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# LESSONS LEARNED FROM A PREDICTION AND POSTDICTION OF A SHAKE TABLE TEST ON AN UNREINFORCED MASONRY AGGREGATE

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***Abstract***

Historical centers of Europe and Croatia are often formed by unreinforced masonry building aggregates that developed as the layout of the city or village was densified. In these aggregates, adjacent buildings can share structural walls with an older and a newer unit connected either by interlocking or just by a layer of mortar. Observations after for example the recent Central Italy and Croatia earthquakes showed that joints between the buildings were often damaged. This indicated a possible out-of-phase behaviour of units which can lead to the interaction which is demanding to capture with numerical models. The analysis of such building aggregates is difficult due to the lack of guidelines, as the advances were impeded by the scarce experimental data. The SERA project AIMS (Seismic Testing of Adjacent Interacting Masonry Structures) comprised a shake-table test of an aggregate of two buildings under two horizontal components of dynamic excitation, accompanied by the blind prediction competition. Each group was provided with a complete set of construction drawings, material properties, testing sequence and the list of measurements to be reported. After the results were reported, participants were able to compare the results, apply actual accelerations, and update their models within the postdiction phase. The prediction and postdiction of EPFL model were based on an equivalent frame model with a newly developed macroelement able to simulate both the in-plane and out-of-plane behaviour of unreinforced masonry piers, and a newly developed 3D material model allowing to simulate the interaction between the units. This paper deals with the prediction submitted by the EPFL team and discusses the results and possible pitfalls in modelling assumptions leading to unsatisfying prediction. Lessons learned are applied by updating the model for the postdiction analyses and discussing the updated results with the goal to improve the way we model unreinforced masonry aggregates using the equivalent frame approach.

*Keywords: Historical centres, Masonry aggregates, Shake table test, Blind prediction, Equivalent frame model*

## 1. Introduction

Historical centers around the Europe formed during long time spans, leading to the formation of masonry building aggregates. In aggregates, adjacent buildings can share structural walls, connected either by weakly interlocked stones or by a layer of mortar. The adjacent buildings can be constructed in different materials, with different distributions of openings and floor and roof heights. Post-earthquake observations show that the opening of the joint may lead to a complicated behaviour and interaction between the units [1,2] which is often ignored in numerical analyses. This is understandable due to a lack of experimental data, caused by a high cost and the complexity of performing tests on large-scale aggregates. These facts have inspired a joint research between École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, University of Pavia, Italy, University of California, Berkeley, USA, RWTH Aachen University, Germany and National Laboratory for Civil Engineering, Portugal, named SERA AIMS – Adjacent Interacting Masonry Structures. As a part of this project, a shake table test was performed on a half-scale stone masonry aggregate at the LNEC laboratory in Lisbon, Portugal. Characterization tests on materials and components of the same typology were performed in parallel. As a part of the campaign, blind prediction competition was organized, with dozen of participants from both the research community and the industry. This paper presents in brief the experimental campaign,

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and our own prediction and postdiction of the mentioned experimental campaign; for the detailed description and interpretation we would like to refer the readers to [3] for the experimental campaign and to [4,5] for the blind prediction competition.

## 2. Case study

The test specimen was a half-scale prototype of a masonry aggregate consisting of two units. Unit 2 had two storeys with height of 1.65 m and 1.5 m for the first and second storey, respectively. Unit 1 consisted of one storey with a height of 2.2 m. Unit 2 had a rectangular shape with four walls and the dimensions 2.5 x 2.5 m$^2$. Unit 1 had an u-shape with three walls and dimensions 2.5 x 2.45 m$^2$. The basic dimensions of the floor plan with beams, and facades are shown in Fig. 1. Unit 1 wall thickness was 30 cm and Unit 2 wall thickness was 35 cm and 25 cm of the first and the second floor, respectively. Spandrels under the openings had thickness decreased to 15 cm. Unit 2 was constructed first, replicating the sequence of construction from the historical centres. After the construction of a segment of Unit 2, the contact area was smoothed by mortar to ensure that there was no interlocking between the units. Different modal properties of two units, paired with this type of connection, led to the separation and out-of-phase behaviour during the test. Fig. 2 shows the constructed specimen before and after applying the plaster.

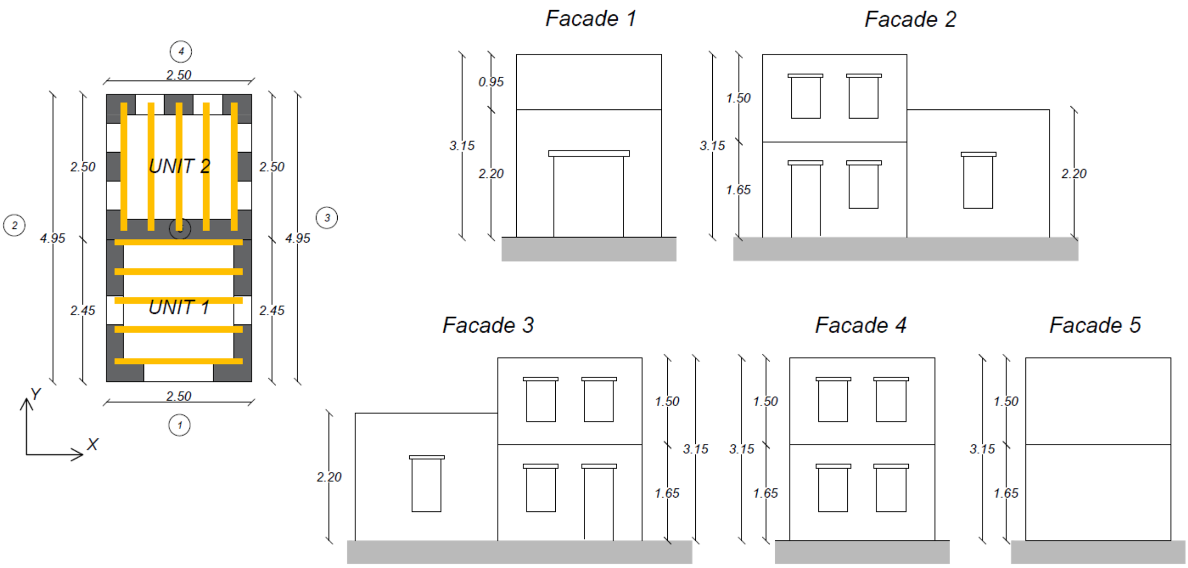


Figure 1 SERA AIMS test specimen floor plan with beam orientation and facade layout of the two units [3]

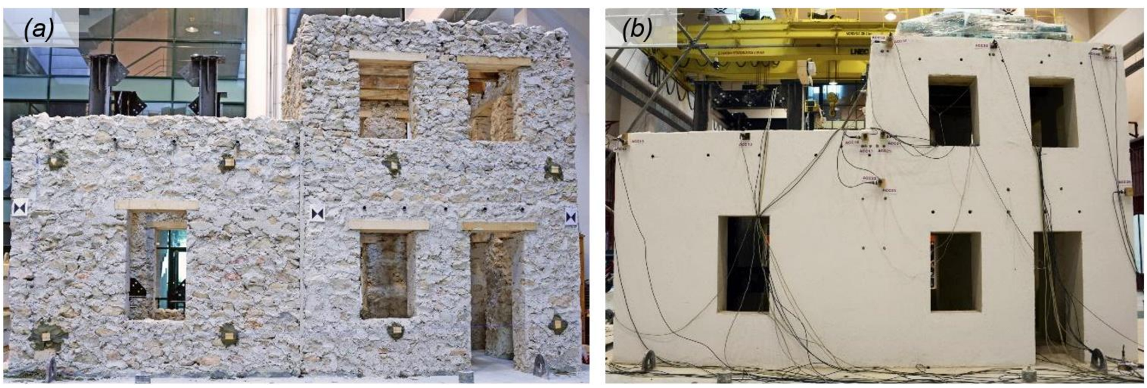


Figure 2 SERA AIMS specimen: a) before plastering; b) after plastering [3]

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## 3. Modelling approach

An equivalent frame model approach using the OpenSEES framework [6] and the newly developed macroelement [7] was used to predict the behaviour of SERA AIMS unit. The macro-element is a three-node, three-dimensional element that can capture the in-plane and out-of-plane dynamic behaviour of masonry walls. Floors were modelled with elastic orthotropic membrane elements, a common practice in equivalent frame models. The orthotropic membrane provides only the membrane stiffness components, resulting in a zero-bending stiffness. Floor-to-wall connections were modelled with a frictional interface, limiting the shear force transmitted between floor and wall as a function of the vertical load acting on a floor node and the friction coefficient [8]. The material model can model the pounding of the beam when the slip is in the towards the wall [9]. Wall-to-wall connections were modelled with a one-dimensional non-linear interface, which provides linear elastic behaviour in compression, with no crushing, and a finite tensile strength paired with exponential softening law. The unit-to-unit connection within the aggregate was modelled with an n-dimensional zero-length element and a material model that captures linear elastic behaviour in the axial direction (perpendicular to the interface between the units) and a finite tensile strength paired with exponential softening law. In the perpendicular plane, the cohesive-frictional behaviour is based on the axial load, a friction coefficient, and an exponential damage law of cohesion [5].

## 4. Prediction and postdiction

After the test, the actual input acceleration, i.e., the recorded shake table acceleration was shared with all teams which participated in the blind prediction [4]. Now it was possible to rerun the analyses using the original prediction model, but with the effective seismic input, what we refer to as prediction in this paper. By doing so, it was possible to remove the ambiguity stemming from different input and obtain more meaningful comparison of results. The comparison of flexural drifts after the strongest longitudinal run (y-direction) [3] shown in Fig. 3 showed a satisfying match with the experimental crack maps, indicating that the model correctly captured the soft storey mechanism in the upper storey of Unit 2.

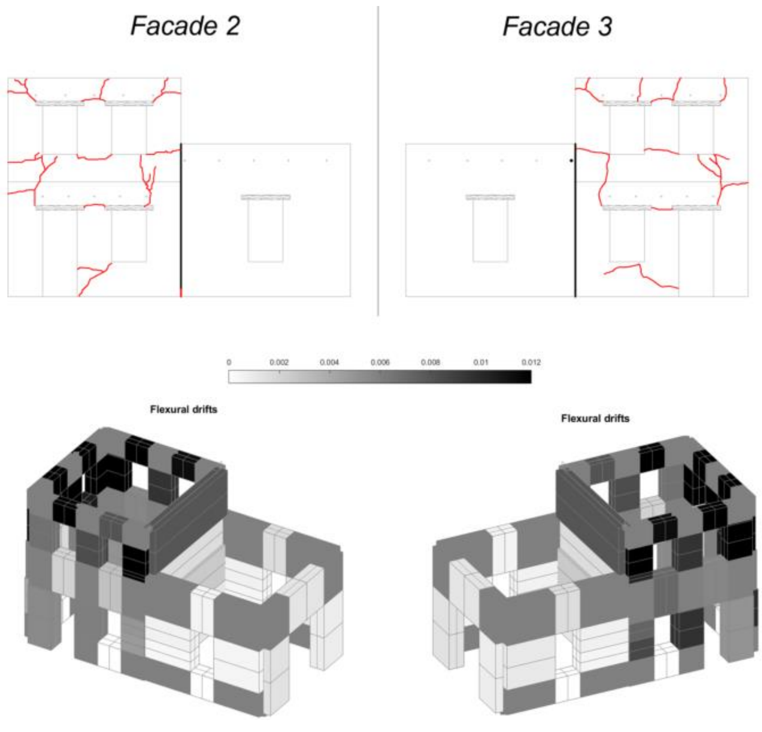


Figure 3 Comparison of the observed and predicted damage using the prediction model with 1% initial stiffness and mass proportional damping

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At the same time, the comparison of recorded and predicted displacements using the prediction model with actual seismic input showed that the numerical model was too stiff and considerably underestimated the displacements. For example, Fig. 4 shows the comparison of the displacement at the corner of the upper storey of Unit 2 and opening of the interface in both directions.

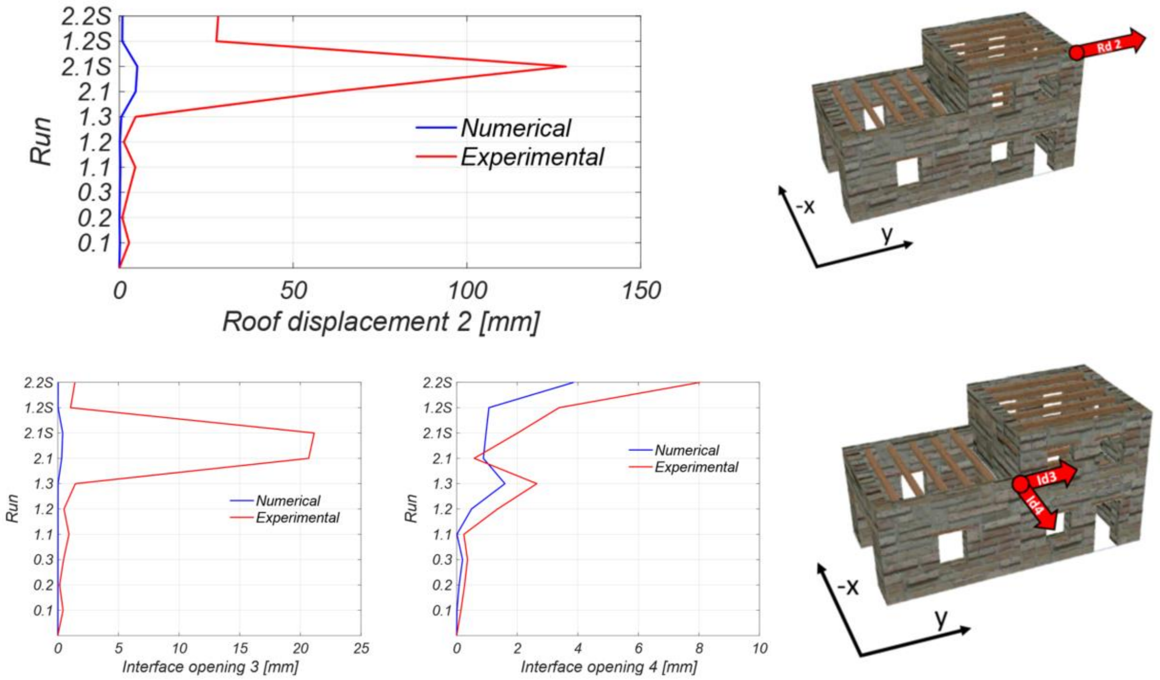


Figure 4 Comparing the response of the prediction model with 1% initial stiffness and mass proportional damping.

Initially the material parameters were taken from vertical compression and diagonal compression tests, but led to overestimating the stiffness [5]. Therefore, in the first phase of the postdiction, material parameters were recalibrated by fitting them against shear-compression tests on the masonry of the same typology, obtaining the values shown in Table 1. Normal and lognormal distributions were assigned to material parameters to account for uncertainties. Result were improved compared to the prediction, but the predicted response was still too stiff, as shown in Fig. 5.

Table 1 Recalibration of material parameters for postdiction [5]

| **Parameter (mean)** | **Prediction** | **Postdiction** |
|---|---|---|
| E [MPa] | 3462 | **2030** |
| G [MPa] | 1524 | **609** |
| $f_c$ [MPa] | 1.30 | **2.93** |

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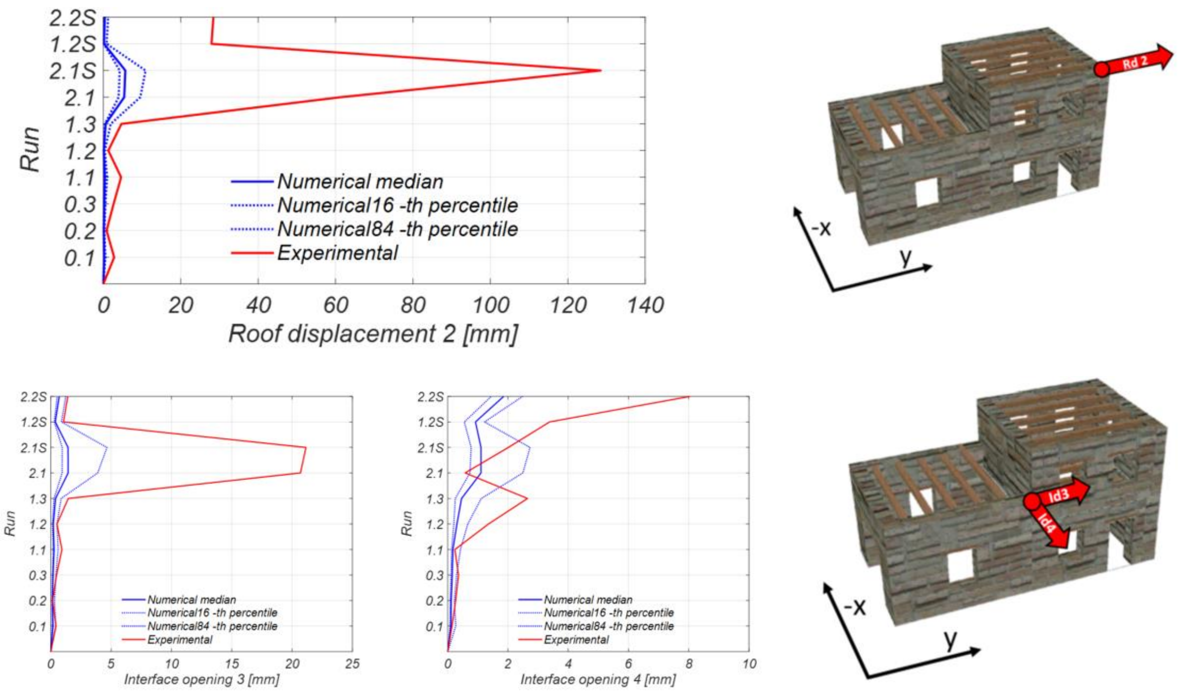


Figure 5 Comparing the stochastic response of postdiction models updated with material parameters calibrated according to shear-compression tests and 1% initial stiffness and mass proportional damping.

The prediction model and initial postdiction model were run with initial stiffness and mass proportional damping with 5% critical damping ratio. To further improve the postdiction, the damping model was updated to secant stiffness proportional damping model with 5% critical damping ratio, leading to the postdiction results shown in Fig. 6. The comparison with experimental results was better, especially considering the upper percentile, but still required further calibration presented in [5].

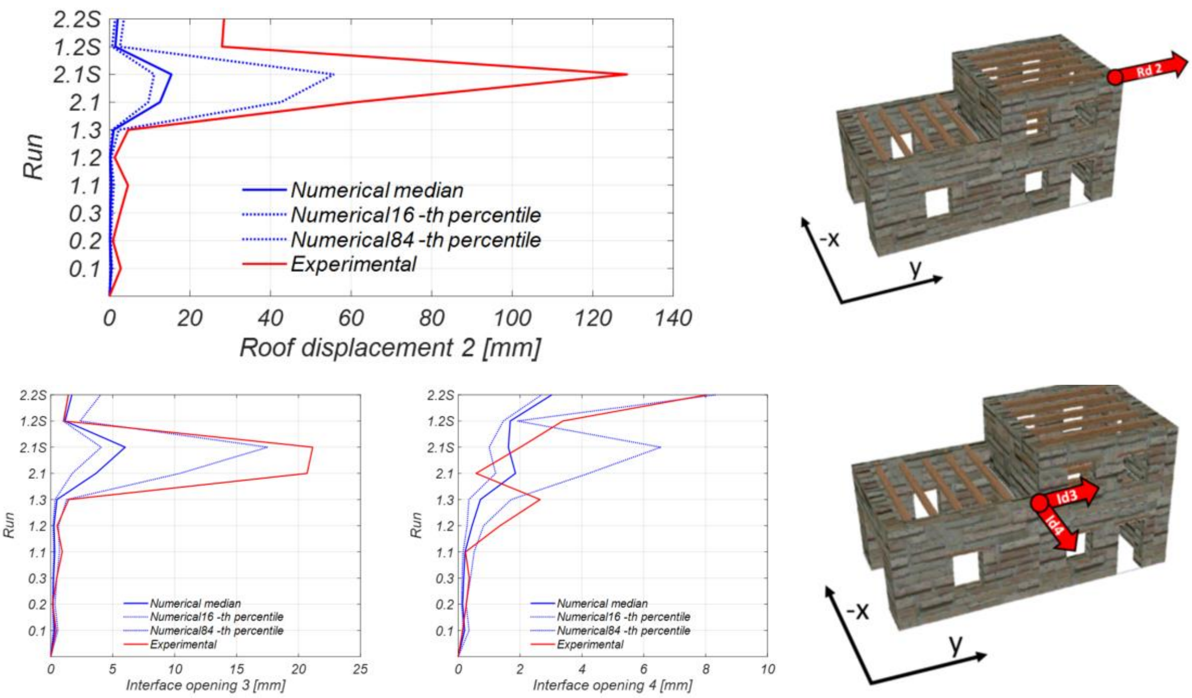


Figure 6 Comparing the stochastic response of postdiction models updated with material parameters calibrated according to shear-compression tests and 5% secant stiffness proportional damping.

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## 5. Conclusions

This paper briefly presented the prediction and postdiction analyses performed for the SERA AIMS blind prediction competition. The equivalent frame model using newly developed macroelement captured the formation of the principal damage mechanisms. However, quantitative comparison with experimental data, even when including the actual seismic input in the analysis showed a too stiff response. First, the material parameters were updated by re-calibrating them against shear-compression tests instead of vertical and diagonal compression tests. This improved the prediction, but again resulted in a too stiff response. Therefore, damping model was updated from initial-stiffness and mass proportional damping to secant-stiffness proportional damping. This further improved the postdiction results. The first two lessons learned were the following:

- Calibration of material parameters based on shear-compression tests leads to a better prediction of building seismic behaviour than based on vertical compression and diagonal compression tests
- Simulating the building that develops out-of-plane mechanisms by nonlinear dynamic analyses in equivalent frame approach is more accurate using the secant stiffness proportional damping model that avoids overdamping the out-of-plane behaviour.

The future work relates to identifying other parameters and modelling decisions to reach even more accurate prediction of the aggregate seismic behaviour.

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