LARGE SCALE SEISMIC VULNERABILITY ASSESSMENT OF HISTORIC URBAN AREAS USING THE APPLIED ELEMENT METHOD

A.A. Khalil(1), A. Elfouly(2), C. Pellecchia(3), E. De Iuliis(4).

(1) *Structural Engineer, Applied Science International llc, khalilaa@appliedscienceint.com*
(2) *Structural Engineer, Applied Science International llc, elfouly@appliedscienceint.com*
(3) *Architecture and Building Engineer, Applied Science International Europe srl, cpellecchia@appliedscienceint.com*
(4) *Civil Engineer, Applied Science International Europe srl, edeluliis@appliedscienceint.com*

Abstract

Recent seismic events in European countries highlighted the vulnerability of the historic part of many European cities. For example, the August 2016 earthquake in Italy caused significant damage to numerous historical buildings in the villages of Accumuli, Pescara del Tronto and Amatrice while only limited damage was reported in the newer part of the cities. Damage was worst in villages that consisted of ancient masonry structures; local authorities reported damage to 50% of the buildings in Amatrice. The fragility of the masonry structures combined with the reduced dimensions of roads and the blockages created by some collapses slowed down the emergency response teams and increased the need for additional precautions and preventive actions in order to avoid disproportionate economic and life losses.

Although several analysis tools were developed for evaluation of single masonry structures, the simultaneous analysis of historic urban areas as well as the detection of critical buildings that, if collapsed, could cause roads interruption and additional damage to the surrounding structures remains an open challenge for computational methods. If achieved, the analysis could assure the efficiency of targeted retrofitting actions and significantly increase the resilience of the urban system by optimizing the use of available economic resources.

One of the main constraints of the study of these types of structures is the need to consider the interactions between aggregated buildings, both during the seismic event and during the collapse. The numerical tool must also have the ability to implement automatic separation between the elements of the structures. Moreover, these heritage buildings have complex structural details such as presence of buttresses, arches and vaults and interaction between structural elements with different types of connections. This type of high fidelity modeling requires enormous amount of computational resources due to the required high element's discretization, especially when the objective is to model large areas or entire neighborhoods.

The work described in this study analyzes the most recent application of the Applied Element Method in the analysis of historic urban areas, with particular focus on the simulation of masonry and heritage structures. Recently published studies highlighted the capability of the method to overcome the limitations of the current structural analysis techniques, both in terms of results accuracy and in terms of use of computational resources [1].

A case study, for a portion of the historic center of the city of Roquebillière, France, has been simulated and assessed within the European Project "INACHUS" identifying target-retrofitting actions, and demonstrating the practicality of using this technique to evaluate the accessibility of strategic roads for rescue operations. The analysis allows the development of a proper emergency plan in case of seismic events and results in an increase of the resilience of the urban system.

Keywords: Masonry structures, Historic Urban Areas, Large-scale Numerical Simulations, Applied Element Method.

1. Introduction

A considerable part of the historic and architectonic heritage in Europe is located in areas with high seismic hazard. Recent earthquakes highlighted the vulnerability of the historic buildings even if subjected to moderate seismic actions. In many cases, damage is caused by detachment of beams from the bearing masonry, detachment of entire portions of walls due for example to the presence of arches or vaults without appropriate lateral force resisting system. In these cases, the structural details act as trigger for the eventual damage or collapse of the building, therefore there is a need to model such complex and heterogeneous structures in an efficient way, reproducing all the significant structural details while optimizing computational cost.

The present paper introduce the complexity in seismic analysis of heritage masonry structures trough the study of typical historical building, representative of construction in the southern European countries using the Applied Element Method [2-5]. Several structural details are implemented and the reliability of the corresponding collapse behaviors are verified and assessed.

The study further develops the structural analysis to entire portions of historical centers, with the aim of providing a valid tool to assess, not only safety of the structures, but also the interaction with other buildings. The aim is to prioritize the operations in case of a seismic event.

2. The Applied Element Method

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 [6].

With AEM, the structure is modeled as an assembly of small elements; the two elements shown in Fig.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.

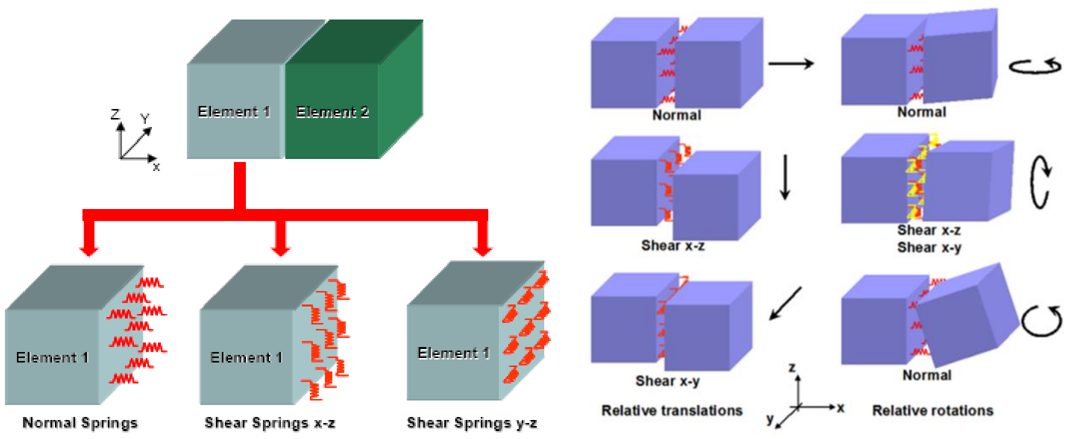


Fig. 1 – Modelling of structure in AEM (left) and degrees of freedom for each element (right).

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 [1].

The AEM code is currently implemented in the software Extreme Loading® for Structures, which was employed in the analysis performed within this work [7].

3. AEM model of masonry historic structure

This section introduce the study of the seismic vulnerability of typical historical buildings representative of construction in the southern European countries [8] using the Applied Element Method (AEM) for high fidelity nonlinear structural analysis. The work is part of activities undertaken within the European Union funded project "INACHUS" (7th framework programme "Technological and Methodological Solutions for Integrated Wide Area Situation Awareness and Survivor Localization to Support Search and Rescue Teams").

The studied historic building has a ground floor and three additional floors (Fig.2). The building consists of masonry walls, timber slabs and a timber roof. The masonry is composed of solid brick works with a thickness varying from 25 to 60cm, while wood beams that support the timber planks constitute the slabs. All the openings are provided with lintels made of masonry arches.

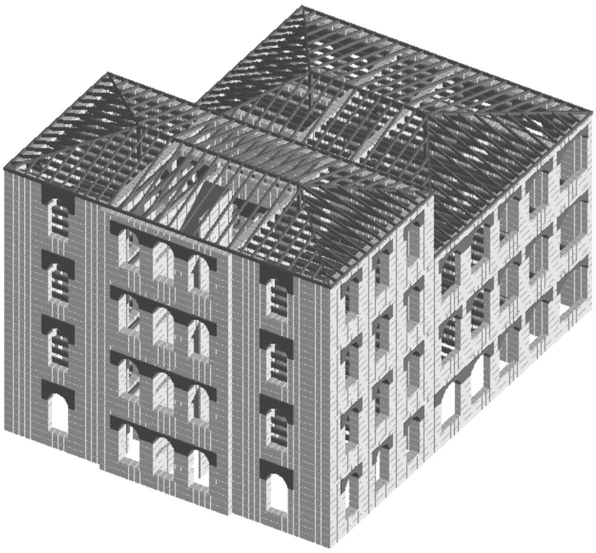


Fig. 2 – Overview of the AEM model of the historical building.

The following table shows the material properties assumed in the AEM model.

Table 1 – Material properties

Material	Young's Modulus MPa	Shear Modulus MPa	Specific Weight Kg/m³	Tensile Strength MPa	Compressive Strength MPa
Masonry	1200	400	2000	0.25	2.4
Wood	11000	560	600	24	24

4. Implemented structural details

In order to model the connections between different structural elements, interface materials were implemented in the model. Mortar material was used as interface between wood beams and masonry. A detail of the model and the corresponding behavior is reported in Fig.4.

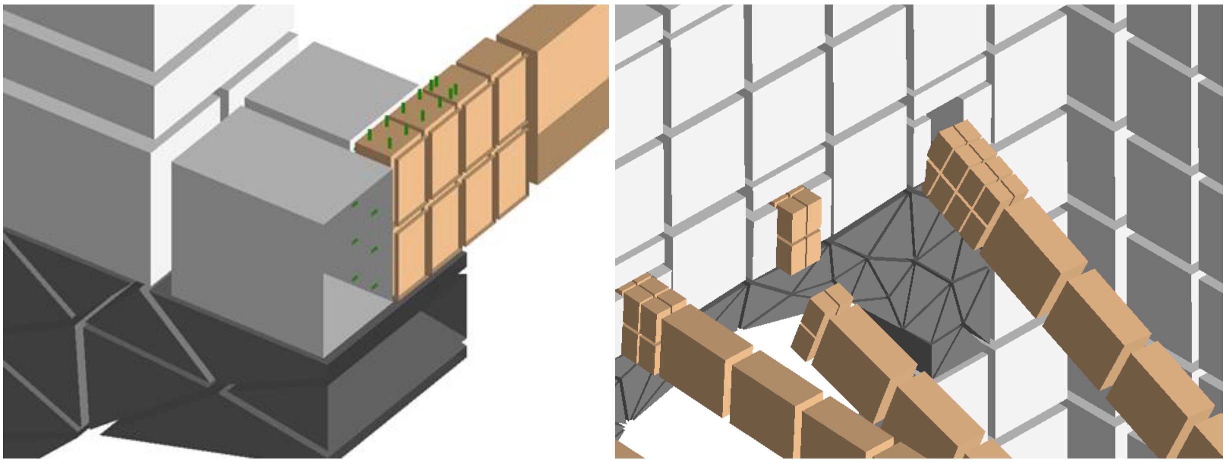


Fig. 4 – Connection detail between beams and walls. Highlight of green springs representing Mortar material interface (left) and collapse behavior detail (right).

Mortar interface material was also implemented to provide constraints at the top of the wall. Detail of the behavior under seismic action is shown in Fig.5.

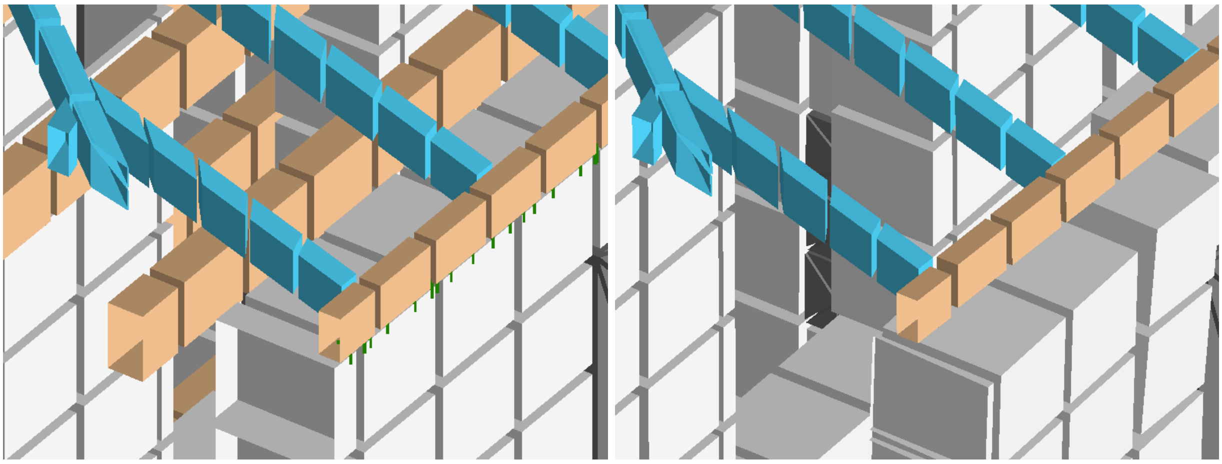


Fig. 5 – Connection detail between roof and walls. Highlight of green springs representing Mortar material interface (left) and collapse behavior detail (right).

Low shear strength bearing material is used as interface material between slabs and walls; therefore, no significant in plane constraint is provided to the walls (Fig.6).

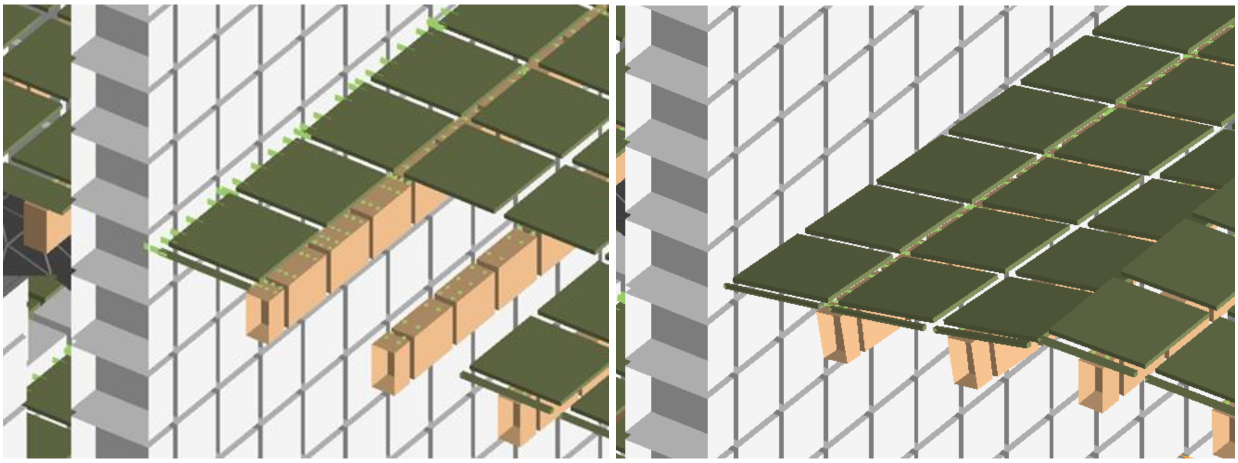


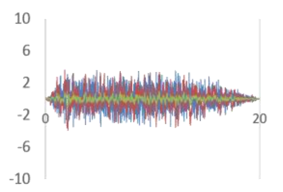
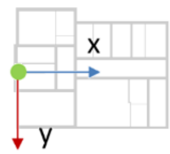
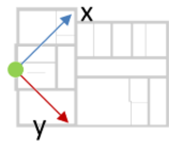
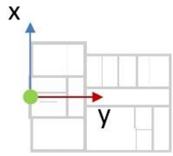
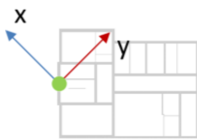
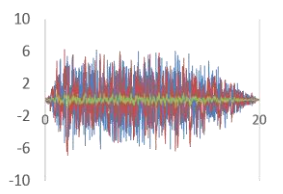
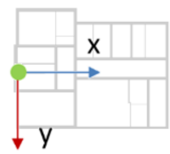
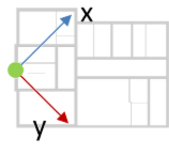
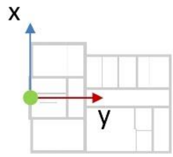
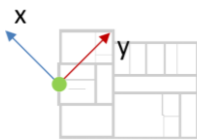
Fig. 6 – Connection detail between slabs and walls. Highlight of green springs representing bearing material interface (left) and collapse behavior detail (right).

The detailed modeling of these structural details allowed reproducing the effective behavior and the actual collapse mechanisms, which are often observed in masonry buildings subject to seismic action. The study further develops the behavior of the global building under seimic action.

5. Global behavior of the structure

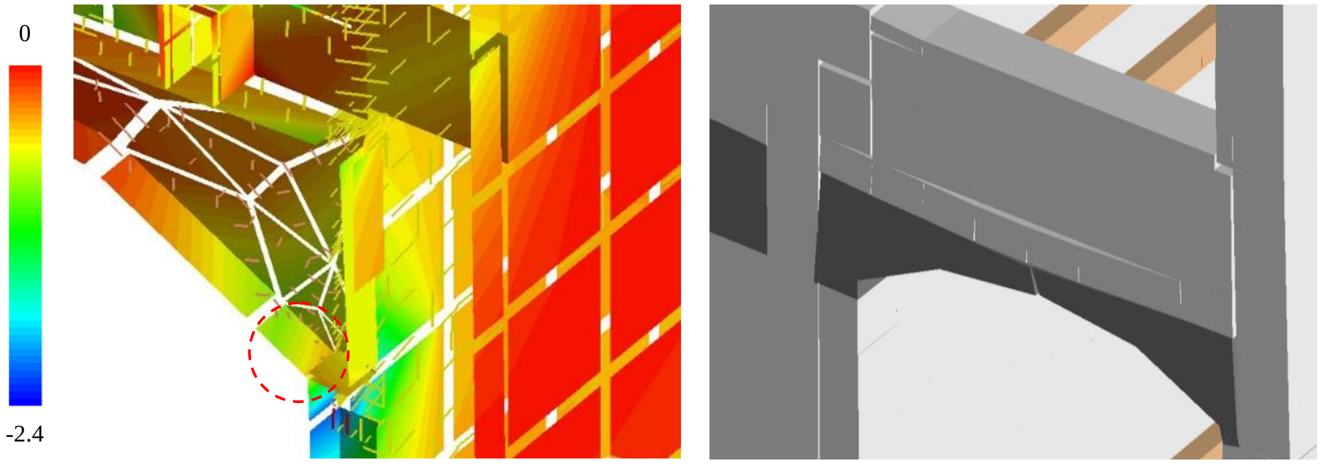
Multiple levels of seismic acceleration were used in order to assess the seismic behaviour of the structure. Synthetic earthquake time histories were derived and scaled for two different levels of intensity (with peak varying between 4 and 7 m/sec²) obtaining different cases of partial and total collapse of the building. Moreover, an assessment of the structural behaviour with different directions of the earthquake components, was carried out. A summary of the analysis cases is reported in Tab.2.

Table 2 – Levels of earthquake considered in the analysis

Int.	EQ time histories	Case 1	Case 2	Case 3	Case 4
Moderate Peak 4m/sec²					
Strong Peak 7m/sec²					

A description of the collapse behaviour is given in the following.

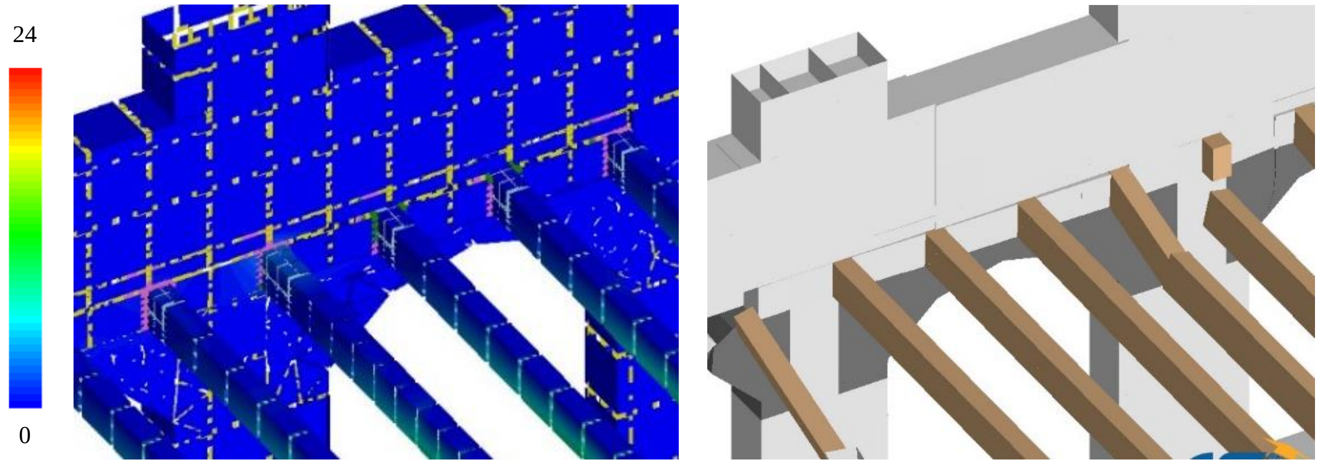
Failure is detected in the arches where the compressive failure occurred after few seconds of earthquake, as shown in Fig.7.



Spring compressive failure　　　Corresponding damage

Fig. 7 – Compressive failure of an arch due to the big opening [MPa].

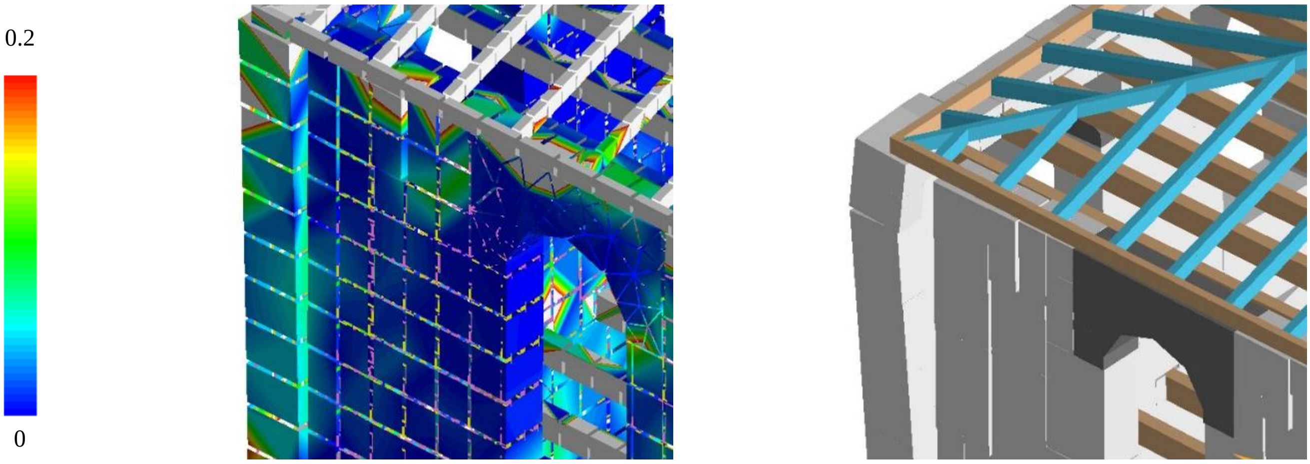
As can be noted in Fig.7, left side, the masonry reaches maximum compressive stress at abutments of the arch, after the first shakings. The arch will fail few seconds later as shown in Fig.7 (right). Because of the major span length, the subsequent failure happens on the right side of the building. Fig.8 shows the tensile failure of the mortar and wood springs near the support.



Spring tensile failure (magenta)　　　Corresponding damage

Fig. 8 – Tensile failure in the connection between girders and walls [MPa].

Since poor connection is considered between roof and walls (Mortar material) the typical out of plane overturning of the wall can be observed, Fig.9.

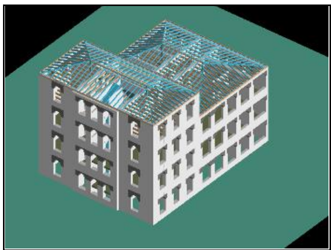
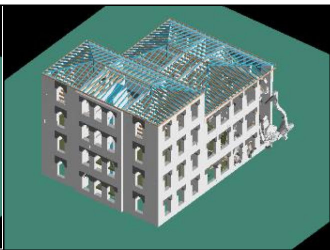
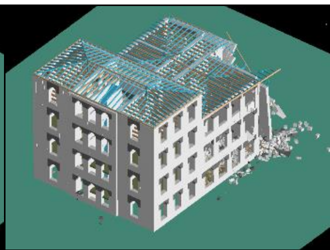
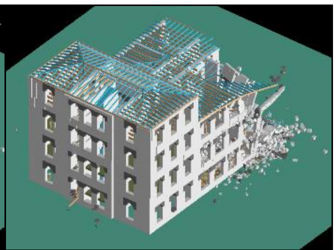
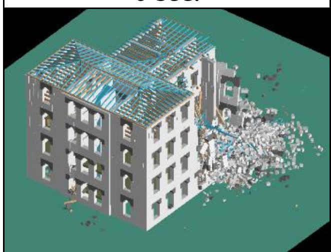
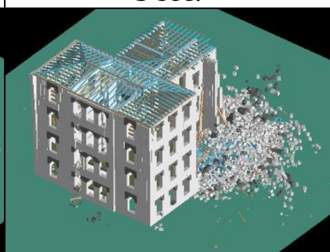
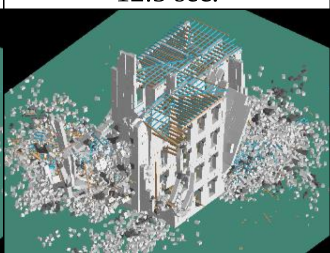
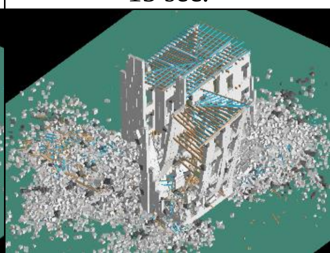
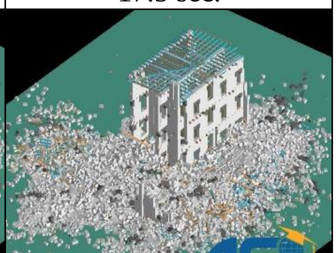


Spring tensile failure (magenta) Corresponding damage

Fig. 9 – Out of plane overturning phenomena reproduced in the analysis [MPa].

Building behaviour during the time-history analysis with earthquake intensity equal to moderate is shown in Tab.3.

Table 3 – Results of the time history analysis corresponding to moderate earthquake

			
0 sec.	2.5 sec.	5 sec.	7.5 sec.
			
10 sec.	12.5 sec.	15 sec.	17.5 sec.
			
20 sec.	22.5 sec.	25 sec.	30 sec.

The partial collapse of the structure is achieved after 30 seconds of shaking. Final collapse shape is shown in Fig.10.

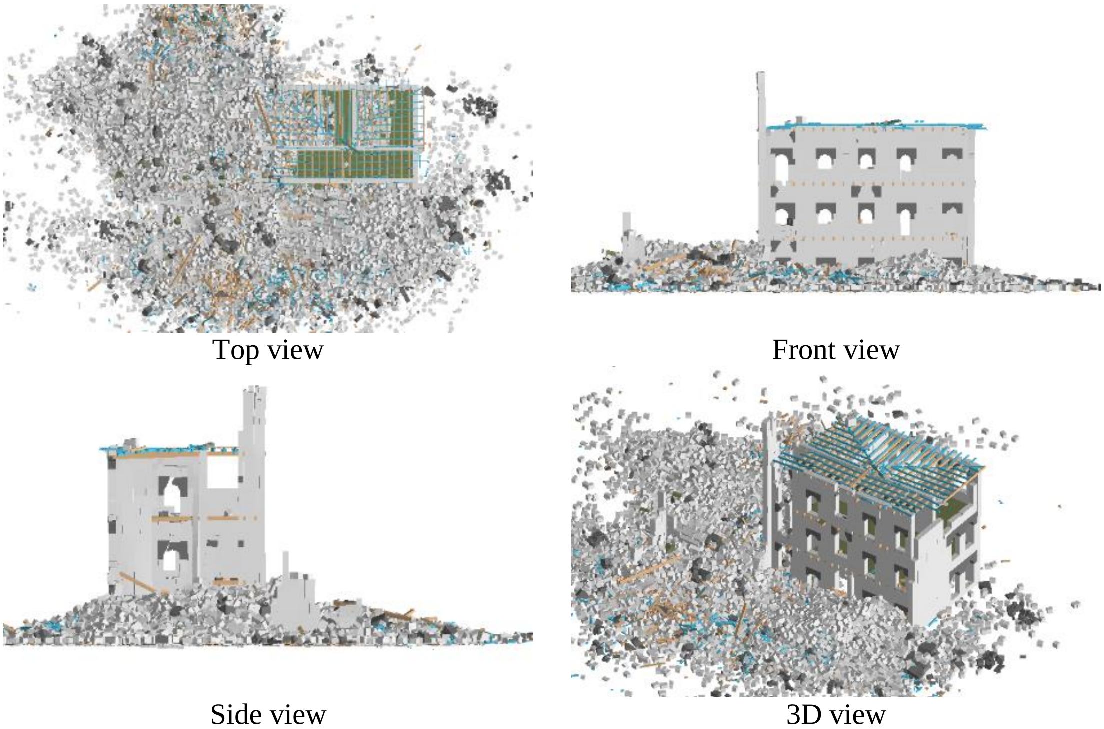


Fig. 10 – Damage state of the building with moderate earthquake intensity.

Moreover, additional studies are conducted on masonry buildings constructed with vaults and arches, as well as on masonry structures with RC roof. Analysis results shown crack patterns comparable with actual masonry behaviour and reasonable collapse mechanisms (Fig.11).

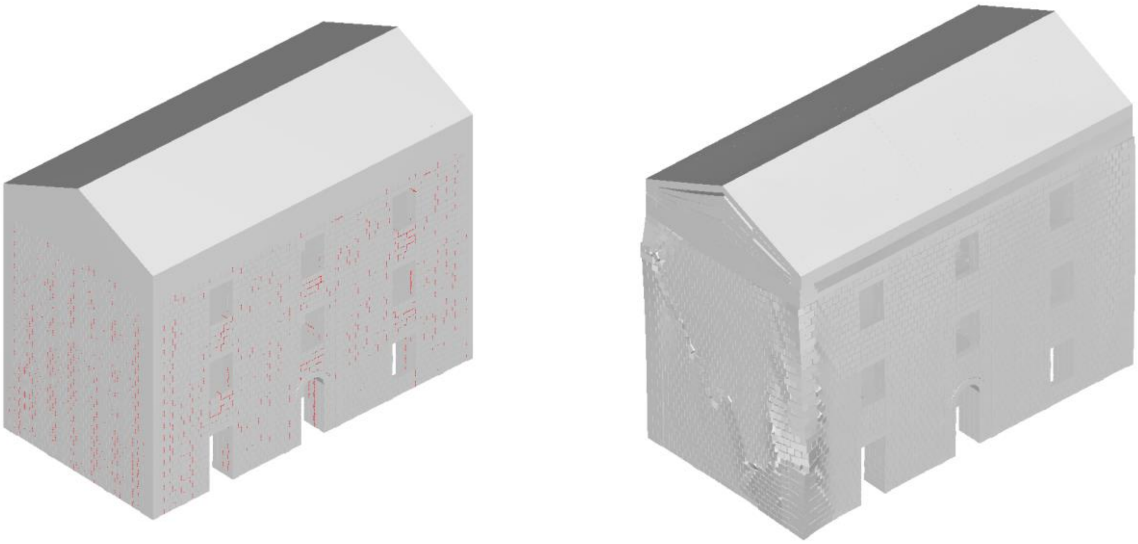


Fig. 11 – Crack pattern (left) and collapse mechanism (right) of a masonry structure AEM model implemented with a RC roof.

Vaults were implemented by explicitly modelling the actual layout of the stones and reasonable results in terms of collapse mechanism were again achieved (Fig.12).

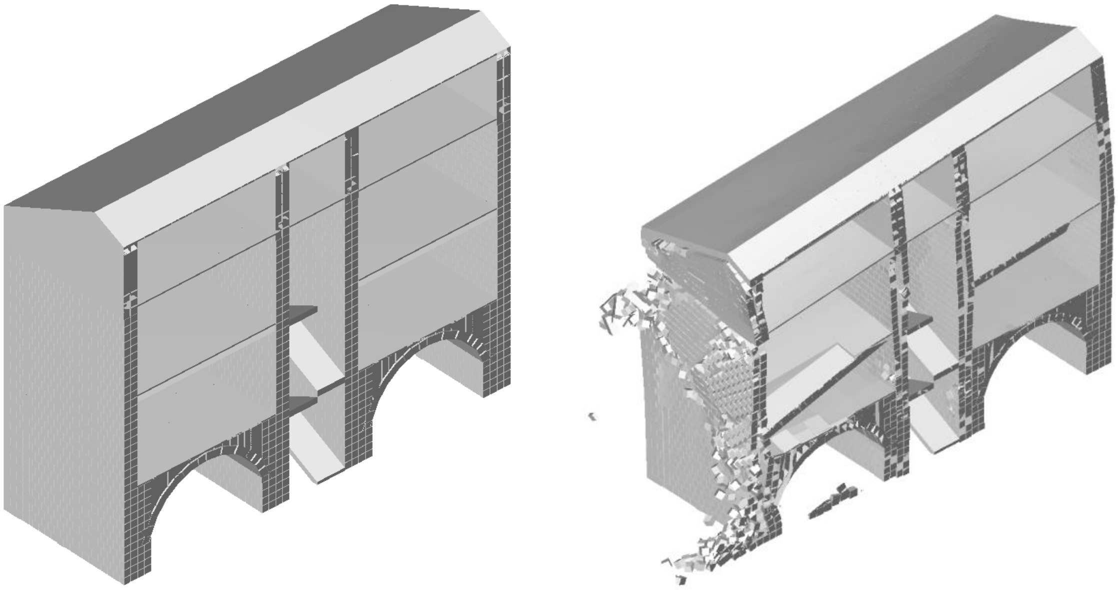


Fig. 12 – Cross section of masonry structure AEM model implementing vaults (left) and collapse mechanism in case of vault failure (right).

6. Large scale analysis

The single building analysis is further developed in seismic assessment of an entire city quarter. A portion of the historic centre of the city of Roquebillière, France (Fig.13) is modelled and analysed using the same time histories previously described.

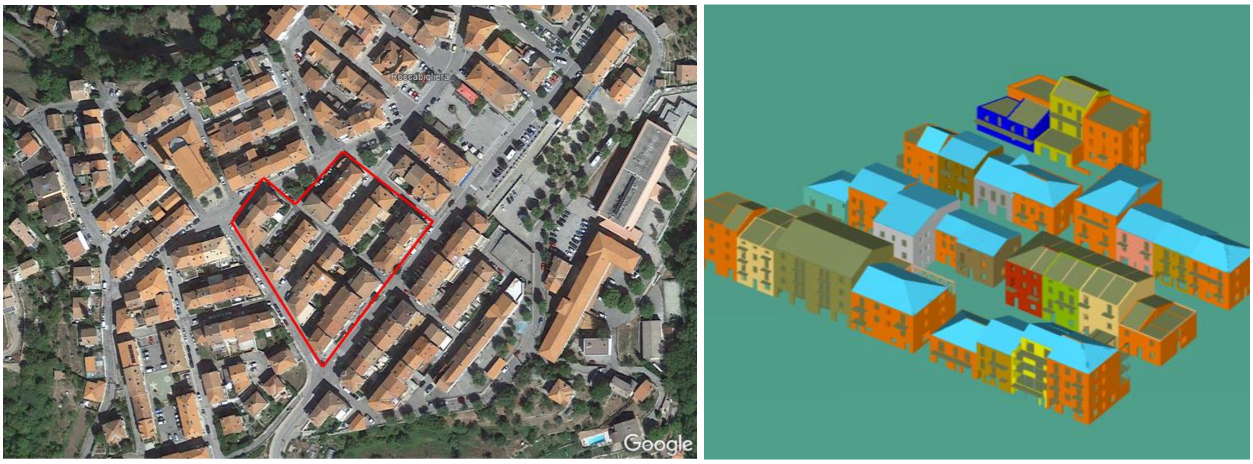


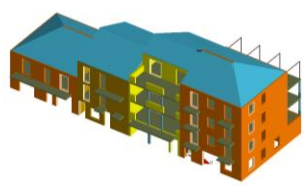
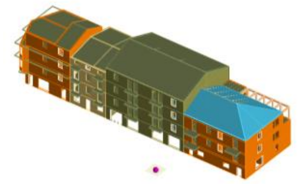
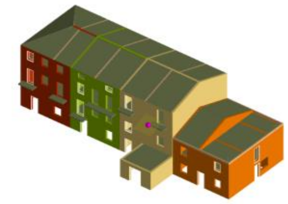
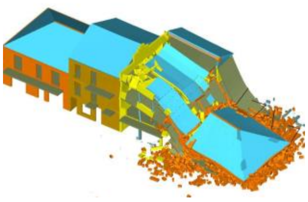
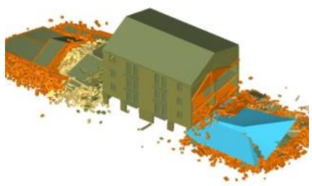
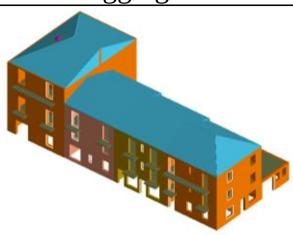
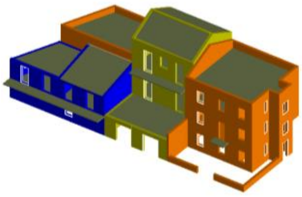
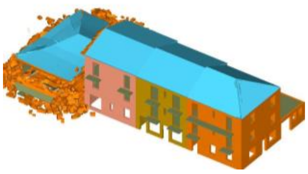
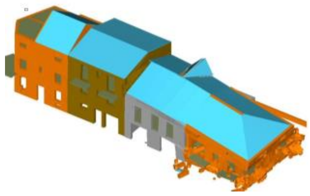
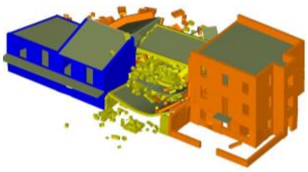
Fig. 13 – Analyzed portion of the historic centre of the city of Roquebillière, France (left), reprinted from Google Earth® Images and AEM analytic model (right).

The models were based on actual dimensions of the aggregate buildings; representative material and structural details were used as per Section 4 (Fig. 14).

Fig. 14 – Dr. Matteo street in the historic centre of the city of Roquebillière, France (left), reprinted from Google Earth® Images and AEM analytic model (right).

An analytic model for each of the 7 aggregate buildings was created and tested in order to evaluate the seismic behaviour of each structure.

Table 4 – Aggregate buildings, results of the time history analysis corresponding to strong earthquake

	Aggregate 1	Aggregate 2	Aggregate 3	Aggregate 4
Analytic model				
Seismic				
	Aggregate 5	Aggregate 6	Aggregate 7	
Analytic model				
Seismic				

Afterwards, the analysis was performed at the same time for all the structures and computational time was about 24 hours (Fig.15).

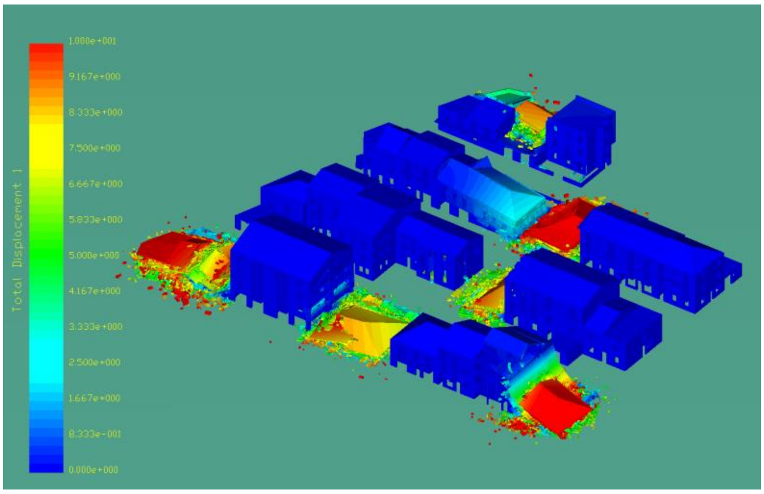


Fig. 15 – Analysis results with "Strong" Earthquake intensity.

Collapse mechanism detected at single building levels were observed together with interaction phenomena between the different buildings, allowing for large-scale assessment of road interruption and point of entry and exit in case of emergency actions (Fig.16).

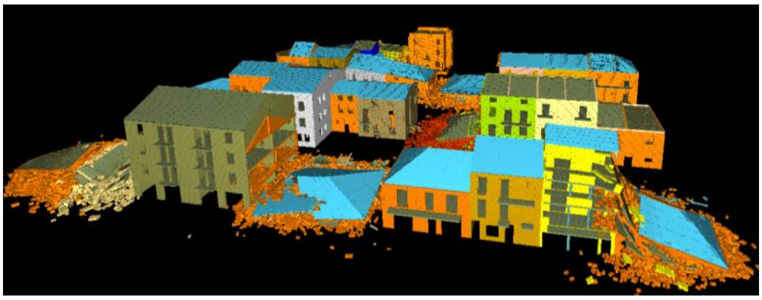


Fig. 16 – Visual damage assessment of the city quarter.

Moreover, selective retrofitting actions can be planned to avoid collapse sequence and optimize the use of economic resources in prevention of large-scale seismic damage (Fig.17).

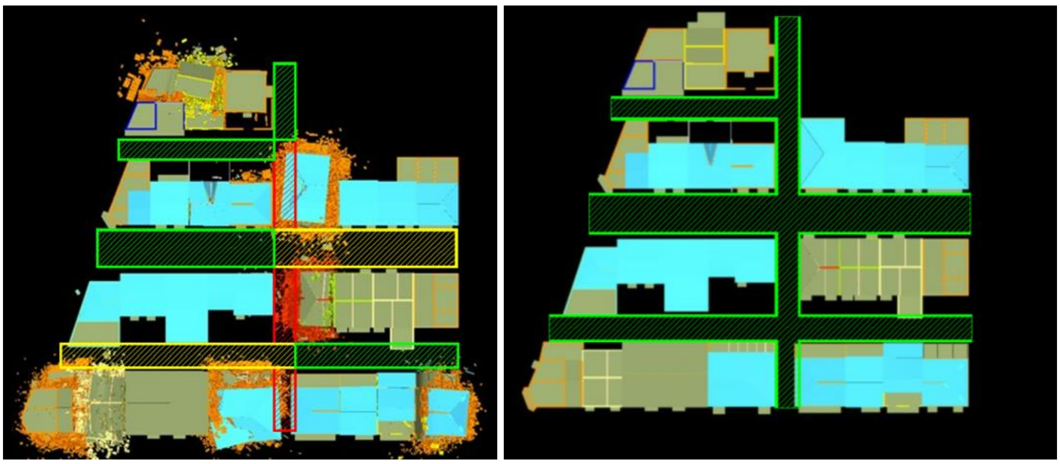


Fig. 17 – Detection of collapsed building and application of selective retrofitting actions.

8. Conclusion

The present work analysed the seismic behaviour of historic structures. A first assessment was carried out evaluating the seismic behaviour of different connections and structural details typical of historic structures.

Using AEM, such structural details were implemented without significantly increasing the size of the model Moreover, AEM analysis was shown to reliably represent actual collapse mechanisms, often observed in masonry and historic structures. Analysis at building level has shown how this computational technique can accurately reproduce the global seismic behaviour of historic structure.

The reduction in computational requirements provided by the AEM solver has allowed the performing of multiple time-history analyses, evaluating the performance of the structure at different levels of seismic loading. Finally, large-scale analyses of an entire city quarter are carried out within reasonable calculation time. The present work opens new challenges for computational techniques in the field of the large-scale seismic assessment, accounting for building interaction and allowing further assessment of road interruptions and safe entries for rescue operations.

7. References

[1] Grunwald C, Khalil A.A, Schaufelberger B, Ricciardi E. M, Pellecchia C, De Iuliis E, Riedel W (2018): Reliability of collapse simulation – Comparing Finite and Applied Element Method at different levels, *Engineering Structures* **176**, 265-278.

[2] Meguro K, Tagel-Din H (2000): Applied element method for structural analysis: theory and applications for linear materials. *Structural Engineering Earthquake Engineering JSCE*, **17** (2), 215-224.

[3] Meguro K, Tagel-Din H (2001): Applied Element Simulation of RC Structures under Cyclic Loading. *Journal of Structural Engineering ASCE*, **127** (11), 1295-1305.

[4] Meguro K, Tagel-Din H (2002): AEM Used for Large Displacement Structure Analysis. *Journal of Natural Disaster Science*, **24** (1), 25-34.

[5] Tagel-Din H, Rahman N (2004): Extreme loading: breaks through finite element barriers. *Structural Engineer*, **5** (6), 32–340.

[6] Malomo D, Pinho R, Penna A (2019). Applied Element Modelling of the Dynamic Response of a Full-Scale Clay Brick Masonry Building Specimen with Flexible Diaphragms. *International journal of Architectural Heritage*, DOI: 10.1080/15583058.2019.1616004.

[7] Applied Science International, LLC (2004): *Extreme Loading for Structures - Theoretical Manual*. ASI, 6th edition.

[8] Bach A, Younes B.Sc. A (2016): Detailed Description for Collapse Simulation - Historic Building, *Project Nr. 2014 7005 – INACHUS*, 7th framework programme.

