed, and the hinged ends of the steel beams are released in bending about their major axis. The 4 kN pocket loads imposed by the springs were modeled as constant node loads on the top node of the 1D element used to model the interaction between the timber joist and the masonry pocket.

The entire sequence of ground motions was reproduced to capture damage progression of the gable. This was considered necessary to ensure the correct stiffness of the gable at the beginning of each motion sequence. The motions were applied as displacement. One second rest periods were applied between the sequences in which a high global damping in the model was active to suppress any relative movement of the gable before the start of the next sequence.

### 3.2 LS-DYNA masonry material

The masonry gable was modeled using an LS-DYNA User Material Model for shell elements developed by Arup. This masonry material model has the capability of replicating typical failure modes in masonry, with the most relevant shown in Figure 5 and Figure 6. It has been extensively validated in past testing campaigns on modern unreinforced masonry, composed of bricks and mortar. The calibration of the material model was conducted on several different scales of specimens, from masonry wallette testing to full-scale houses tested dynamically [6][7][8].

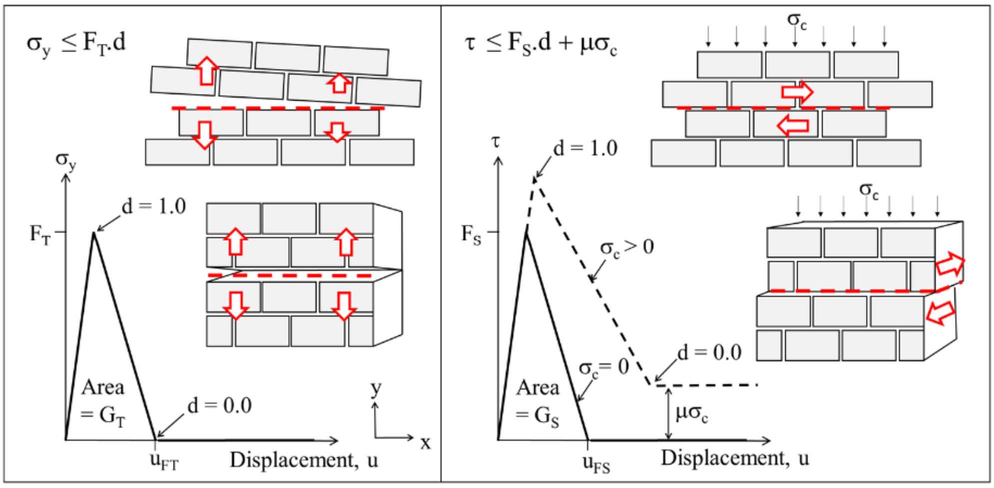


Figure 5: Bed joint characteristics. Left: tension; Right: shear [6];

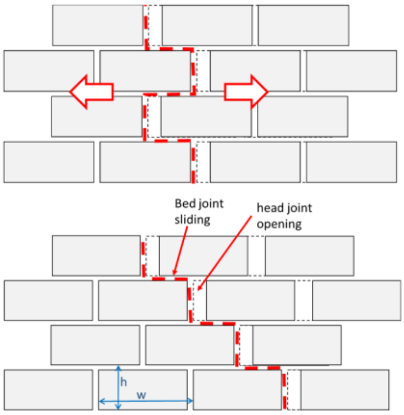


Figure 6: Horizontal and diagonal tension.

# 4 ANALYSIS PREDICTION

## 4.1 LS-DYNA results vs test

Table 2 shows the comparison in terms of intensity and the record that led to the gable collapse during the experiments and as predicted by the LS-DYNA simulation. The LS-DYNA model of the gable provided an accurate prediction of the gable collapse, correctly estimating the record that led to the collapse of the flexible roof gable experiment. For the rigid roof gable experiment, the LS-DYNA model slightly underpredicted the gable's capacity to sustain vertical loads during the motions, estimating collapse at one intensity lower than the experiment (85.7% of PBA). Notably, this was on the conservative side.

| | Experiment | LS-DYNA simulation |
|---|---|---|
| Rigid gable | EQ2@350% (1.93g PBA) | EQ2@300% (1.65g PBA) |
| Flexible gable | EQ2@150% (0.82g PBA) | EQ2@150% (0.82g PBA) |

Table 2: Comparison of record/intensity that led to gable collapse in experiment and LS-DYNA simulation.

Cracking patterns for the rigid roof gable are captured with a reasonably good match between the experiment and the model, as shown in Figure 6. One notable difference is the horizontal crack in between the two levels of joists in the LS-DYNA model, which appears at the lower joist height in the experiment. The numerical prediction also shows more vertical and diagonal cracking than the experiment.

Figure 8 shows the collapse mechanism comparison between the experiment and the model. The latter captures the deformation along the height of the damaged gable before collapse.

(a) (b)

(c) (d)

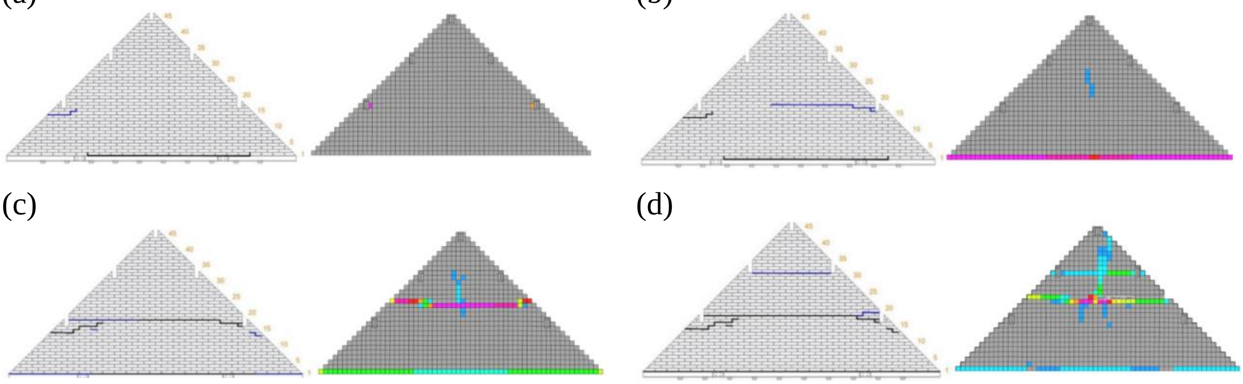

Figure 7: Progression of damage in the rigid roof gable experiment and LS-DYNA simulation at (a) EQ1@50%, (b) EQ2@200%, (c) EQ2@250%, (d) EQ2@300%. Note that the color scaling in each LS-DYNA figure differs to better visualize the crack pattern at each moment.

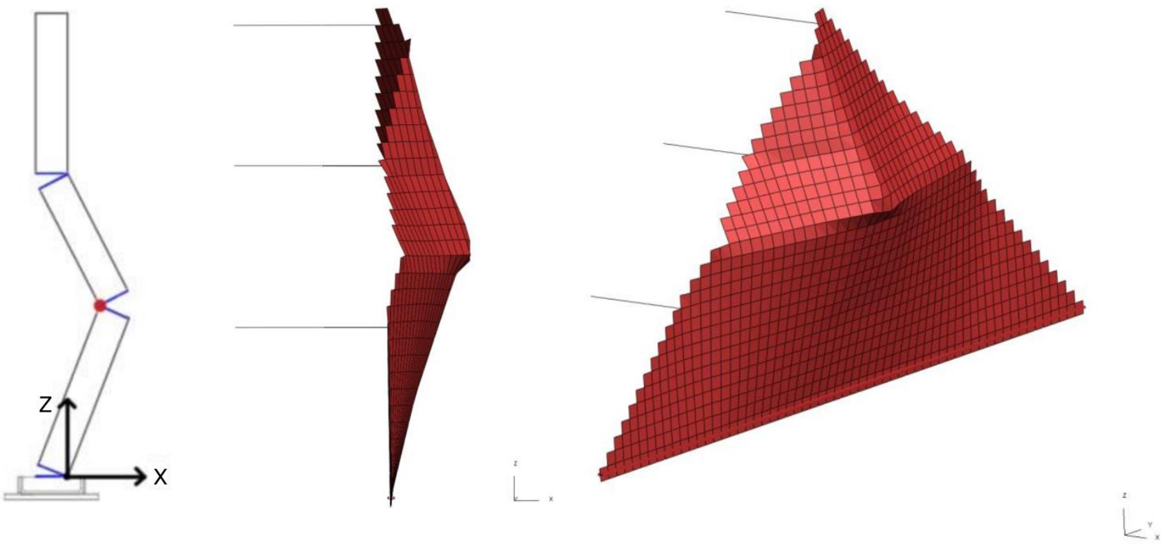


Figure 8: Collapse mechanism of the experiment (Left) and model (Middle: side view; Right: isometric view). Model deformations are magnified x2.

The cracking pattern resulting from the flexible roof gable is less well predicted than that of the rigid roof gable (Figure 9). The simulation captures the formation of a horizontal crack at the base of the gable from the small intensities, but it shows a rocking mechanism during most of the analysis, without a significant increase in the cracking state of the gable, except for the progression of the crack at the base. Close to the collapse of the gable, the model shows predominantly diagonal and vertical crack patterns concentrated at the top of the gable, missing the horizontal bed joint cracks that occur in the test at earlier stages.

Figure 10 shows the collapse mechanism comparison between the experiment and the model. The model captures the deformation of the gable before collapse, concentrated at the top of the gable, despite the collapse mechanism is influenced by the vertical and diagonal cracks.

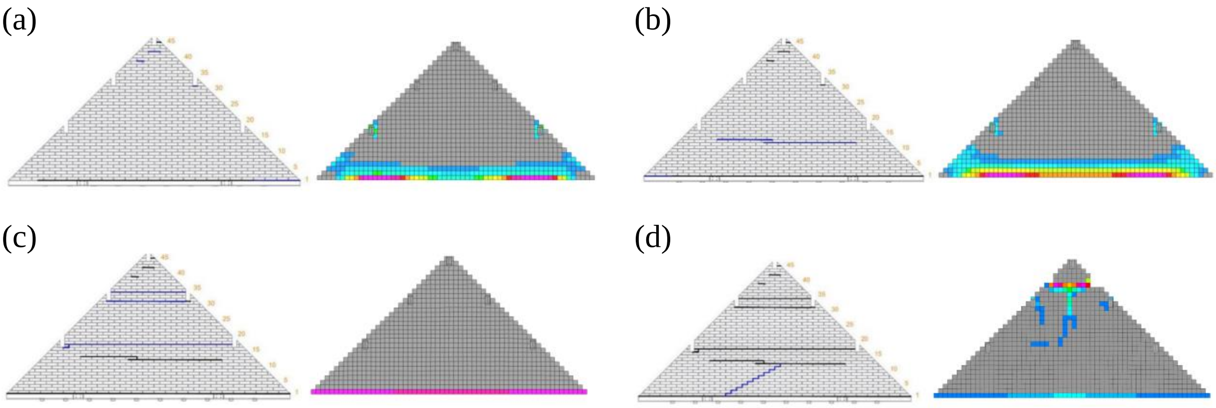


Figure 9: Progression of damage in the rigid roof gable experiment and LS-DYNA simulation at (a) EQ1@50%, (b) EQ1@75%, (c) EQ2@100%, (d) EQ2@150%. Note that the color scaling in each LS-DYNA figure differs to better visualize the crack pattern at each moment.

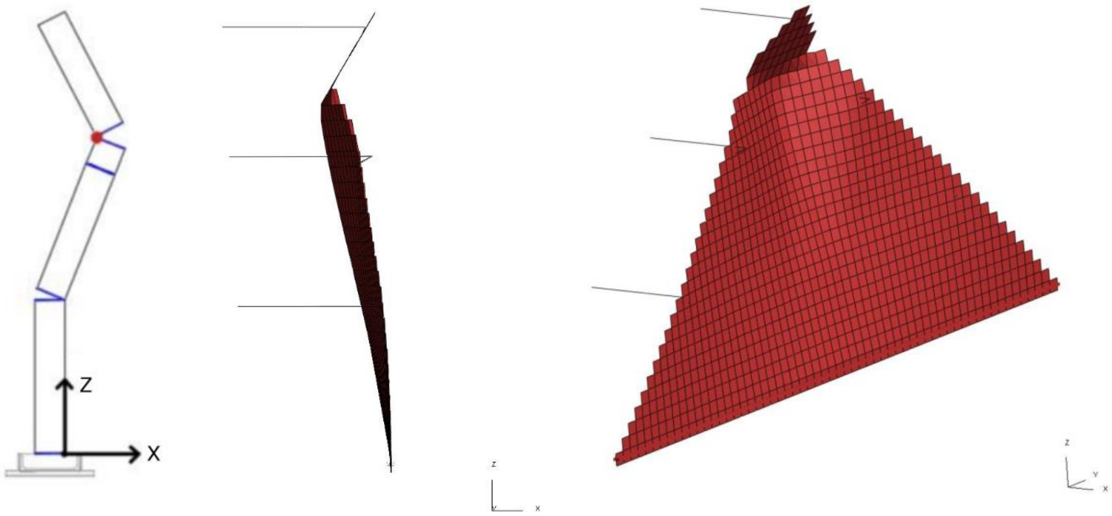


Figure 10: Collapse mechanism of the experiment (Left) and model (Middle: side view; Right: isometric view). Model deformations are magnified x2.

## 4.2 Observations

Several sensitivity studies were carried out as part of the prediction. These studies highlighted the influence of the tensile bed joint strength and energy required to trigger the onset of a crack, in defining the order in which cracks would occur. Similarly, explicitly modelling the timber joist pocket restraining effect, or ability of the joist to slide in the masonry pocket, was found to be influential in determining the intensity at which the gables collapsed.

Replicating the entire sequence of records allowed to estimate more accurately the damage state and increased flexibility of the gable towards the gable collapse. In the assessment of an existing building, this emphasizes the importance of carrying out inspections that can evaluate the current state of the building and masonry state.

The diagonal cracking due to tensile failure of the vertical head joints was more pronounced in the models then the experiments, this is currently a known limitation of the material model. This type of failure mode could be selectively switched off to not influence the cracking pattern, while replicating experiments like the one part of this study.

The material model in LS-DYNA did not require extensive additional calibration to perform a relatively accurate prediction, this is noting that the previous calibration was done on similar masonry types. The modeling approach shown in this study proved suitable for assessing masonry buildings or masonry building components.

## 5 CONCLUSIONS

A numerical simulation of the shake table test of two URM gable specimens was performed using the finite element software LS-DYNA. The LS-DYNA model of the gable provided an accurate prediction of the capacity for gable collapse, correctly estimating the record that led to the collapse of the flexible roof gable experiment. For the rigid roof gable experiment, the LS-DYNA model slightly underpredicted the capacity, estimating collapse at one intensity earlier than the experiment.

Cracking pattern prediction showed that the LS-DYNA models were more susceptible to diagonal and vertical cracking than the test experiments.

Figure 11 shows the overall entries to the prediction contest in terms of predicting the maximum intensity of motion that the gables could resist. The dashed lines represent the outcomes from the experiments. The prediction outcome presented herein is Submission 6. The overview demonstrates the effectiveness of the proposed modeling approach in predicting the gable collapse. This effectiveness is mainly attributed to the previous validation and calibration done on the LS-DYNA User Material Model on modern masonry typologies, in combination with the use of non-linear time history analysis. The latter models the seismic source as motions explicitly and represents the dynamics of the problem and the development of damage in the analysis, capturing the non-linear effects of unreinforced masonry.

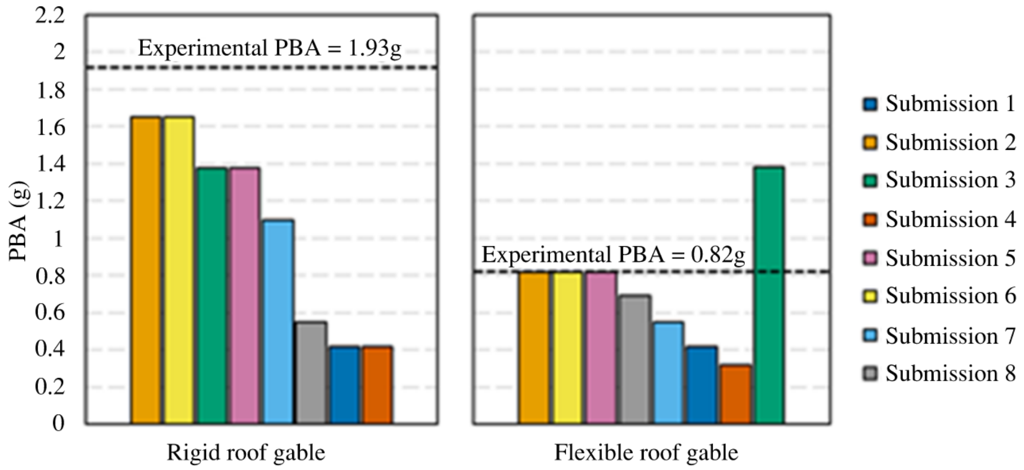


Figure 11: The ERIES SUPREME prediction contest results in terms of intensity of motion that led the gables to collapse (Courtesy of ERIES SUPREME [2]).

Further sensitivities studies on the experiment, including a post-diction calibration of the modeling approach, are extensively described in [9].

## AKNOWLEDGEMENTS

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