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Seismic testing of adjacent interacting masonry structures – shake table test and blind prediction competition

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Abstract: Across historical centres in Europe, stone masonry buildings form 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 stones or by a layer of mortar. Observations after for example the recent Central Italy earthquakes showed that joints between the buildings were often the first elements to be damaged, leading to a complex interaction between the units. The analysis of such building aggregates is difficult due to the lack of guidelines, as the advances were impeded by the scarce experimental data. Therefore, the objective of the project AIMS (Seismic Testing of Adjacent Interacting Masonry Structures), included in the H2020 project SERA, was to provide such data by testing an aggregate of two double-leaf stone masonry buildings under two horizontal components of dynamic excitation. The test units were constructed at half-scale, with a two-storey building and a one-storey building. The buildings shared one common wall, while only a layer of mortar connected the façade walls. The floors were at different heights and had different beam orientations. Prior to the test, a blind prediction competition was organized with twelve participants from academia and industry that were provided with all the geometrical and material data, construction details, and the seismic input. The participants were asked to report results in terms of damage mechanisms, recorded displacements and base shear values. Results of the shake-table campaign are reported, together with a comparison with the blind predictions. Large scatter in terms of reported predictions highlights the impact of modelling uncertainties and the need for further tests.

Keywords: Historical centres; Stone masonry; Masonry aggregates; Shake table test; Blind prediction

1. Introduction

Historical centres of Europe densified during long time spans. This process led to the formation of masonry building aggregates. In aggregates, facades of adjacent buildings often share the structural walls, connected either by weakly interlocked stones or only by a layer of mortar. Due to long time spans, it is common for the adjacent buildings to be constructed with different materials, different distributions of openings and floor and roof heights. Post-earthquake observations have shown that the opening of the joint leads to complicated behaviour and interaction of the units (Carocci 2012; da Porto et al. 2013), which are often not captured in the analyses. However, analysis is difficult 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 program 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 building aggregate at the LNEC laboratory in Lisbon, Portugal. Complementary tests on materials and components were performed in parallel. As a part of the campaign, blind prediction competition was organized, with multiple participants from both the research community and the industry. This paper gives a short summary of the experimental campaign and the results of the blind prediction competition; for a detailed description and interpretation of the results please refer to (Tomić et al. 2022a) for the experimental campaign and to (Tomić et al. 2022b) for the blind prediction competition.

The existing large-scale experimental campaigns on masonry aggregates are limited to a campaign performed at the EUCENTRE (Senaldi et al. 2020; Guerrini et al. 2019). The double-leaf stone masonry aggregate consisted of two three-storey units weakly connected by interlocking stones and connected slab beams. An incremental, unidirectional dynamic test was performed on the original specimen up to the near-collapse state for a peak ground acceleration (PGA) of 0.35 g, when an out-of-plane mechanism formed in both the north and south gables. After this step, the specimen was strengthened, and the experiment continued. Due to interlocking stones and connected slab beams, the separation at the interface was limited. Therefore, the present campaign replicated the properties of this campaign, while changing the interface properties by removing interlocking stones and the connection between the slab beams.

Several research groups modelled the behaviour of masonry aggregates and derived conclusions on the behaviour and vulnerability of the units within aggregates (Senaldi et al. 2010; Senaldi et al. 2019.; Formisano 2017; Formisano and Massimilla 2018; Maio et al. 2015), or developed vulnerability indexes related to the aggregate behaviour (Formisano et al. 2015). However, due to the lack of experimental data, the analyses are still missing nonlinear models for the interaction between units, and a wider discussion on uncertainties related to modelling the aggregate behaviour. For this purpose, we believe blind prediction competition and discussion following it will present a significant contribution to the open questions.

In this paper, first, the test specimen is presented, together with a testing sequence and principal observed damage mechanisms. Then the blind prediction competition is introduced, together with an example analysing the variability within the predicted results. Finally, some preliminary conclusions are drawn, as an introduction to a future discussion.

2. Experimental campaign

The test specimen was a half-scale prototype of a masonry aggregate, consisting of two units. Unit 2 consisted of two floors and a total height of 3.15 m. Unit 1 consisted of one floor with a height of 2.2 m. Unit 2 had a rectangular shape with four walls and the dimensions 2.5 x 2.5 m2. Unit 1 had an u-shape with three walls and dimensions 2.5 x 2.45 m2. The basic dimensions of the floor plan with beams, and facades can be seen 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 first unit to be constructed, replicating the sequence of construction from the historical centres. After the construction of a segment of Unit 2, the contact area was smoothened by mortar to ensure no interlocking between the units. Then, Unit 1 segment was constructed, ensuring that the contact between the units was a mortar-mortar interface. This type of connection, paired with different modal properties of two units, facilitated the separation and out-of-phase behaviour during the test. Fig. 2 shows the constructed specimen before applying the plaster.

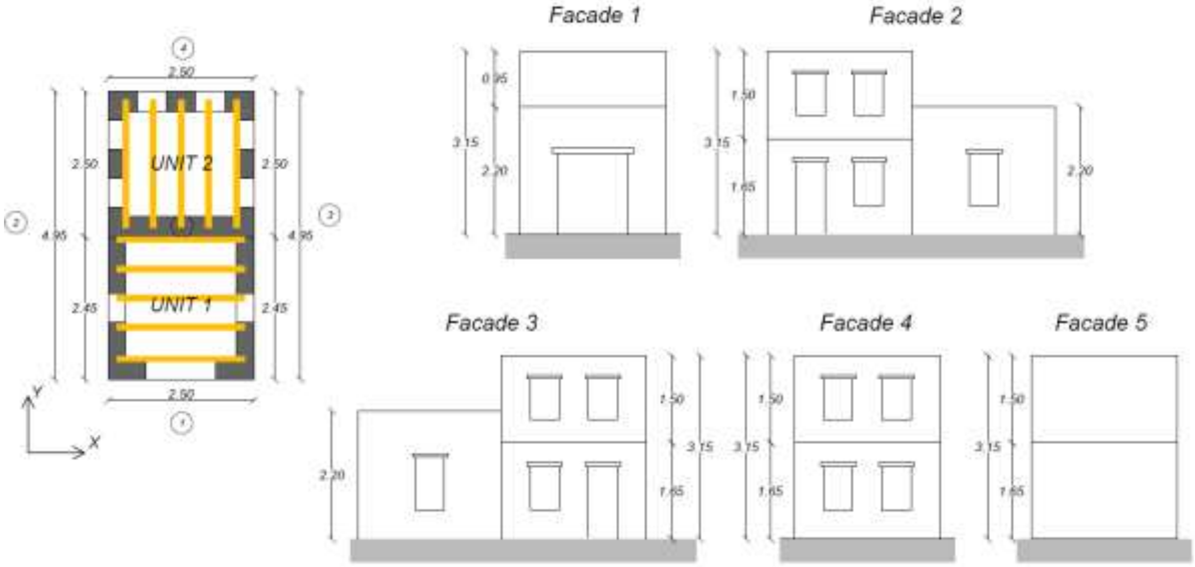

Fig. 1 - SERA AIMS test specimen floor plan with beam orientation and facade layout of the two units (Tomić et al. 2022a).

The material for the construction of the stone masonry walls was replicating as much as possible to the one used for a shake table test conducted at the EUCENTRE (Guerrini et al. 2017; 2019 Senaldi et al. 2017; 2020). The mortar was commercial hydraulic lime mortar mix, with added EPS spheres in volumetric proportions 2:3 of EPS spheres to mixed mortar to lower the stiffness and strength. Walls were constructed as double-leaf stone masonry, with no interlocking of the leaves except at the corners and next to the openings. Irregular broken stone pieces were used to fill the voids between the leaves. In this way, it was ensured that the results of the two tests are easily compared. Two units of the aggregate are connected by a dry joint.

Floor diaphragms were composed of 8x16 cm wooden beams and 2 cm thick wooden planks orientated orthogonally to beams. Diaphragms had different orientations, with Unit 1 beams spanning in the x-direction and Unit 2 floors in the y-direction To prevent early out-of-plane failure, PVC tubes were placed into walls, alongside and in direction of each beam. Steel angles were designed to anchor beams into walls.

Fig. 2 – SERA AIMS specimen before plastering (Tomić et al. 2022a).

The nominal testing sequence was composed of four steps of increasing intensity, each divided in three substeps. Three substeps were the excitation in y-direction (longitudinal), x-direction (transversal), and bidirectional excitation. Actual and applied testing sequences differed, as shown in Table 1.

Table 1. Actual applied testing sequence of the SERA AIMS shake-table test (Tomić et al. 2022a).

Run number	**Run notation**	**Direction**	**Level of shaking (shake-table capacity)**	**Nominal PGA**	**Effective PGA**
1	0.1	Y	12.5%	0.110 g	0.113 g
2	0.2	X	12.5%	0.078 g	0.075 g
3	0.3	Bidirectional	12.5%	0.110 (y)/0.078 (x) g	0.114 (y)/0.072 (x) g
4	1.1	Y	25%	0.219 g	0.170 g
5	1.2	X	25%	0.156 g	0.178 g
6	1.3	Bidirectional	25%	0.219 (y)/0.156 (x) g	0.208 (y)/0.174 (x) g
7	2.1	Y	50%	0.438 g	0.593 g
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8	2.1S	Y	50%	0.438 g	0.615 g
9	1.2S	X	25%	0.156 g	0.258 g
10	2.2S	X	50%	0.313 g	0.425

Run 2.1 resulted in a widespread damage to the specimen. Soft storey mechanism formed in the upper storey of Unit 2, involving out-of-plane motion of Facades 4 and 5, and in-plane flexural mechanism of Facades 2 and 3. In-plane facades acted as flanges due to the effective interlocking at the wall-to-wall connections. After this run, the specimen was strengthened. Crack maps after Run 2.1 are shown in Fig. 3.

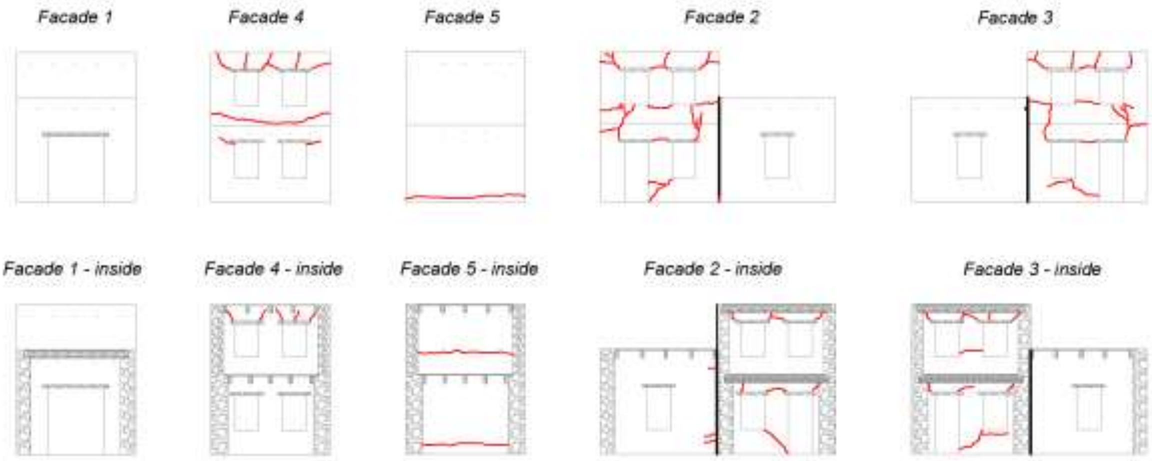

Fig. 3 – Crack maps after Run 2.1. Black color marks previous damage, and red new damage (Tomić et al. 2022a).

3. Blind prediction competition

Twelve participants coming from both the industry and academia submitted thirteen models. Thirteen models comprised three discrete element models (DEM), four solid finite element model (FEM), two shell FEM, two equivalent frame models (EFM), one hand calculation, and one limit analysis model. Eleven out of thirteen participants performed nonlinear time history-analysis. Special connection was paid to the behaviour of nonlinear connections, including unit-to-unit, floor-to-wall, and wall-to-wall connections.

The effective seismic input and testing sequence varied compared to nominal as shown in *Table 1*, making a direct comparison between numerical and experimental results difficult. Nevertheless, a two-fold comparison was performed: (i) Quantitative comparison between submissions for bidirectional Run 3.3, and (ii) Qualitative-quantitative comparison of predicted and experimental damage mechanisms. An example of quantitative comparison is shown in Fig. 4 where the submitted results for roof displacements, interface openings and base shear are compared for the bidirectional Run 3.3.

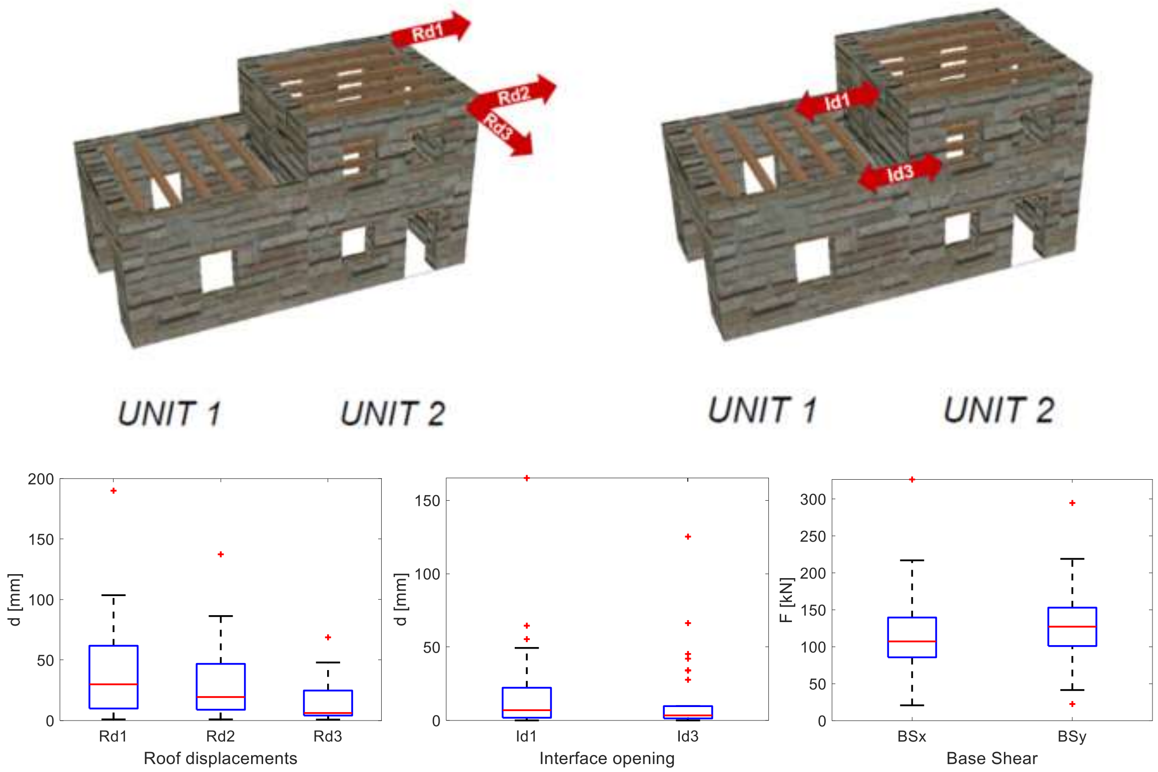

Fig. 4 - Comparison of predicted results for Run 3.3. Edges of the box mark 25th and 75th percentile, and red crosses mark outliers (Tomić et al. 2022b).

Comparison in terms of predicted and observed damage mechanism is shown in Table 2. It shows that the limit analysis model emerged as a winner in terms of the correct prediction of the damage mechanisms. It should be noted that while the limit analysis submission predicted mechanisms were correct, the predicted PGA for the activation of the mechanisms was significantly underestimated (Tomić et al. 2022b).

Table 2. Damage mechanisms reported by the SERA AIMS blind prediction participants. IP = in-plane mechanism; OOP = out-of-plane mechanism. Green circle means true positive, red circle false positive, and red cross false negative (Tomić et al. 2022b).

Unit and storey	**Direction and failure mode**	**HAC 1**	**DEM 1**	**EFM 1**	**FEM 1**	**DEM 2**	**FEM 2**	**DEM 3**	**LIM 1**	**EFM 2**	**FEM 3**	**FEM 4**	**FEM 5**	**FEM 6**
Unit 1	x-IP	🟢	x	x	x	x	🟢	x	🟢	🟢	🟢	x	🟢	x
Unit 1	y-IP	🔴	🔴											🔴
Unit 1	x-OOP	x	x	🟢	x	x	🟢	x	🟢	🟢	x	x	x	x
Unit 1	y-OOP					🔴								
Unit 2 1st floor	x-IP	🔴	🔴	🔴		🔴	🔴				🔴	🔴		🔴
Unit 2 1st floor	y-IP	🟢	🟢	🟢	x	🟢	x	🟢	🟢	🟢	🟢	x	x	🟢
Unit 2 1st floor	x-OOP													
Unit 2 1st floor	y-OOP	x	🟢	🟢	x	🟢	x	x	🟢	🟢	🟢	🟢	x	x
Unit 2 2nd floor	x-IP		🔴	🔴		🔴	🔴			🔴	🔴		🔴	
Unit 2 2nd floor	y-IP	x	🟢	🟢	x	🟢	x	🟢	🟢	🟢	🟢	🟢	🟢	x
Unit 2 2nd floor	x-OOP													
Unit 2 2nd floor	y-OOP	x	🟢	🟢	x	🟢	x	🟢	🟢	🟢	🟢	x	x	x
True positive		2	4	5	0	4	2	3	6	6	5	2	2	1
False positive		2	3	2	0	3	2	0	0	1	2	1	1	2
False negative		4	2	1	6	2	4	3	0	0	1	4	4	5

4. Conclusions

This paper presented in brief the experimental campaign that was performed as a part of SERA – AIMS project at LNEC facilities in Lisbon. The two-leaf stone masonry aggregate was tested under unidirectional and bidirectional excitation. Basic material, geometrical properties, construction details, and testing sequence are reported, together with principal damage mechanisms and crack maps.

Accompanying blind prediction competition featured twelve participants and thirteen submitted models, featuring different modelling approaches and different modelling assumptions with regards to material models, connections between the elements, and analysis types. The scatter in the reported displacements, base shear values, and formed damage mechanisms was significant. Even if all the participants started with the same set of material parameters and the information on geometry and construction details, the analyses still resulted in different predictions. The scatter was high even within the groups featuring same modelling approach or certain modelling assumptions.

This paper intended to provide an overview of the experimental campaign and blind prediction competition. Separate submissions by participants to the Special session will provide more detail on particular models and modelling assumptions. Therefore, future discussion as a part of special session should lead to fruitful discussion and help to draw conclusions on the impact of certain modelling assumptions.

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