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DAMAGE PATTERN ANALYSIS OF THE BASILICA DI COLLEMAGGIO USING AEM MICRO-MODELING

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Abstract

This work focuses on the numerical analysis of the Aspe, Nave, and Transept of the 'Basilica di Collemaggio', which was seriously damaged and partially collapsed after the 2009 L'Aquila earthquake. The research team acquired the geometry of the structure through a terrestrial laser scanner. A detailed numerical model was developed using an Applied Element Method micro-modeling technique. The numerical model includes the actual arrangement of walls, arches, vaults, and voids in the masonry. The non-linear behavior of the masonry was modeled through equivalent springs. Non-linear dynamic analyses were performed considering both the in-plane and out-of-plane behavior of the structure. The proposed technique was able to simulate crack development and damage propagation. Comparing the numerical results to the acquired survey data, the model proved consistent and reliable. Therefore, this numerical approach could be used to study the behavior of the structure with different retrofit solutions.

Keywords: Applied Element Method, Collapse Analysis, Monumental Masonry Structures, Non-linear Dynamic Analysis, Seismic Damage Simulation.

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1 INTRODUCTION

The ‘Basilica Santa Maria di Collemaggio’ is a world-known medieval church located in L’Aquila, Italy. The original structure was built in 1270 and then modified and renovated over the centuries. However, despite previous retrofit interventions, the 2009 L’Aquila earthquake caused the partial collapse of the central vault and part of the transept.

Ancient masonry structures subject to seismic actions have been the objective of several studies [1] [2] [3]. The main challenge when dealing with type of structures lies in obtaining a reliable representation of structural behavior and damage propagation [4].

Different numerical methodologies, from simplified analytical procedures [5] to more complex dynamic methods [6], were developed to study the seismic vulnerability of existing masonry buildings. To limit computational resources, numerical models are often simplified or analyzed only in two dimensions [7]. Nonetheless, many masonry structures have irregular layouts, resulting in complex three-dimensional behavior under seismic action. In addition, the structural system of historical and ancient masonry buildings is typically the result of centuries of transformations, overlay of different structures, technologies, materials, construction techniques, and retrofitting strategies [8]. As a consequence of that, the seismic assessment of so complex structural systems is often considering conservative assumptions, both in terms of numerical representation of the seismic behavior and of the overall capacity of the structure [4].

As an example, the actual in-plane stiffness of complex shells and domes may be neglected, while assumptions are made on the rigid or flexible behavior of composite wood and reinforced concrete (RC) slabs. The actual stiffnesses of connections such as masonry-beams connections or dowel-type connections of wooden structures are often conservatively assumed as pinned or rigid connections and local failure mechanisms such as pull-out phenomena and out-of-plane mechanisms are often not considered in the overall seismic assessment of the structure [9].

The use of simplified methodologies and models, or analyses limited to the two-dimensional behavior, can lead to underestimating the seismic performance of the structure, which in turn results in a critical increase of seismic retrofitting actions, critical in the case of architectural heritage [10].

This work aims at developing a high-refined numerical model of the Apse, Nave, and Transept of the ‘Basilica di Collemaggio’, using the Applied Element Method (AEM) approach. The AEM has advantages both in terms of reduction of computational effort [11], and accuracy of the results [12]. A discrete micro-modeling approach was used, which allowed the representation of the actual behavior of each structural element, considering peculiar geometry arrangements, edge interlocks, the presence of transversal elements in the masonry, as well as different masonry patterns deriving from the overlay of different construction techniques over the centuries.

In particular, the nave arches and columns, the choir and apse vaults, and the transept ‘columns were detailed and reproduced considering the actual arrangement of the units. Next, nonlinear dynamic analyses were performed employing the nearest record of the 2009 L’Aquila earthquake. Finally, the derived damage state was compared with the actual crack distribution observed after the earthquake. It was observed that the crack patterns derived from the numerical analysis were in overall accordance with the actual damaged state of the Basilica.

2 NUMERICAL APPROACHES

In structural analysis, Finite Element Method (FEM) is the most common methodology adopted in the seismic assessment of the structure. Nevertheless, analysis of existing masonry structures would require employing 3D FEM elements to account for typical damage mechanisms in masonry, such as rocking phenomenal, shear slinging, or diagonal cracking. However, this may lead to a prohibitive computational time when dealing with a comprehensive numerical model of an entire complex structure such as Basilicas [11].

In addition, local collapse mechanisms, often among the primary sources of seismic damage for existing masonry structures, cannot be automatically accounted for in continuous numerical procedures. In fact, in FEM-based analysis, elements are connected at the nodes and two elements cannot displace independently. To reliably account for failure mechanisms, multiple node IDs need to be introduced in the model, increasing computational resources and the risk of stress singularity at the node separation.

Furthermore, to account for crack propagations and subsequent effects on the overall stiffness of the structure, special techniques need to be introduced in the analysis, such as the "smeared cracks" [13] or the "discrete crack" modeling [14]. However, both techniques require the assumption of locations and directions of cracks' propagation, which is not easily predictable in a complex 3D model of masonry structures.

Nevertheless, most of the research in existing masonry structures employed FEM seismic analysis [15]. However, the non-linear range behavior of the structure in a collapse simulation, considering damage propagation and local failures, is generally missing.

Thanks to the significant reduction of computational resources [11], advanced computational techniques, such as the Applied Element Method (AEM) [16], overcome these aspects by considering both in- and out-of-plane behavior of the masonry [17], and including the dynamic properties of the entire masonry structure within the non-linear time-history analysis.

3 MODEL OF MASONRY USING THE APPLIED ELEMENT METHOD

The AEM consists in discretizing the structure into relatively small rigid elements connected through zero-volume springs (Figure 1).

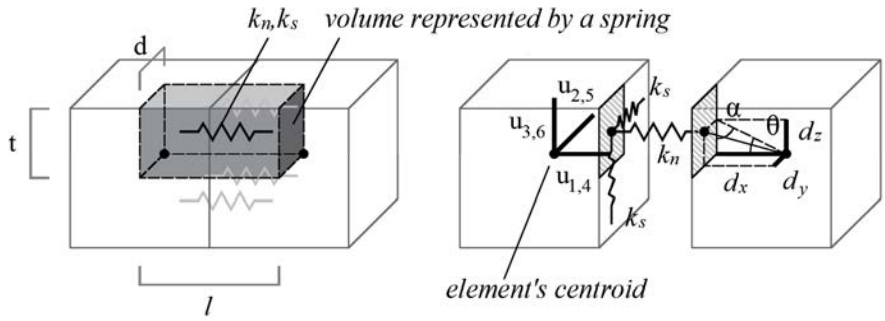

Figure 1: AEM analytic model

The most convenient approach, in the AEM framework, to the analysis of the existing masonry structure, is a micro-modeling approach considering the combined properties of unit and mortar.

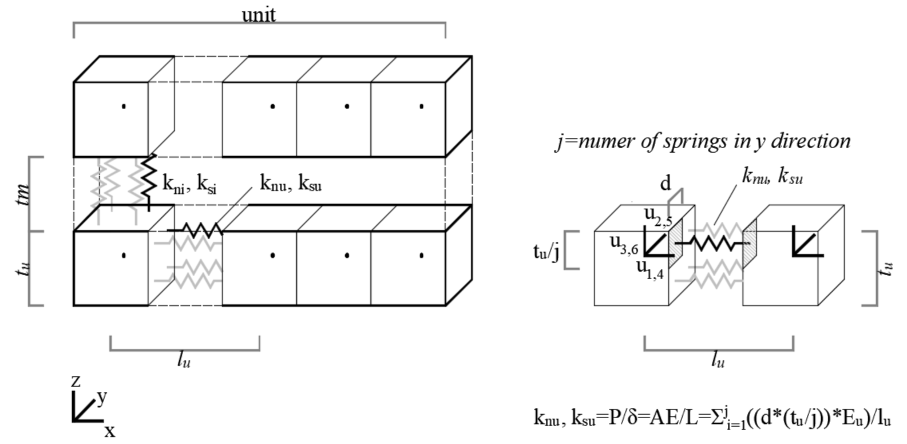

Figure 2: Springs employed in micro modeling of masonry (left) and stiffness of unit springs (right)

For springs connecting elements within the units, normal stiffness k_{nu} and shear stiffness k_{su} are determined according to (1).

$$k_{nu} = \frac{E_u \cdot d \cdot t_u/j}{l_u}$$
$$k_{su} = \frac{G_u \cdot d \cdot t_u/j}{l_u} \quad (1)$$

Where E_u and G_u represent the Young and Shear modulus of the unit, t_u the height of the unit, l_u the distance between the element's centerline and t_u/j and d respectively the length of the pertinent area of one spring in y and z directions, as per coordinate system reported in Figure 2. The unit behavior and cracks developing within units are defined using those springs. The behavior of the combined unit and interface mortar is represented using equivalent spring properties derived from the spring in-series formulation (Figure 3).

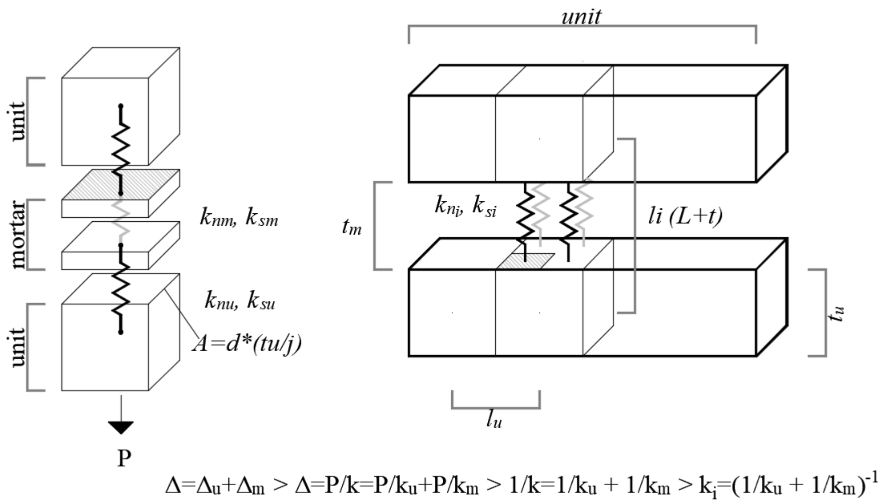

Figure 3: Equivalent springs representing unit-mortar interaction

The equivalent stiffness of the springs connecting two different units, respectively normal equivalent stiffness k_{ni}, and shear equivalent stiffness k_{si}, are derived as follows (2).

$$\frac{1}{k_{ni}} = \frac{l_i - t_m}{E_u \cdot d \cdot l_u/j} + \frac{t_m}{E_m \cdot d \cdot l_u/j};$$
$$\frac{1}{k_{si}} = \frac{l_i - t_m}{G_u \cdot d \cdot l_u/j} + \frac{t_m}{G_m \cdot d \cdot l_u/j} \tag{2}$$

Determining the stiffness of both unit and equivalent springs, the stiffness matrix for each set of springs is assembled formulating the geometrical relations between the centroid of each element and the contact point of the spring on the element surface.

4 NUMERICAL MODEL

The AEM numerical model of the Apse, Transept, and Nave was developed based on a laser scanner survey (Figure 4).

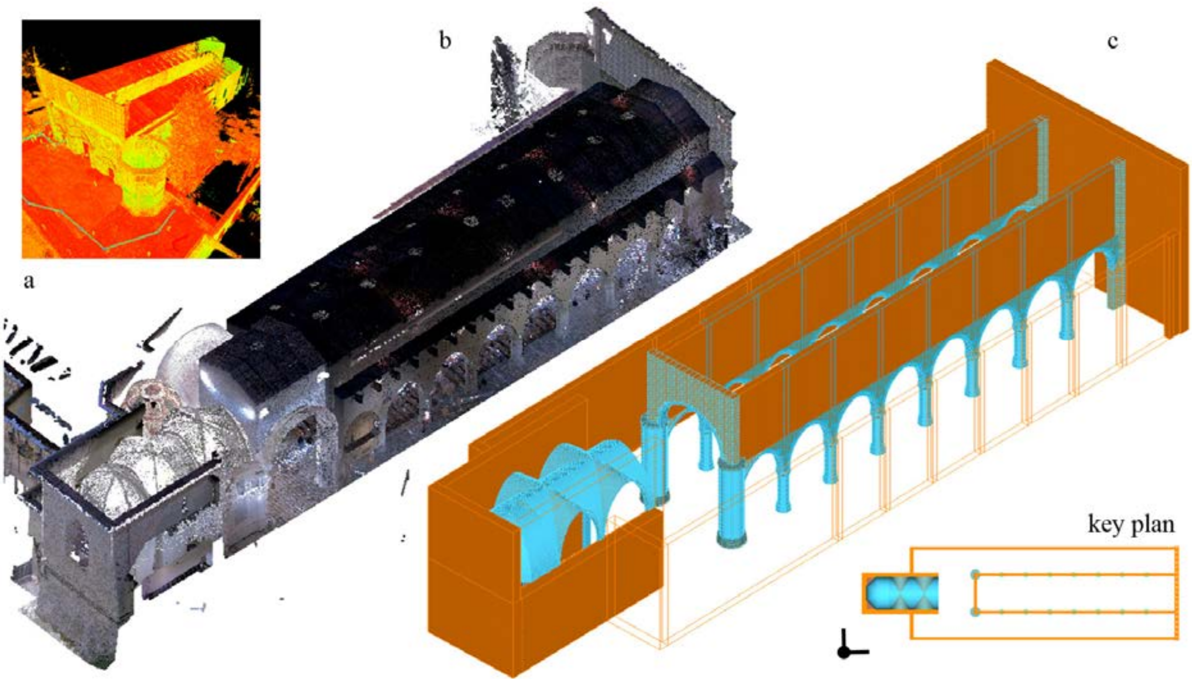

Figure 4: Laser scanner survey of the Basilica (a), processed point cloud (b), and developed numerical model (c)

The nave's columns and arches were modeled following the specific layout derived from the laser scanner survey, including the unit's arrangement and dimensions (

Figure 5).

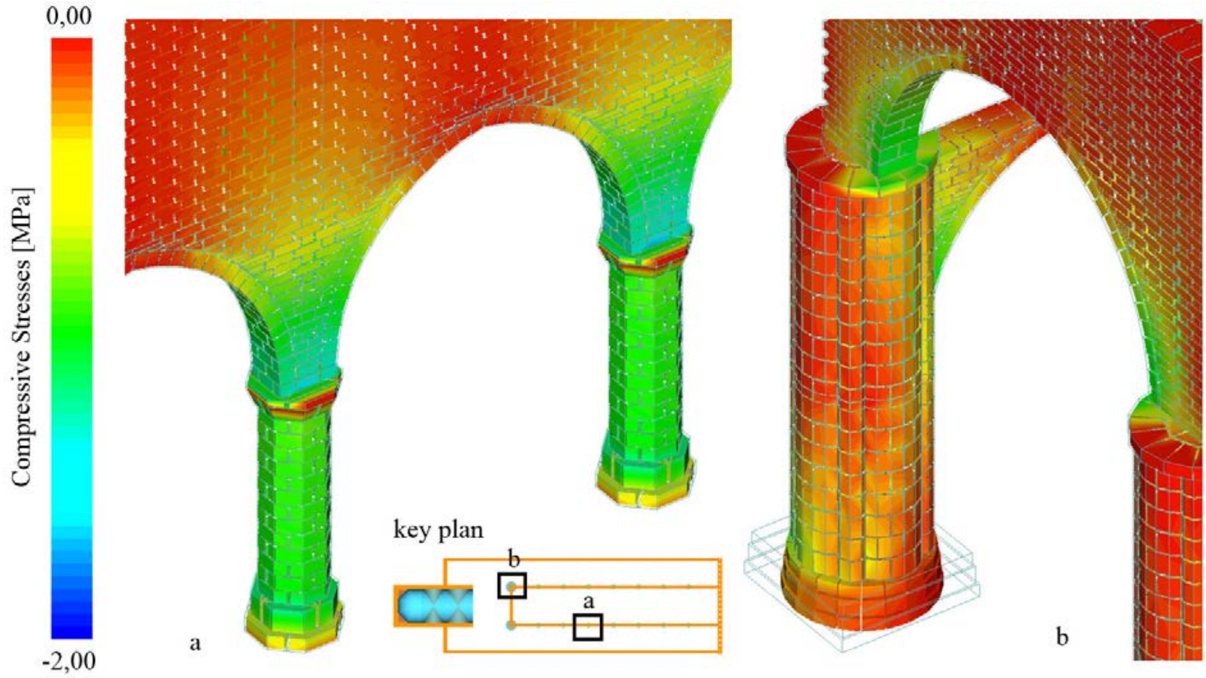

Figure 5: Distribution of compressive stresses in nave's (a) and transept (b) columns, dead load only

The choir and apse vaults were also reproduced based on the processed point cloud and considering the actual arrangement of units (Figure 6).

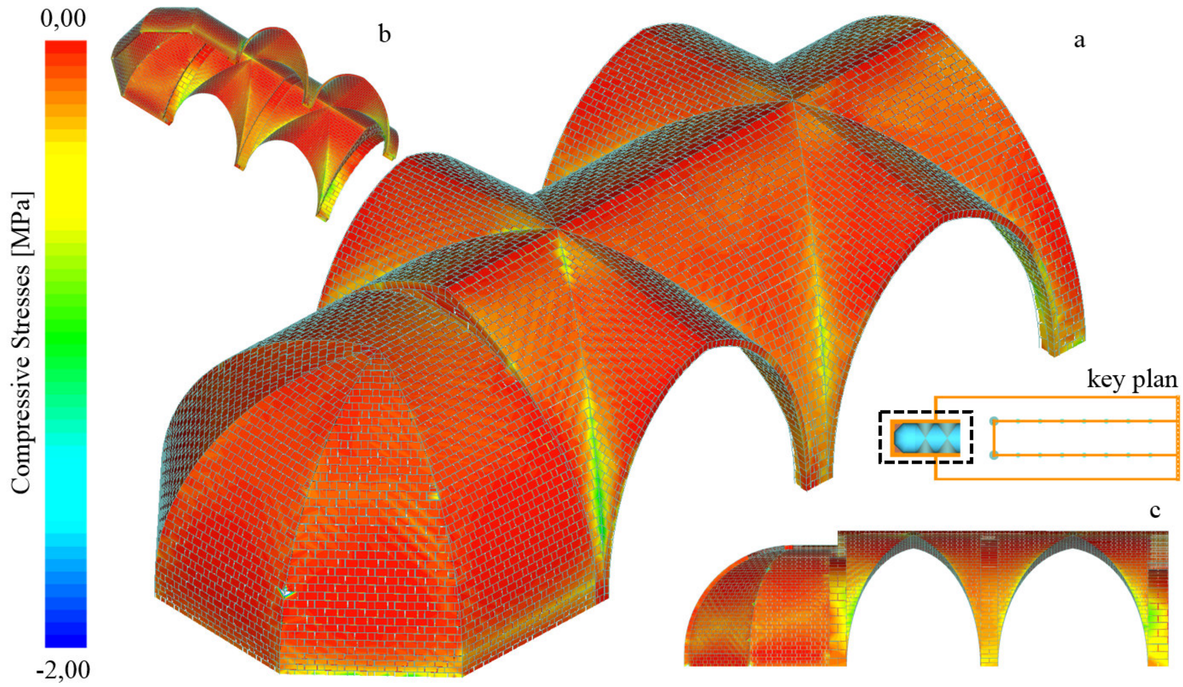

Figure 6: Distribution of compressive stresses in choir and apse's vaults; top (a), bottom (b) isometric view and side (c) view

The final numerical model consists of more than 130.000 units and 13.000.000 equivalent springs (5 x element face); non-linear time-history analysis performed the output of one second in approximately 1hour, using a 3.5GHz 6cores and 12threads processor and approximately 42Gb of RAM.

4.1 Material models

Two different masonry patterns were considered in the numerical model; the nave walls had one interlock unit for every two longitudinal units and the façade wall had inner voids and interlock units between the two unit layers (Figure 7).

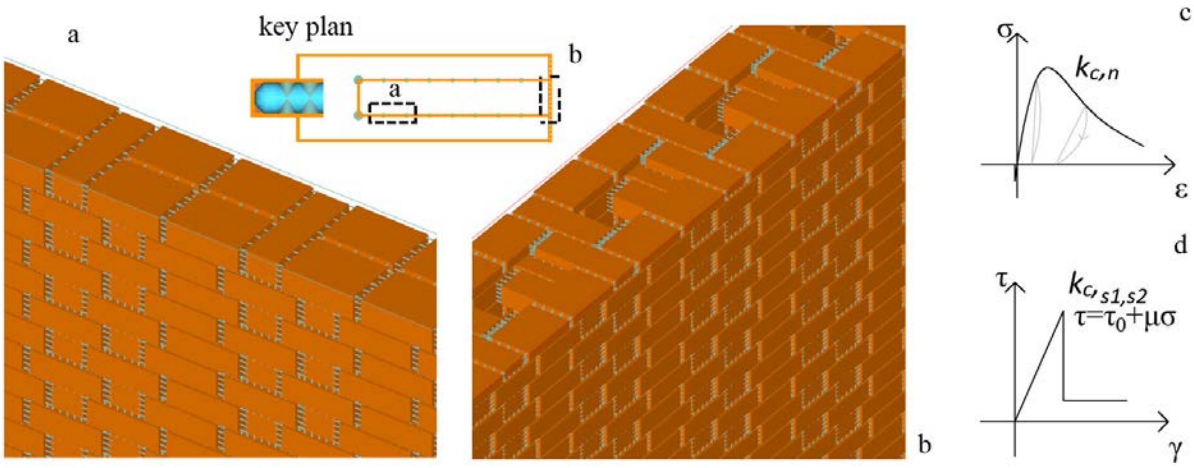

Figure 7: Masonry patterns considered in the nave walls (a) and in the façade wall (b) and related material models for axial (c) and shear (d) stresses

The Maekawa & Okamura model [18] is assumed for representing the axial behavior of the masonry subject to normal stresses (Figure 7, c), while the Mohr-Coulomb friction model is implemented for equivalent springs subject to shear (Figure 7, d).

Table 1 shows the assumed material properties for masonry.

fc [MPa]	τ_0 [MPa]	E [MPa]	G [MPa]	w [kg/m^3]
2.0	0.035	1230	410	2000

Table 1: Material properties of masonry [19].

5 NON-LINEAR DYNAMIC ANALYSIS

Non-linear dynamic analyses were carried out considering the nearest time history record of the 2009 L'Aquila Earthquake (L_Aquila IT-2009-0009 Station AQK, Data from ESM Database [20], Figure 8).

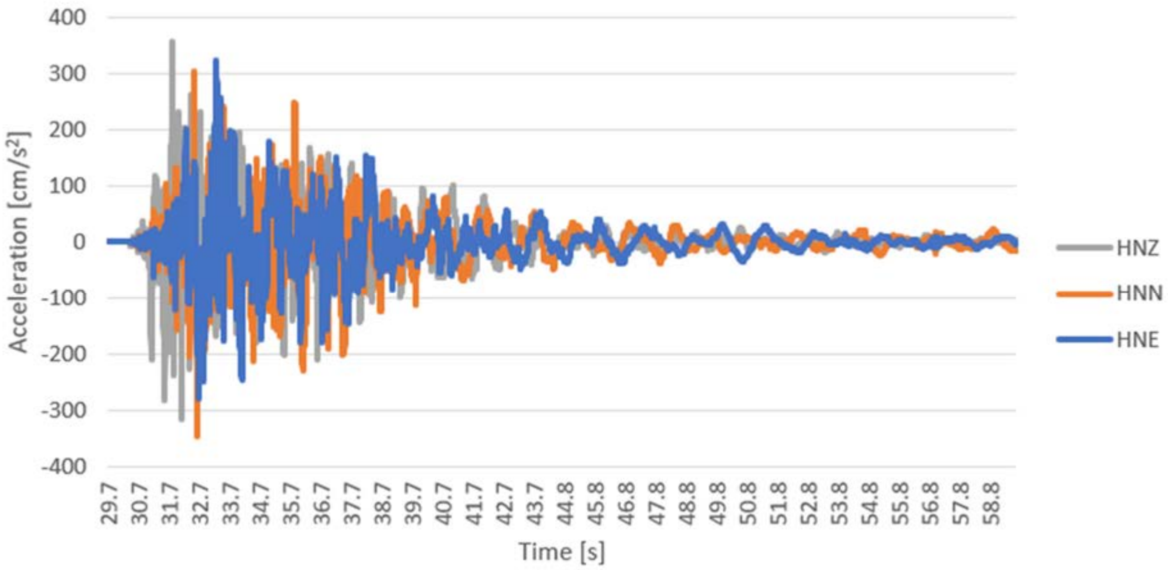

Figure 8: Ground motion at the nearest gauge to the Basilica di Collemaggio. Data from [20]

A comparison between the crack pattern derived from the numerical analysis and the actual distribution of cracks observed after the 2009 L'Aquila earthquake is depicted in Figure 9. It was observed that first principal strain of 0.02 is a good criterion to identify cracking in the masonry structure.

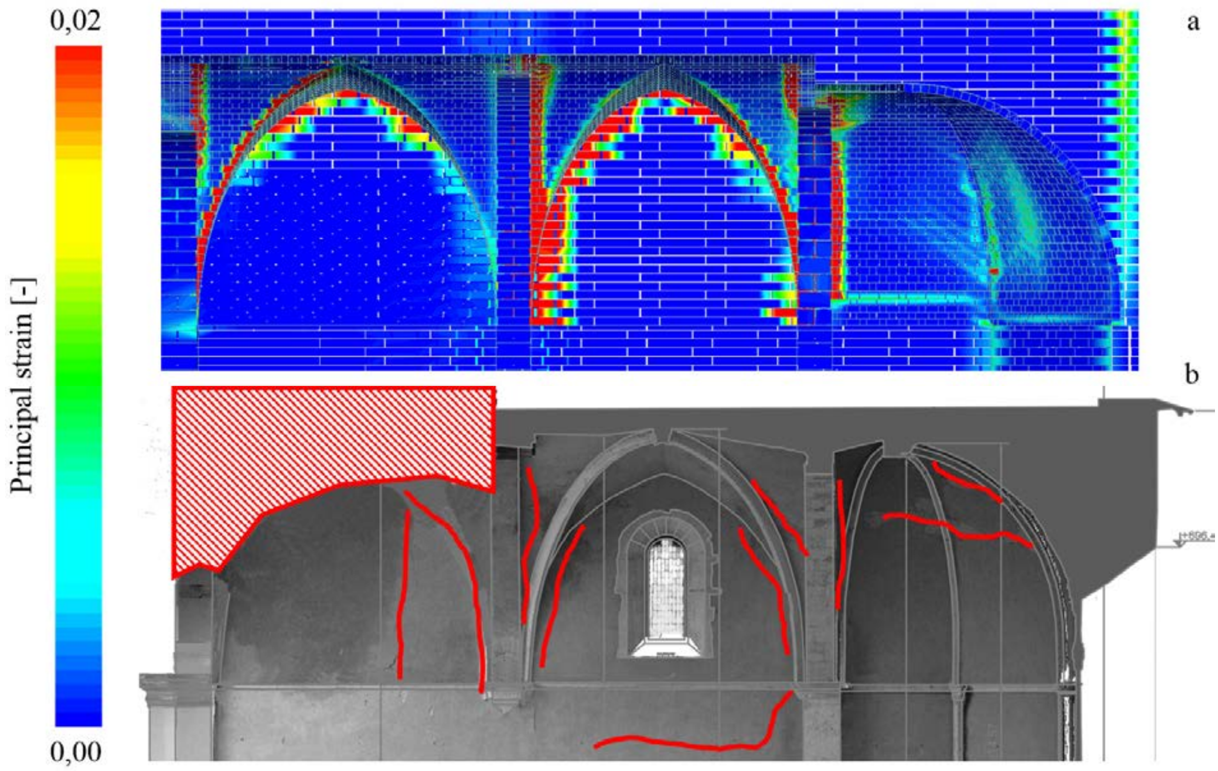

Figure 9: Comparison between the analysis results (a) and actual distribution of cracks observed after the 2009 L'Aquila earthquake (b); orthophoto reproduced with permission from [21]

The analysis results showed good accordance with the actual damage state observed after the shock, except for the collapse of the first of the choir's vault (Figure 10).

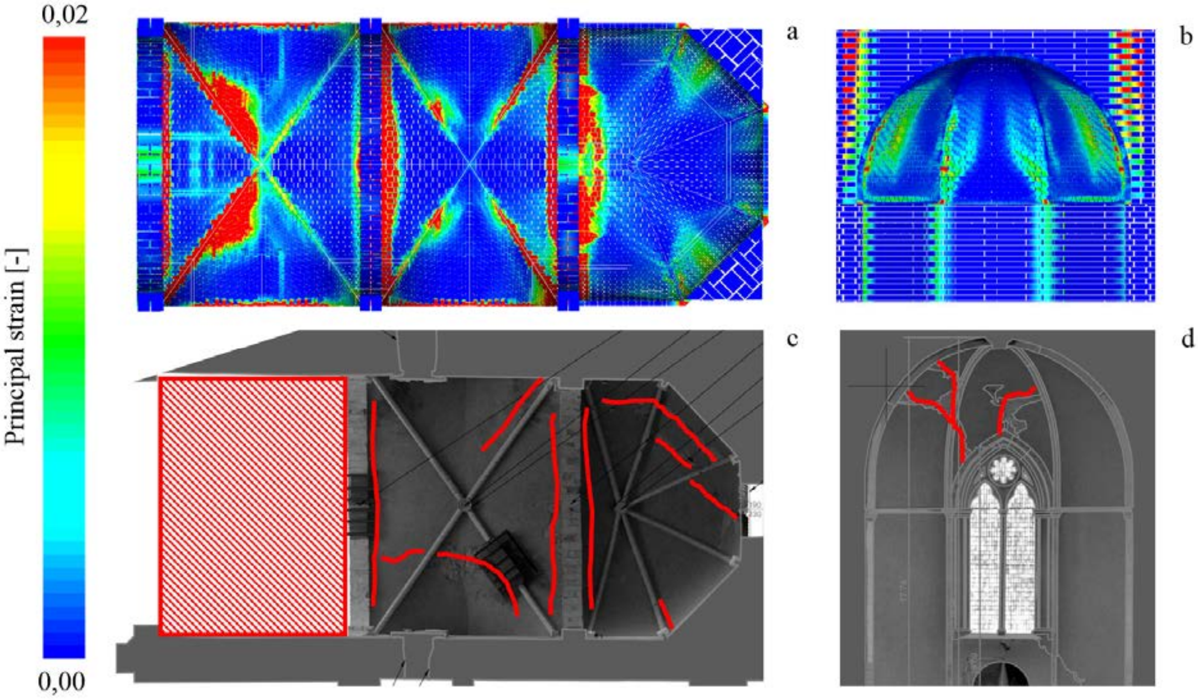

Figure 10: Comparison between the analysis results (bottom view, a, and side view, b) and actual distribution of cracks observed after the 2009 L'Aquila earthquake (bottom view, c, and side view, d); orthophoto reproduced with permission from [21]

However, it is worth noticing that the numerical model did not include the collapsed portion of the transept, which could have induced the subsequent collapse of the choir's vault.

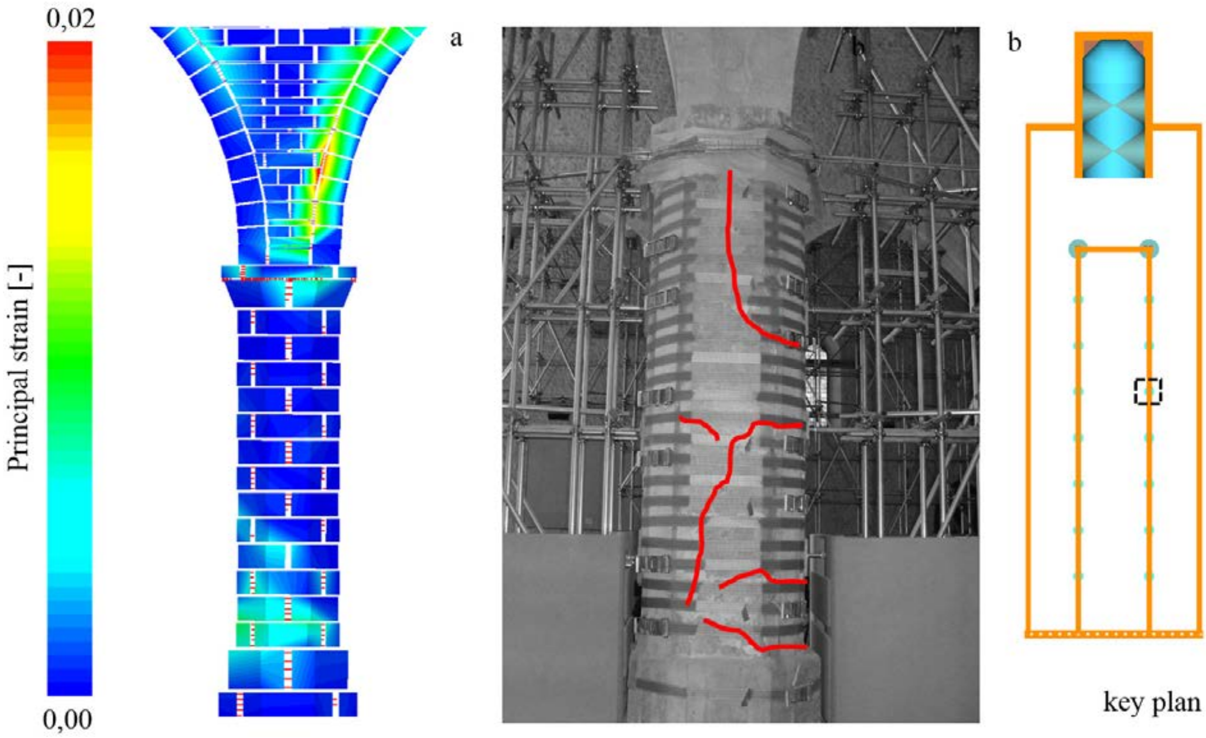

Figure 11: Comparison between the analysis results (a) and actual distribution of cracks observed after the 2009 L'Aquila earthquake (b) in one of the nave's columns.

Finally, a good accordance between the actual damage and the analysis results was also found in observing the springs in a crack state (Figure 11, a, red color) resulting from the analysis in comparison with the actual cracks in one of the nave's column (Figure 11, b).

6 CONCLUSIONS

Ancient masonry buildings, such as the Basilica Santa Maria di Collemaggio in L'Aquila, are complex structural systems, deriving from centuries of transformation and overlapping of different construction techniques. In seismic retrofit of these monumental buildings, the designer must strike a balance between the effectiveness of the retrofitting actions and the preservation of the architectural heritage. However, the assessment of the seismic performance of so complex structural system is often challenging and applying simplified procedures and numerical methodologies can lead to the overestimation of the retrofitting strategies.

While prohibitive in the past, a high-refined numerical model of entire monumental buildings is nowadays possible thanks to the advances in computational performance and the development of new computational methodologies. Among others, the Applied Element Method, AEM, has shown promising results in representing the seismic behavior of ancient masonry structures, while accounting for different masonry patterns, complex arrangements of masonry such as vaults and domes, and peculiar structural details. Automating cracks developments and damage propagation, the methodology can accurately account for local damage prevention and provide a reliable representation of the overall seismic performance of the structure.

In this work, a numerical model of the Basilica di Collemaggio was developed and analyzed using AEM micro-modeling technique that includes accurate geometry representation based on laser scanning as well as material properties for masonry blocks and mortar joints. Non-linear dynamic analysis carried out using one of the nearest recorded time-history has shown an overall damage state comparable with what was observed after the strike of the 2009 L'Aquila earthquake.

Future developments of the presented work are aiming at the complete definition of the numerical model, including the main dome, to simulate and compare the final collapse state of the Basilica.

After validating the final numerical model, different retrofitting solutions will be assessed and compared considering the effectiveness of the actual renovation carried out after the 2009 earthquake.

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