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SEISMIC VULNERABILITY ASSESSMENT OF THE HISTORICAL BUILDINGS IN ITALY USING AEM

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Abstract

In recent years, Italy was hit by several significant seismic events, causing numerous human losses and thousands of injuries. These events are concentrated along the Apennines mountain chain, where many small and ancient historical cities are located. Earthquakes caused extensive and severe damage to the territory's valuable real estate heritage including eminent churches, important palaces, a variety of monumental buildings and structures. The evaluation of the seismic vulnerability of such buildings is a difficult task and presents significantly higher level of complexity if compared to the case of new structures. This is due to the inherent uncertainty characterizing ancient buildings, regarding structural characteristics and construction techniques, mechanical properties of the heterogeneous material like the masonry, and pre-existing damage due to past actions. Hence, there is a need for an efficient computational technique for analyzing such structures and providing reliable results so that the governments can intervene and optimize the use of available economic resources.

The present work describes the study of the seismic vulnerability of a typical historical building representative of construction in the southern European countries using the Applied Element Method (AEM) for high fidelity nonlinear structural analysis. The work makes use of some findings obtained within the European Union funded project "INACHUS" (7th framework programme "Technological and Methodological Solutions for Integrated Wide Area Situation Awareness and Survivor Localisation to Support Search and Rescue Teams"). In AEM, the structure is discretized through an assemblage of relatively small elements connected by a set of non-linear springs located at contact points distributed along the element faces. Normal and shear springs transfer the normal and shear stresses between the elements. Through the springs it is possible to represent the non-linear material behavior, the element separation or contact, and eventual collision.

The paper reports the results of the seismic simulations, analyzing the effects of the implementation of different structural details, such as presence of arches and vaults and interaction between structural elements with different types of connections that have a significant effect on the behavior of such historical buildings. The modelling of these details requires prohibitively expensive computational resources in the common modelling techniques based on FEM, due to the significant increase of the number of elements and the need to maintain the nodes compatibility. Moreover, in many cases, historical buildings suffered significant damages due to detachments between different structural parts even with low seismic acceleration. The paper demonstrates the application of the AEM method implemented in the software Extreme Loading for Structures (ELS) for performance based design of these kinds of historical structures.

Keywords: AEM, Historical buildings, Masonry structures, Non-linear dynamic analysis, Seismic vulnerability.

1. Introduction

The present work aims to show the application of the Applied Element Method for the seismic analysis of historical buildings widespread in the South Europe. The document reports a case study of a representative building located in the historical center of Amatrice, the small town of central Italy destroyed by the 24 August 2016 earthquake.

Main dimensions of the building for the AEM modelling were taken from satellite images available through Google Earth software, while material properties and structural details were assumed based on the extensive knowledge of the building techniques and the materials used for such kind of structures. Recent seismic events such as the events in Molise 2003, L'Aquila 2009, Emilia-Romagna 2012, and Central Italy 2016 have favored incorporating such knowledge in the Italian standards [1],[2].

Applied Element Method (AEM) allows explicit modelling of all the structural details considered crucial for the dynamic behavior of the structure such as arches, vaults, masonry edges, and connections between slabs and walls. The modelling of such details in traditional modelling techniques requires the use of enormous computational resources as documented more extensively in other publications such as [3].

The record of the Amatrice earthquake at the AMT station located 8.9 km South-East of the epicenter was extrapolated from [4] and applied in the time history analysis of the structure. The analysis allowed reproducing in a high fidelity way the dynamic behavior of the masonry historic buildings and catching the more relevant collapse mechanisms and the related cause.

2. Applied element method theory

The Applied Element Method (AEM) was developed to be capable of predicting with a high degree of accuracy the continuum and discrete behavior of structures. AEM was proven to be able to track the structural behavior passing through all stages of the application of loads: elastic stage, crack initiation and propagation as well as yielding, element separation, element contact, and collision with the ground and with adjacent structures. International publications in the area of structural engineering verify that the AEM can cover with a reasonable accuracy the fields of application [5]. With AEM, the structure is modeled as an assembly of small elements; the two elements shown in Figure 1 are assumed to be connected by one normal and two shear springs located at contact points, which are distributed around the elements edges. Each group of springs completely represents stresses and deformations of a certain volume.

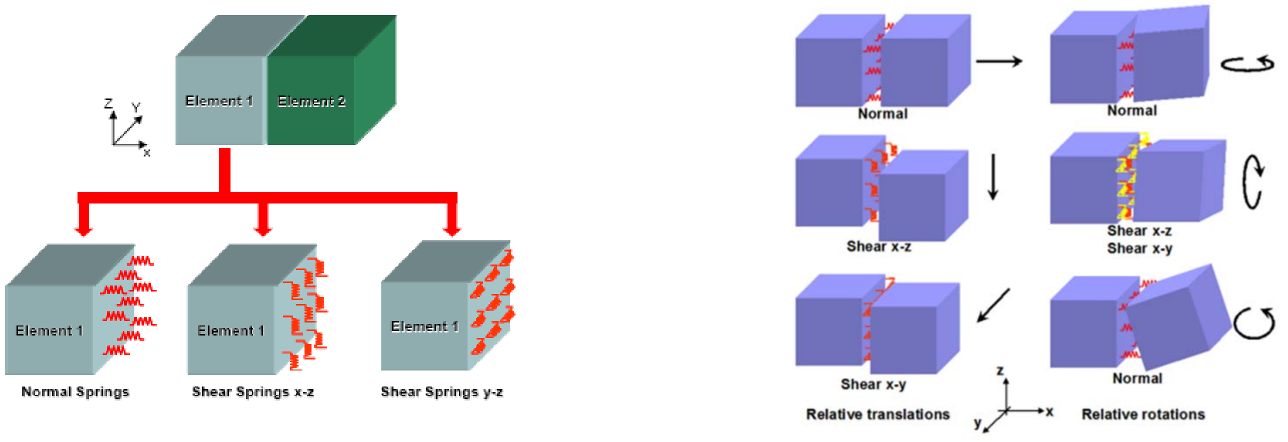


Fig. 1: Modelling of structure in AEM (left) and degrees of freedom for each element (right) [6].

Each element center of gravity is calculated and this is where the degrees of freedom are calculated. The use of 3D elements with springs connecting them at the faces leads to avoiding many of the problems that exist in modeling progressive collapse using Finite Element Method (FEM). FEM assumes full compatibility at the nodes, which makes automatic prediction of crack location complicated for large problems unlike the AEM which can automatically predict crack initiation, crack widening, and element separation. Moreover, in 3D nonlinear FEM the time of analysis can be 10-30 times larger than the AEM analysis when attempting to solve the same problem [3]. The AEM code is currently implemented in the software Extreme Loading for Structures, which was employed in the analysis performed within this work [6].

3. Model of the representative building

The modeled structure is a typical historic building representative of the constructions widespread in the southern Europe countries. The building is taken from the Amatrice historic center, with the dimensions estimated from the Google Earth images and the material properties based on the findings of [2]. The structure is a 3-story stone masonry building with a footprint of 14 m x 7.25 m. Stone masonry walls constitute the load bearing system with a thickness varying over the height from 100 cm to 50 cm. The slabs consist of stone-vaults at the first floor and timber or concrete slabs at the upper levels. A reinforced concrete gable roof connected to masonry with reinforced concrete curbs was modeled. This kind of roof is common in such kind of buildings, since it was part of “inappropriate retrofit” works undertaken between the ‘60s and ‘80s to replace the old and deteriorated timber roofs. Fig. 1 shows an overview of the AEM model of the building.

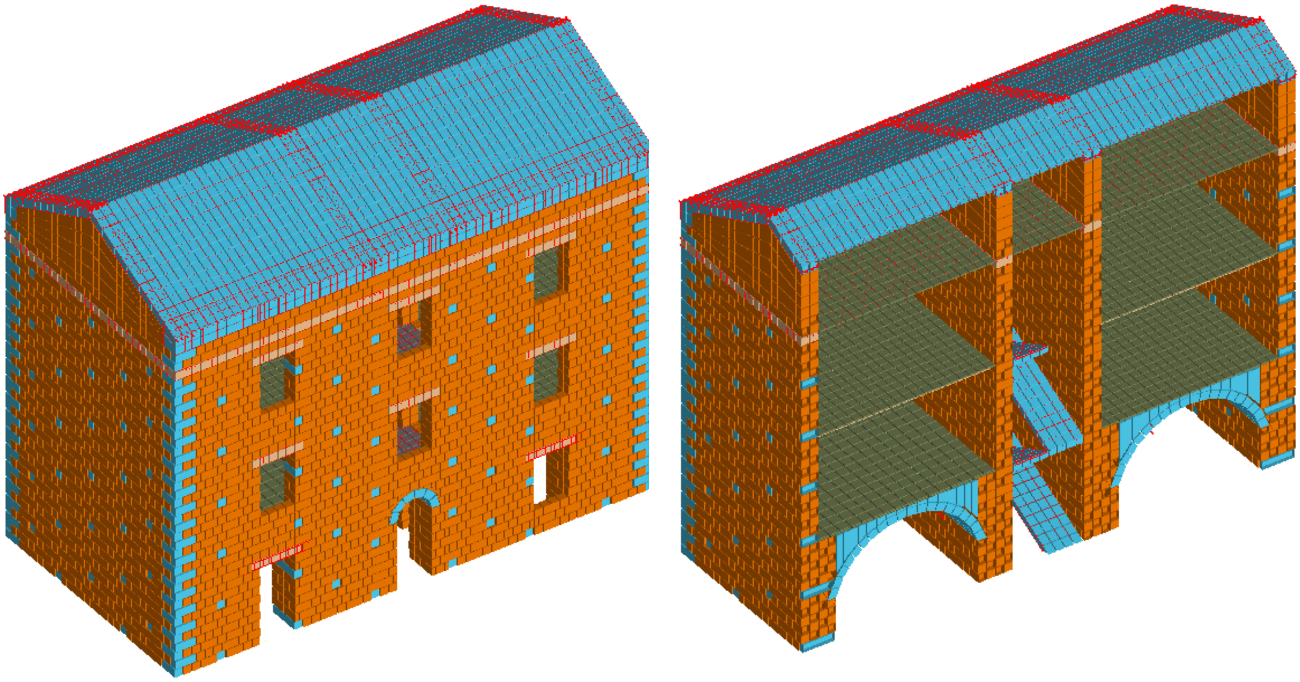


Fig. 2: 3D view of the AEM model (left) and cross section of the AEM model (right).

4. Materials

The typology of masonry, which is widely used in Southern Europe, is typical stone masonry realized with roughly squared blocks, assembled with poor lime mortar. The mechanical characterization of the masonry is based on Reference [2]. Reinforced concrete is assumed as C20/25 and material properties are calculated following [1]. Reinforcement is assumed to be steel AQ 50 , widespread until the ’70s [7]. Timber slabs and girders are assumed as solid wood with the properties assumed based on [8]. Table 1 reports the properties of the principal materials inserted in the model.

Table 1 - Material properties

Stone masonry with rougly squared blocks and lime mortar				
f (MPa) compressive strength	τ_0 (MPa) shear strength	E (MPa) Young's modulus	G (MPa) Shear modulus	w (kN/m^3) Specific weight
2.0	0.035	1230	410	20

Concrete				
fck (MPa) compressive strength	f_{ctk} (MPa) tensile strength	E (MPa) Young's modulus	G (MPa) Shear modulus	w (kN/m^3) Specific weight
20	2	29962	13620	25

Steel				
f_{yk} (MPa) yield strength	f_{tk} (MPa) tensile ultimate strength	E (MPa) Young's modulus	G (MPa) Shear modulus	w (kN/m^3) Specific weight
270	500	206000	81000	78.4

Solid wood				
f_{yk} (MPa) tensile strength	f_{tk} (MPa) compressive strength	E (MPa) Young's modulus	G (MPa) Shear modulus	w (kN/m^3) Specific weight
14	20	10500	660	4

5. Modelling of the structural details

Connectivity between perpendicular walls in the masonry historic buildings is a crucial aspect that contributes to reduce their vulnerability, permitting to the walls to react as a unique resistance system to the horizontal forces. The presence of quoins at the masonry edges is therefore a common structural detail adopted in the historic building that affects their seismic response. In the AEM model of the building explicit modeling of the quoins at the wall edges was performed. Fig. 7 shows the AEM model of the masonry edges with quoins modeled as rigid elements connected by nonlinear springs with the stone masonry properties.

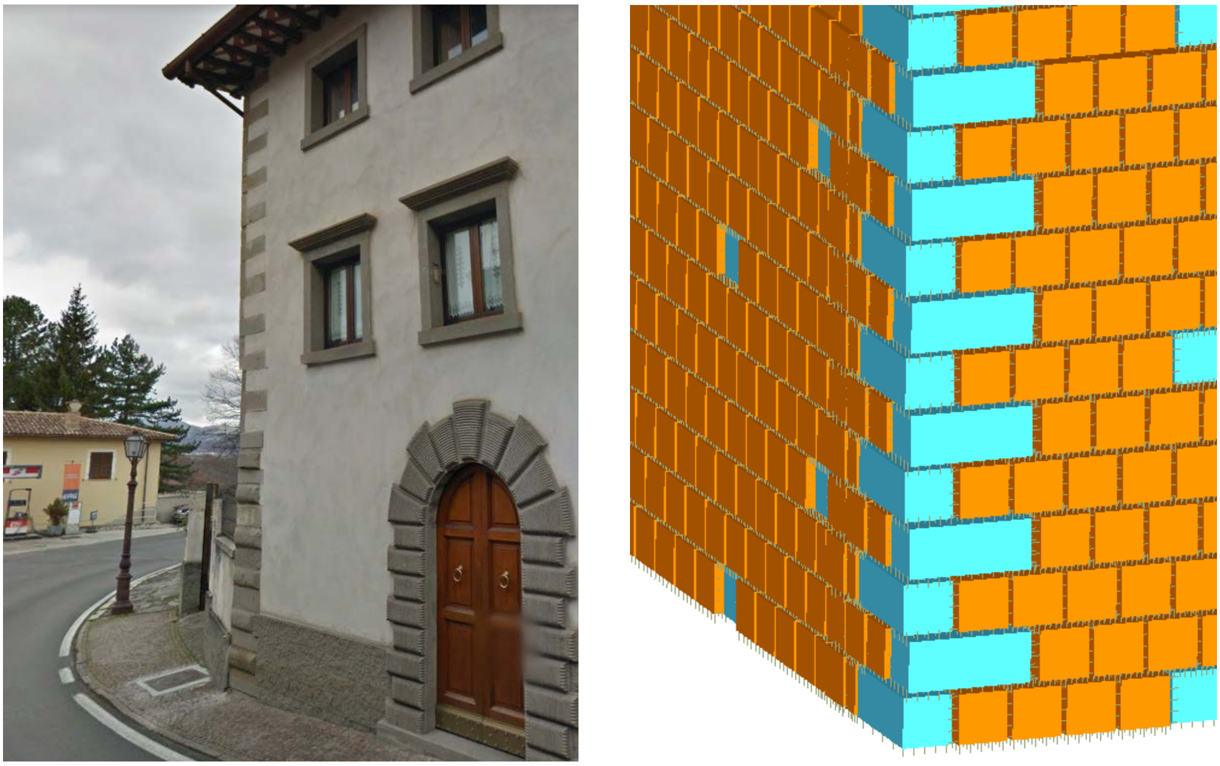


Fig. 3: Google Earth image of a building of the Amatrice historic center (left) and AEM modelling of the quoins at the masonry edges (right).

Stone masonry walls of such buildings usually consist of two-wall facing connected by transversal elements. This structural detail was implemented in the AEM model through the modelling of transversal rigid elements connected to the surrounding elements with nonlinear springs with the stone masonry properties. Fig. 4 shows the AEM model details.

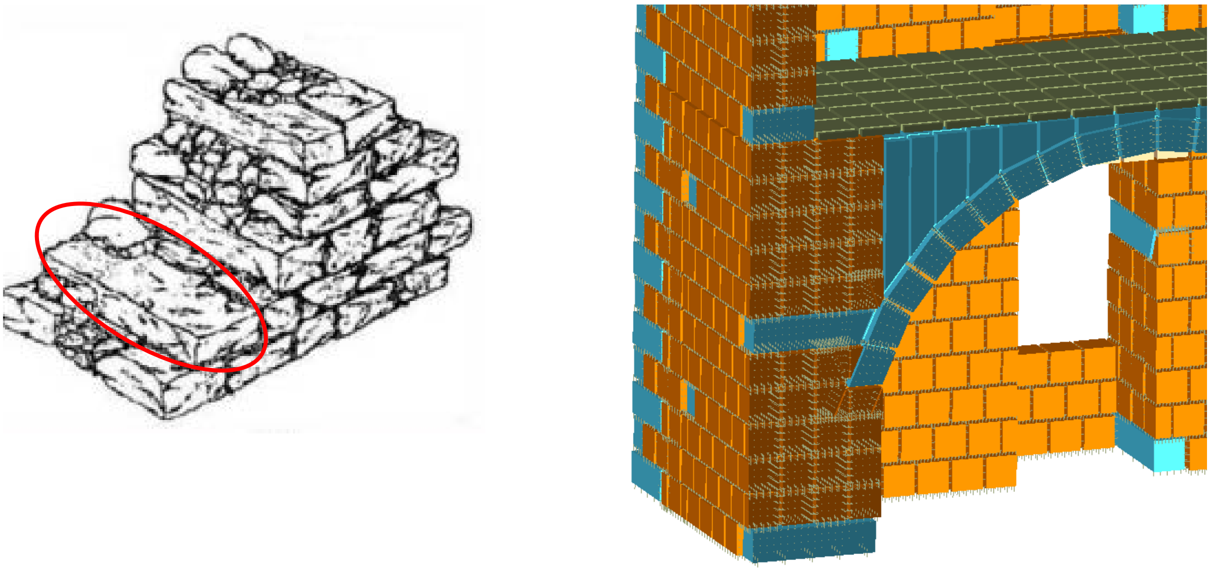


Fig. 4: Image of stone masonry wall with two-wall facing connected by transversal stones (left); AEM model of the same structural detail (right).

Arches and vaults are common structural elements in the historic buildings. Their appropriate modelling is crucial in the study of the behavior of the masonry historic buildings, indeed the lateral static forces at the springer may act as trigger for damage or collapse of the structure. The AEM model of such structural parts is realized with an explicit modelling where the rigid elements simulate the stones, which are connected by nonlinear springs with the properties of the mortar actually detected. Fig. 5 shows the level of detail implemented in the structural model of the vault.

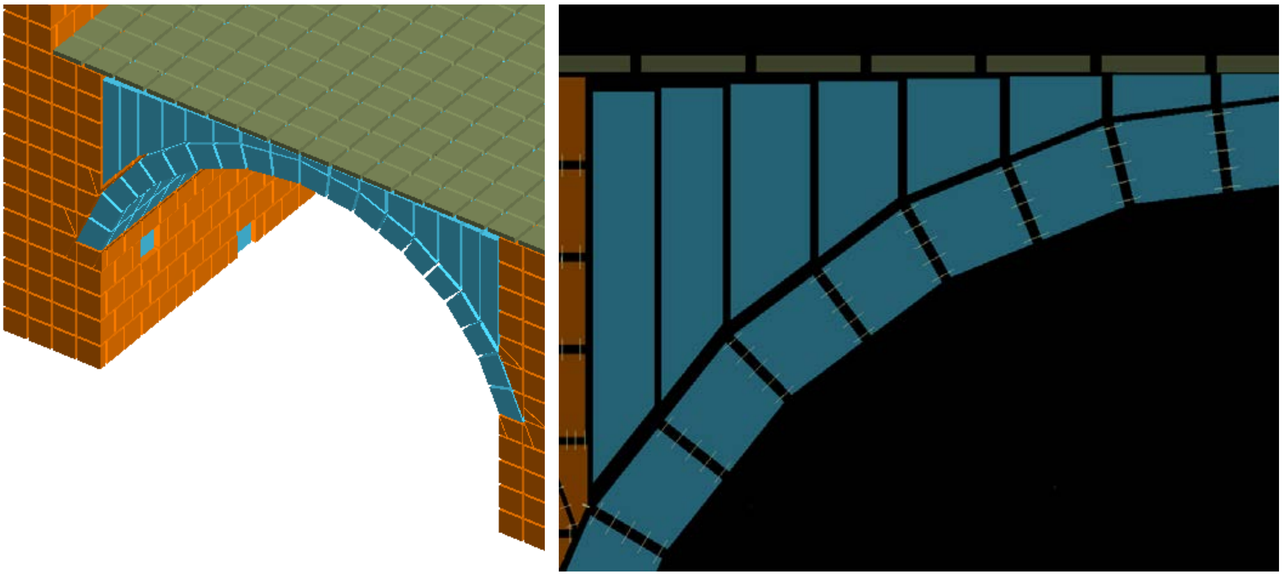


Fig. 5: 3D view of the vaults AEM model (left); Detail of the vault AEM model (rigid elements plus connecting springs) (right).

The type of connection between different structural elements, for example timber beams and walls, affects the dynamic behavior of the historical buildings. In many cases, the ancient masonry structures show extensive damages due, for example to the detachment between slabs and walls. In order to model the connection between different structural parts of the building, interface materials were implemented in the AEM model. A poor lime mortar is assumed as interface between the main elements that constitute the analyzed structure. Table 2 shows the material properties assumed for lime mortar.

Table 2 – Lime mortar material properties

Lime mortar				
f_{ck} (MPa) compressive strength	f_{tk} (MPa) tensile strength	E (MPa) Young's modulus	G (MPa) Shear modulus	w (kN/m³) Specific weight
2	0.2	1900	864	19

Fig. 6 reports a cross section of the entire building (left) and a detail of the AEM model of the timber beam at the intersection with the masonry walls (right). Both images show the nonlinear springs representing the lime mortar interfaces as yellow lines. Lime mortar interface is modeled at different locations as for example at the connections between the vaults and the walls, between reinforced concrete girders and walls, and at the connection of the roof curb with the masonry.

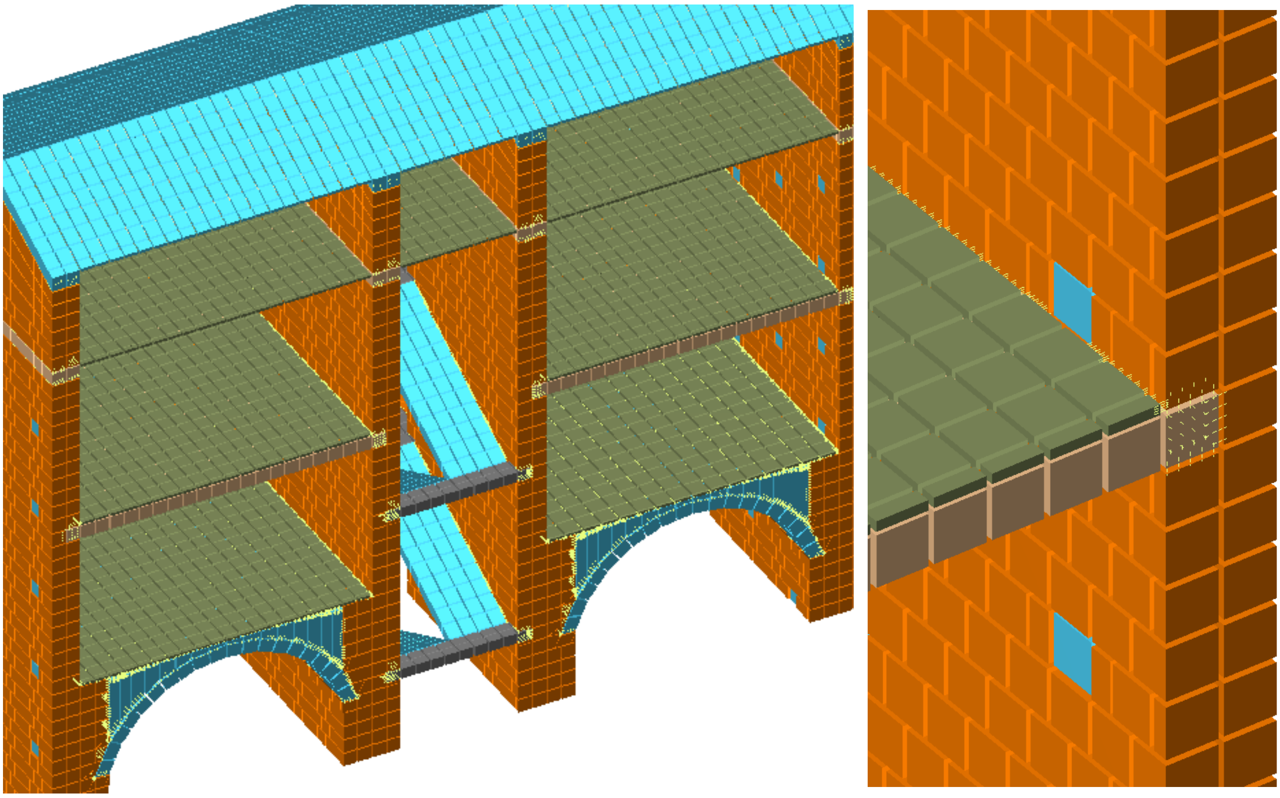
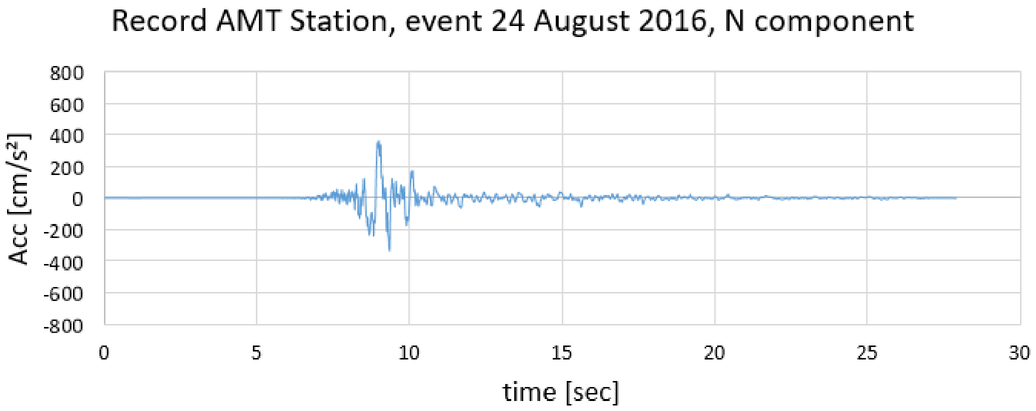
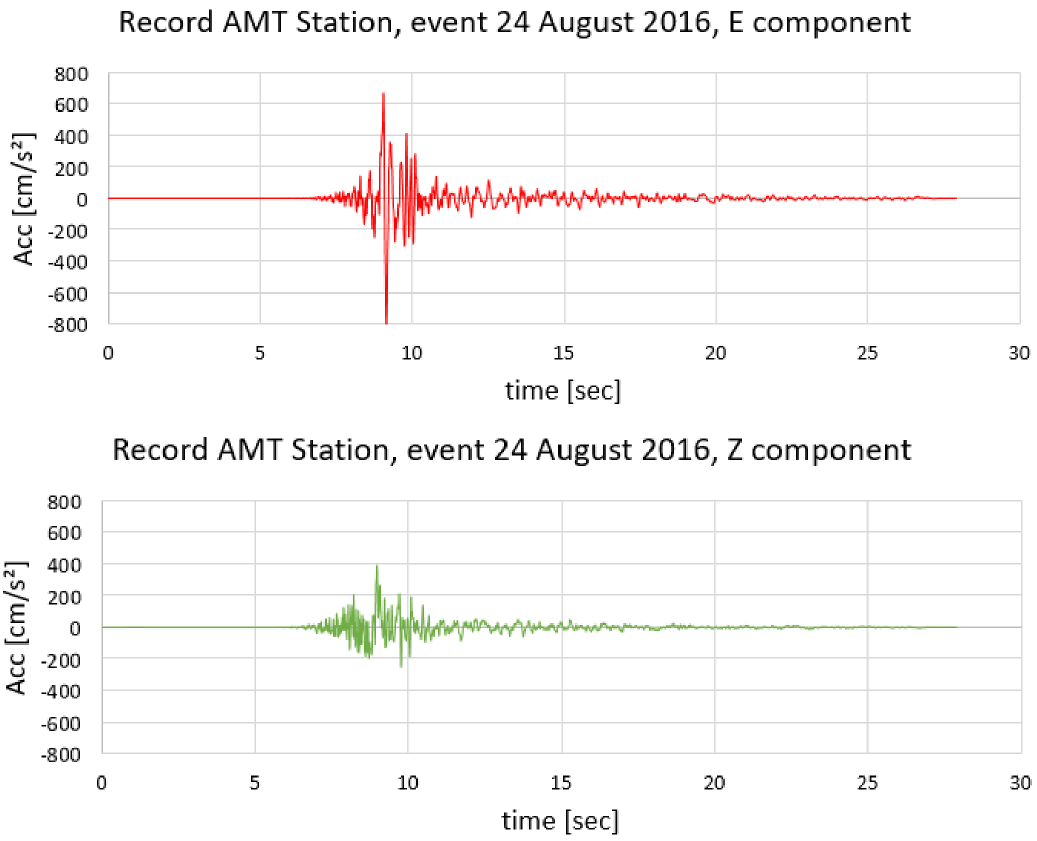


Fig. 6: Cross section of the entire building-lime mortar interfaces (left); Nonlinear lime mortar springs at the intersection between timber beam and wall (right).

6. Seismic load

The seismic event of August 2016 that devastated the Amatrice historical center, was chosen as seismic input for the simulation of the AEM model. Fig. 7 shows the accelerograms recorded at the Amatrice's station (AMT) in X, Y and Z direction during the event of 24 August 2016. Data for courtesy of [4].



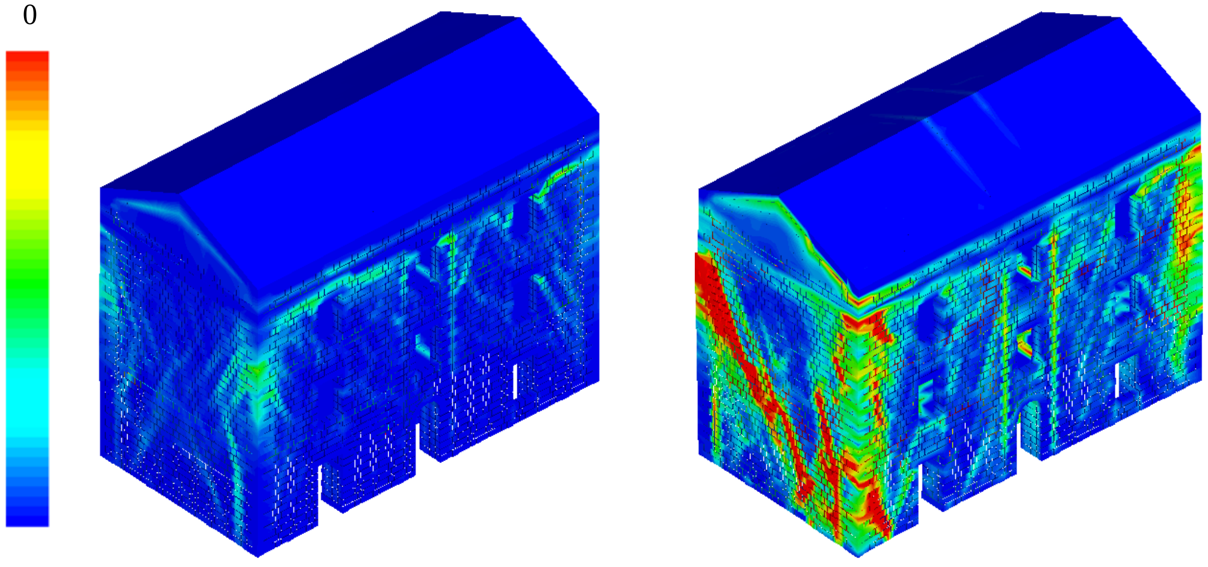

Record AMT Station, event 24 August 2016, E component

Record AMT Station, event 24 August 2016, Z component

Fig. 7 – X,Y,Z recorded accelerograms of the AMT station during the seismic event of 24 August 2016

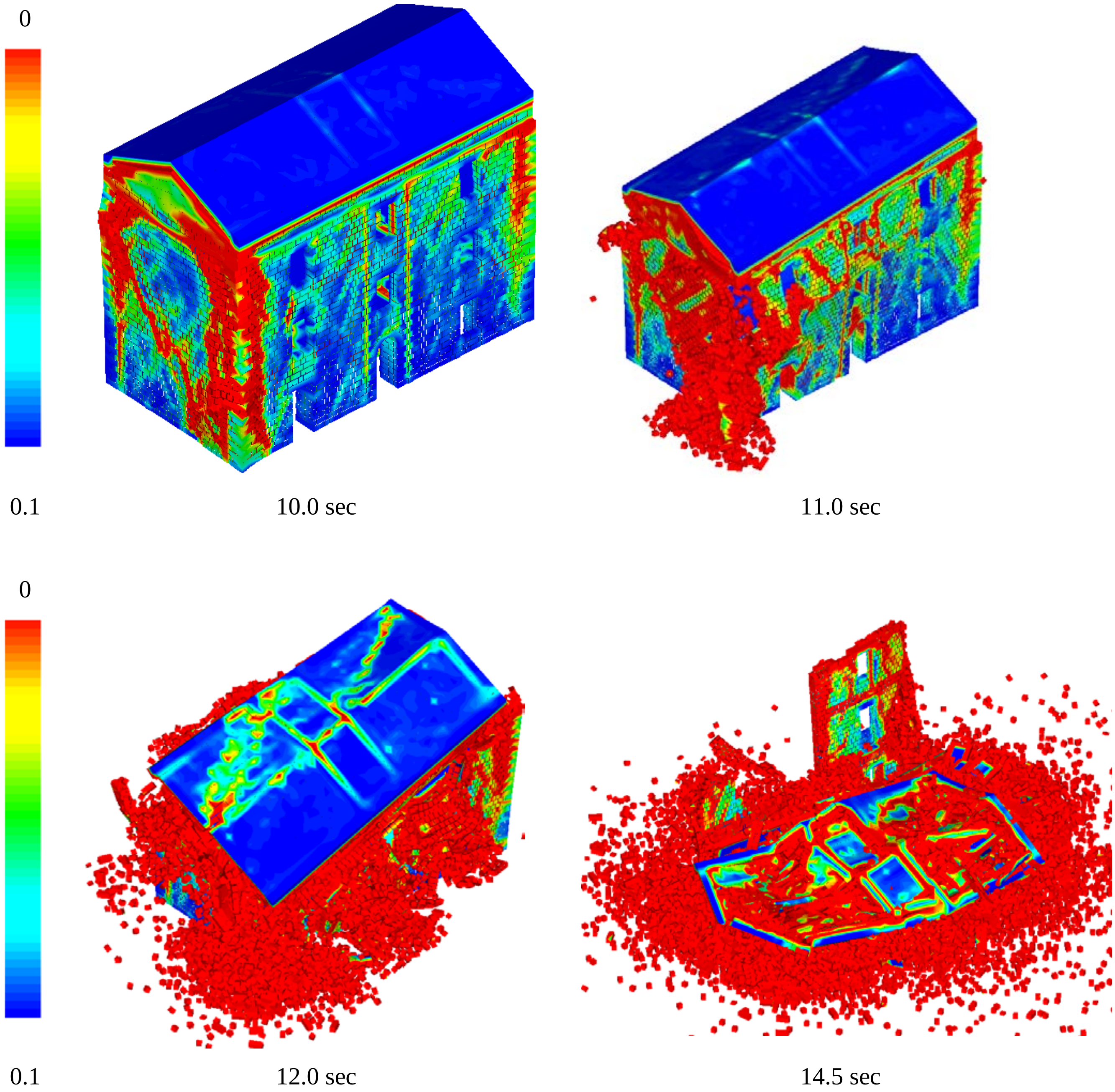
7. Results of the analysis

A nonlinear dynamic analysis of the representative building was carried out by subjecting the structure to X,Y and Z recorded accelerograms of the Amatrice seismic event. **Error! Reference source not found.** reports the AEM simulation results plotting the principal normal strains.



9.0 sec

9.5 sec



10.0 sec 11.0 sec

12.0 sec 14.5 sec

Fig. 8: AEM simulation results – Principal normal strains (values from 0 to 0.1) at different time frame

The analysis of the results shows that at approximately 9.5 sec., where the East component of the shaking achieves the maximum value, the edge wall perpendicular to the principal direction presents several cracks (shear crack and sub-vertical cracks) due to the combined action in plane and out of plane, Fig. 9 (left). After this wall loses its bearing capacity, the related slabs lose their support and the entire building starts to collapse. At the end of the analysis, the rigid and heavy reinforced concrete roof collapses, crushing the masonry beneath and despite the heavy damage suffered, its shape is still clearly recognizable, Fig. 9 (right). It is worth noting that such kind of behavior of reinforced concrete roofs, built to replace the ancient timber roofs, was observed in different building collapses during the recent seismic events, proving the ineffectiveness of this structural retrofit.

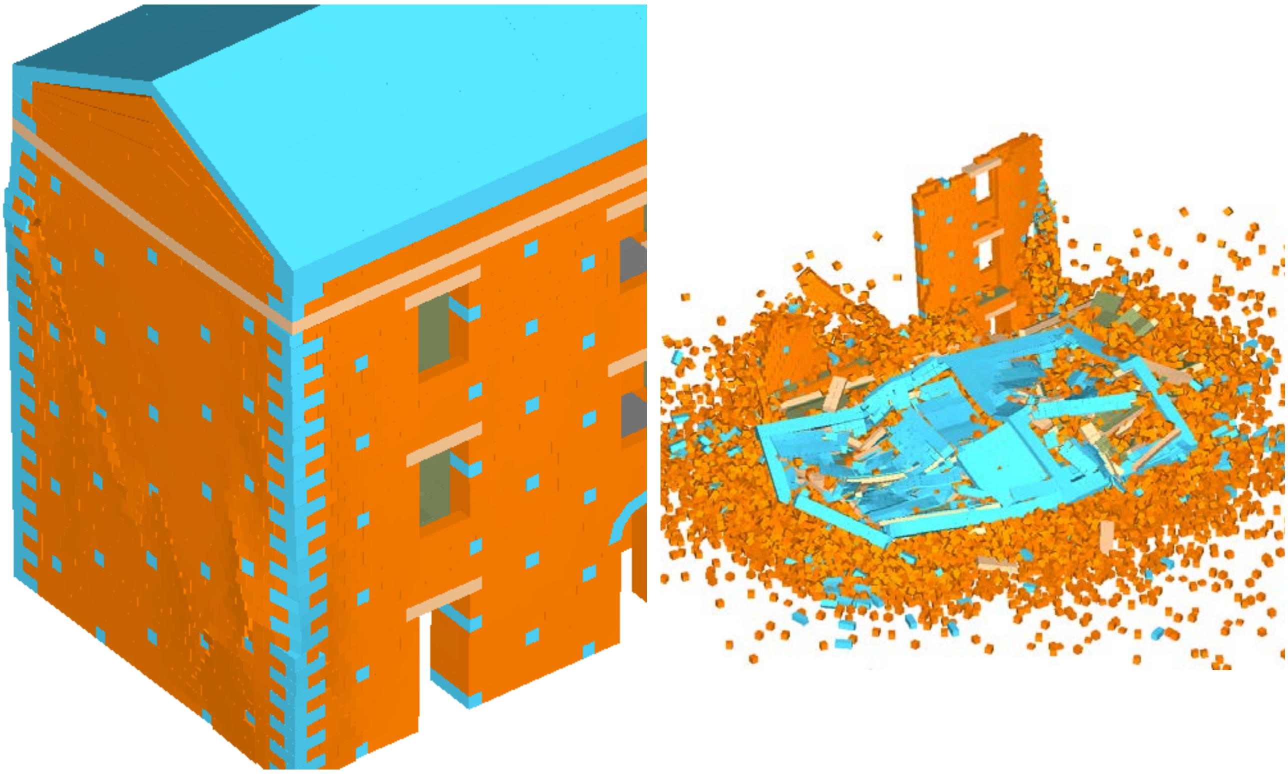


Fig. 9: Shear and sub vertical cracks in the masonry (left) and final collapsed shape (right)

8. Conclusions

The study of the ancient historic building presents many difficulties related for example to the modelling of particular structural elements (arches, vaults), characterization of different materials adopted, assessment of the level of connection between different structural elements, assessment of pre-existing damages due to past actions. The AEM technique permits creation of high fidelity models, where all the structural elements and the related details can be implemented without a significant increase in the computational requirements. The present work reports the AEM simulation of a representative historic building of the Amatrice historic center. The structure was subjected to the seismic event of 24 August that destroyed the small town. The results show how the AEM simulation can reproduce accurately the dynamic behavior, identifying typical collapse mechanisms of such kind of buildings.

9. References

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