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SEISMIC ASSESSMENT OF A MASONRY CROSS-VAULT USING THE APPLIED ELEMENT METHOD

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Abstract

The evaluation of the seismic behavior of unreinforced masonry vaults is still an open challenge because of their complex geometries and bond patterns, the difficulty in defining the appropriate material properties and modelling strategies. In this study the LNEC-3D shaking table tests on full-scale masonry cross vault specimens being part of the SERA Project Blind Prediction are represented within a AEM software and assessed with dynamic analyses. The purpose of this post-prediction is the validation of the employed material characteristics and the modelling approach. The Applied Element Method is based on the mechanical interaction between rigid bodies and zero-thickness nonlinear interface springs. Only the unreinforced specimens has been assessed. The masonry material has been modeled by a simplified version of the elasto-plastic fracture model for simulating the cyclic cumulative damage of masonry elements subjected to uniaxial compression; the hysteretic constitutive law that governs the cyclic response of shear springs is based on a Mohr-Coulomb yielding criterion, where cohesion is set to zero right after reaching the maximum shear strength. A great correspondence between the results of the dynamic nonlinear analyses and the experimental results has been achieved, highlighting the importance of the selected brick pattern and material model.

Keywords: Masonry, Masonry Vaults, Applied Element Method, Nonlinear Time History Analysis, Shaking-table Tests.

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1 INTRODUCTION

Masonry has been used as primary construction method for thousands of years across different cultures and regions. From ancient civilizations such as Egyptians, Romans, and Greeks to modern construction, masonry is a versatile and widely adopted technique.

When dealing with historical buildings, one of the most employed horizontal elements is represented by masonry vaults, whose static and seismic assessment is crucial for cultural heritage preservation and safety for human life. Certainly, vault's vulnerability with respect to seismic action has been proved by systematic post-earthquake damage surveys, highlighting the complexity of their behavior. As reported in [1], the collection of seismic damages built by the Italian government shows that considering palaces and churches, seven out of twenty-eight failure mechanisms are referred to arches and vaults. [2].

The scientific community has been putting a lot of effort in studying how masonry vaults behave when horizontal actions are considered, but still, this represents an open challenge which requires historical investigation, literature review, inspections, structural modelling and numerical analyses [3]. As a matter of fact, [4] have highlighted that few researchers have worked on masonry vaults since 1960. The very first shaking table test on a scaled model was performed in 2012 [5], and the first 1:1 scaled vaults was tested on a shake-table in 2020 [6].

Hence the interest of simulating the LNEC-3D shaking table tests on full-scale masonry cross vault specimens being part of the SERA Project Blind Prediction [7], with the aim of validating the employed numerical modelling strategy, the Applied Element Method (AEM), considering that structural modelling plays a significant role in evaluating the realistic response of the structure.

The experimental campaign, on which the blind prediction is based, was conducted on a full-scale masonry cross-vault, first on an unstrengthened configuration and then on a retrofitted, with textile reinforced mortar (TRM), one.

In this work, first axial compression tests on wallet are reproduced to define material properties as input; secondly, dynamic properties of the specimen are calibrated according to natural frequencies and mode shapes [8]; once the main modeling parameters are defined, sensitivity analyses are then performed on shear resistance and ultimate strain parameters to simulate the actual behavior of the specimens tested; and finally, results for unstrengthened case are reported.

2 THE APPLIED ELEMENT METHOD FOR MODELLING MASONRY VAULTS

The AEM, originally conceived by [9], identifies the structural systems composed of discrete elements, modelled as single unit rigid bodies which only has the mass and the damping of the system. The mechanical properties of the connection between each adjacent unit such as unit-mortar properties in case of masonry structures are defined by uniformly distributed zero-thickness interface springs considering simplified micro-modelling approach [10]. These springs simulate the non-linear dynamic behavior of the materials they represent, up to the breaking of the bonds. Subsequently, the separation between the rigid bodies occurs and the bodies move and can collide according to the laws of bodies in space.

The discretization of each masonry element vertically and horizontally, as shown in Figure 1 a), allows to observe the unit failure.

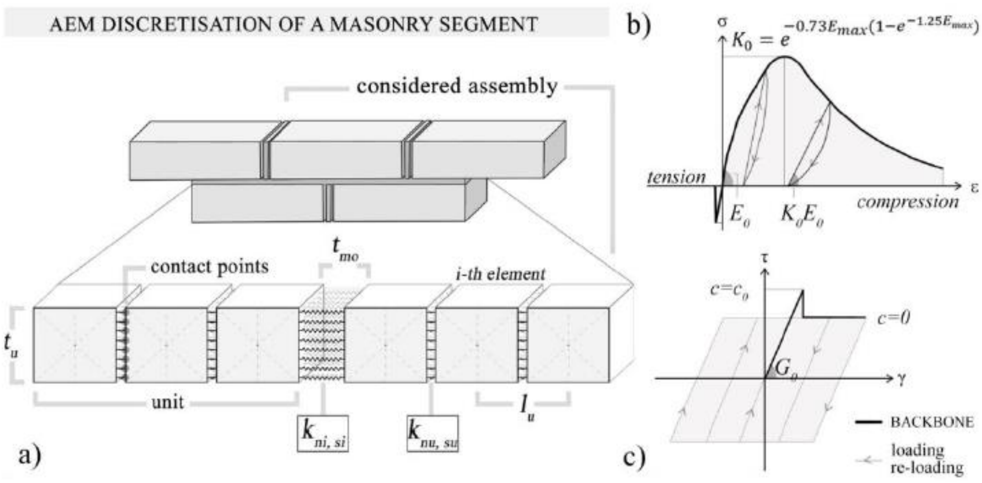


Figure 1: Three-dimensional discretization of a masonry segment according to the AEM (a), interface springs constitutive laws under normal (b) and shear (c) cyclic loading [11].

The software *Extreme Loading for Structures* (ELS) which is based on the discrete element method AEM has been utilized to construct the structural model of the cross-vault and assess its seismic performance by using a set of unidirectional Non-Linear Time History Analysis (NLTHA).

In ELS, the cyclic cumulative damage of masonry elements subjected to uniaxial compression is simulated by a simplified version elasto-plastic fracture model proposed in [12] Figure 1 b) and a bilinear law with linear softening up to ultimate strain is employed for the tensile behavior.

For what concerns the cyclic response of the interface springs under shear, the hysteretic constitutive law maintains a Mohr-Coulomb yielding criterion with zero cohesion immediately after attaining the maximum shear strength Figure 1 c).

Eventually, local failures of each spring lead to strength stiffness degradation of the whole component and related cracking progress up to overall loss of connection when all given interface springs are failed (i.e., zero stiffness).

Through the studies, it is observed that the response of the masonry components loaded by in-plane actions are represented adequately by the use of AEM (e.g., [13], [14], [15]). Likewise, out-of-plane response under different loading schemes as quasi-static by [16] and [17], dynamic as blast loading by [18] and shake-table motions by [19] are also captured successfully.

The numerical models of historical large-scale buildings are also constructed using AEM (e.g., [20] and [21]) for the sake of seismic assessment and these models are supported by some recent shake-table responses of reduced and full-scale prototype structures, showing good agreement ([22], [23], [11]).

3 BRIEF DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

The experimental campaign of shake-table tests on a full-scale unreinforced masonry cross-vault is deeply described in [8] and herein briefly summarized.

The tests took place at *Laboratorio Naciónal de Engenharia Civil* (LNEC), Portugal, in 2021 with the aim of better understanding the seismic behavior of masonry cross-vaults and to evaluate the power of different modelling and analysis methods to predict the response of masonry vaulted structures subjected to seismic events. The specimens tested were three: a 1:5 scale model consisting 3D-printed blocks with dry joints; a 1:1 scale model of an unreinforced masonry cross-vault; a 1:1 scale model retrofitted with textile reinforced mortar. In this paper, only the full-scale unstrengthened model has been considered.

3.1 Geometrical and material properties

The geometrical configuration of the specimen tested is shown in Figure 2. It consists of a square plan 3.5 m x 3.5 m, a net span equal to 2.9 m, a rise of 1.2 m and a thickness of 0.12 m. Brick unit dimensions are 45 x 120 x 230 mmm with mortar joint 10 mm thick. The Western edge of the vault is attached to two fixed masonry piers, properly confined with steel profiles, and the Eastern one is free to move along both horizontal directions standing on steel masses with wheels. The four piers are all connected with 2xϕ32 rebars with rod ends to prevent torsional effects.

The material properties derived from tests on masonry wallets (axial and diagonal compression tests on wallets and shear tests on triplets) are resumed in Table 1.

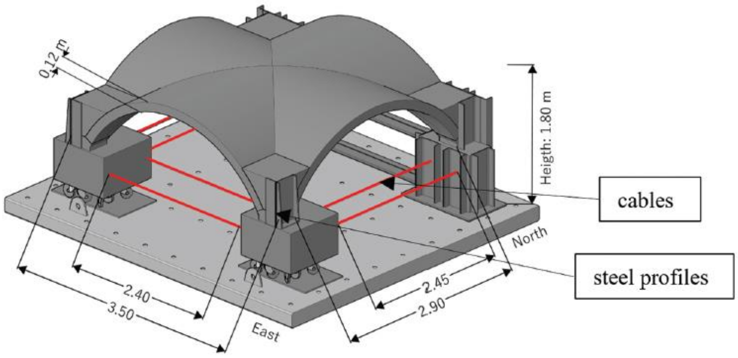


Figure 2: Geometrical model of the full-scale specimen [7].

Density [kg/m^3]	Young's Modulus [MPa]	Shear Modulus [MPa]	Friction Coefficient [rad]	Tensile Strength [MPa]	Compressive Strength [MPa]	Shear Strength [MPa]	Cohesion [MPa]
2255.2	2223.0	762.0	0.785	0.31	9.1	0.46	0.031

Table 1: Summary of masonry mechanical properties

3.2 Instrumental setup and input definition

The instrumental setup consists of displacement transducers, load cells and piezoelectric accelerometers used for recording the response during both seismic and dynamic identification tests; its configuration is shown in Figure 3.

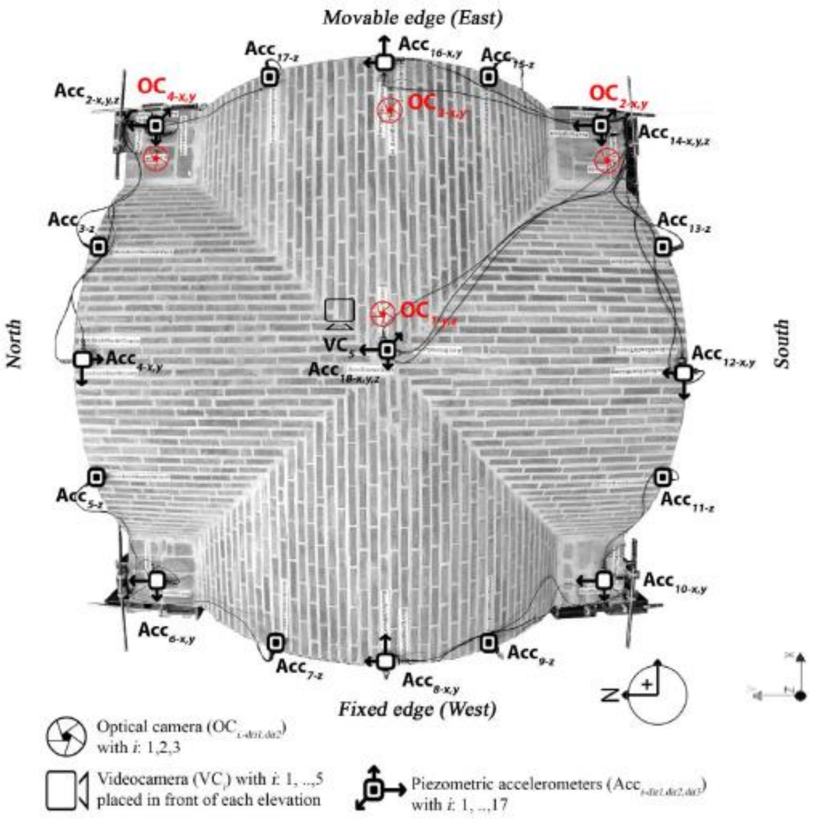


Figure 3: Instrumental setup of the unstrengthened specimen [7]

The seismic input adopted for both unstrengthened and strengthened specimens is the record of L’Aquila earthquake, occurred on the 6th of April 2009 (also known as AQA). The acceleration time series used corresponds to the North-South component, applied to the longitudinal direction of the specimen (i.e. Y axis, North-South direction).

The tests consisted of several sequences of seismic simulations, summarized in Table 2, with increasing step of amplitude in order to account for damage accumulation. Dynamic identification tests were performed at the beginning of the campaign and between each step to evaluate changes in vibration frequencies as the damage increases. Results of the first identification test, i.e. undamaged model, are shown in Figure 4.

	% AQA Earthquake						
Unstrength-end specimen	10%	25%	50%	75%	**Repairing and Strenghten-ing**		
Strengthened specimen		25%	50%	75%	100%	125%	150%

Table 2: Summary of the sequential seismic tests

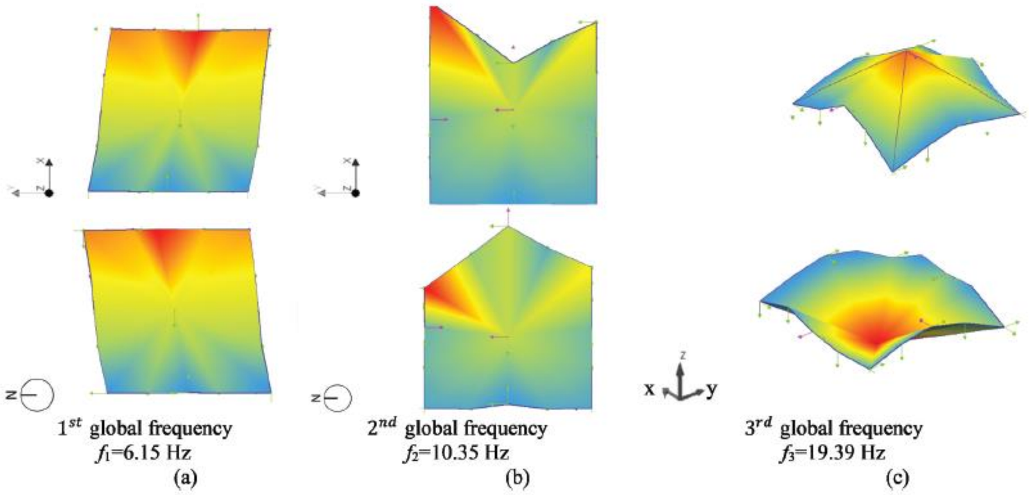


Figure 4: Natural frequencies and mode shapes of the unstrengthened specimen: (a) first global longitudinal mode; (b) second global transverse mode; (c) third global vertical mode [7]

4 NUMERICAL MODELLING

The experimental campaign briefly described above has been used to validate the numerical modeling strategy adopted in this work, which basically consists in a simplified micro-modeling approach, as discussed in chapter 2. The geometry has been built starting from AutoCAD drawings provided in the blind prediction, tying to reproduce the actual brick pattern of the cross-vault, as shown in Figure 5, by making use of 8-node hexahedron elements. The size of the vaults brick is equal to the size of the actual brick plus the thickness of mortar joint (10 mm), which is considered as a zero-length joint. Masonry has been modeled as an equivalent homogeneous material, whose mechanical properties are the ones reported in Table 1.

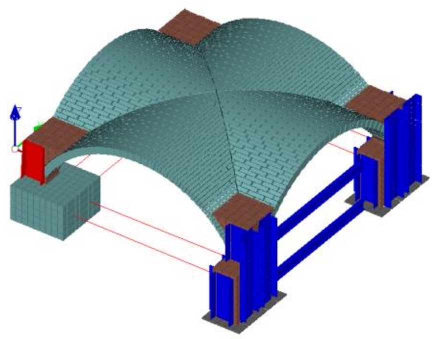


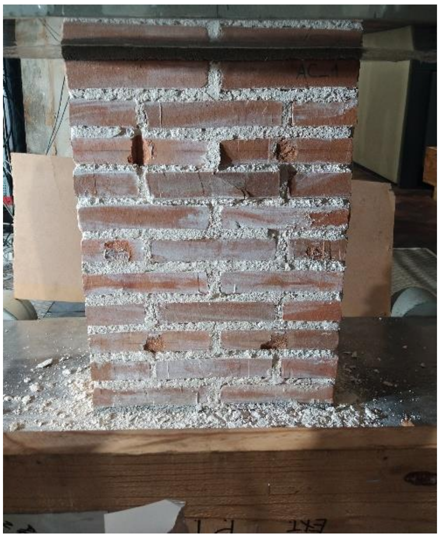
Figure 5: Numerical models developed within Extreme Loading for Structures software unstrengthened specimen.

5 PRELIMINARY VALIDATION OF THE NUMERICAL MODEL

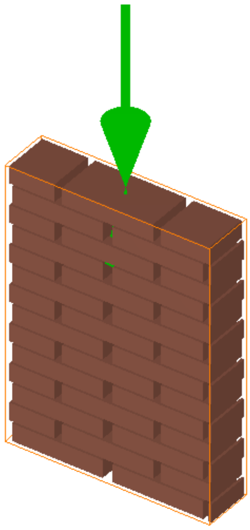
A preliminary validation of the numerical modeling strategy has been assessed by simulating axial compression (AC) tests on wallets and performing an eigenvalue analysis, herein discussed.

5.1 Simulation of AC tests

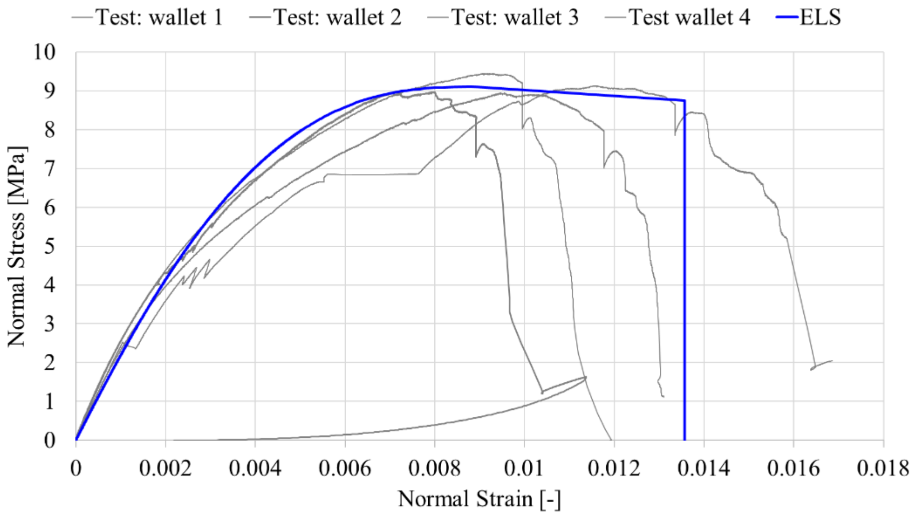
The main goal of this step in the modeling sequence is to confirm the material characterization within ELS software. The material model used is the one discussed in chapter 2, which is the Concrete Model in ELS. This simulation, carried out by imposing the vertical axial load with a constat velocity of 0.003 mm/s, has confirmed all the significant variables: stiffness, maximum compressive strength and post-peak strength degradation.



(a)



(b)

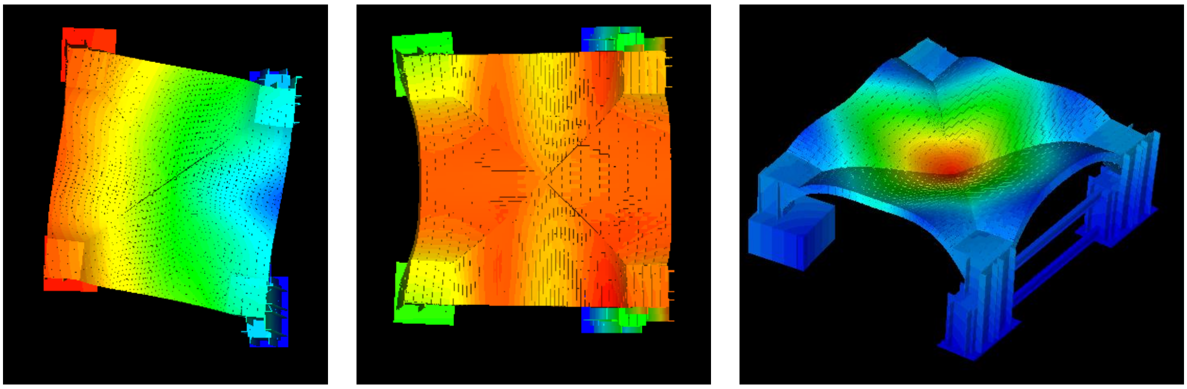


(c)

Figure 6: Simulation of the AC tests: (a) one of the four tested wallets; (b) numerical model of the wallet in ELS; (c) comparison between stress-strain curves obtained from tests and numerical modeling in ELS.

5.2 Eigenvalue analysis results

An eigenvalue analysis has been performed in order to evaluate the global dynamic behavior of the numerical model; its results, illustrated in Figure 7, have been compared with the ones obtained from the very first dynamic identification test (i.e., undamaged unstrengthened specimen) shown in Figure 4. The comparison of results is summarized in Table 3, showing a difference of 3% between test and numerical model as regards the first global mode, which is the longitudinal one (i.e., along the direction the signal has been applied).



$f_1 = 5.98$ Hz (a) $f_2 = 14.83$ Hz (b) $f_3 = 24.67$ Hz (c)

Figure 7: Comparison between axial compression results obtained from tests and numerical modeling in ELS.

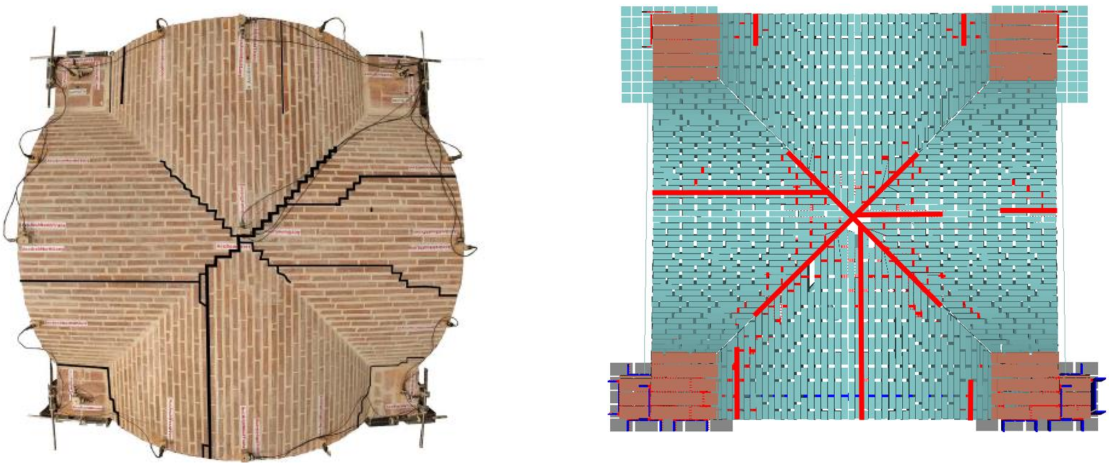
	Natural frequency [Hz]		
	$\mathbf{f_1}$	$\mathbf{f_2}$	$\mathbf{f_3}$
Dynamic identification test	6.15	11.62	19.39
Numerical model ELS	5.98	14.83	24.67
Difference	3%	28%	27%

Table 3: Comparison of natural frequencies of the undamaged specimen obtained from the first dynamic identification test and eigenvalue analysis of the numerical model within ELS: (a) first global longitudinal mode; (b) second global transverse mode ; (c) third global vertical mode.

6 NONLINEAR TIME HISTORY ANALYSES RESULTS

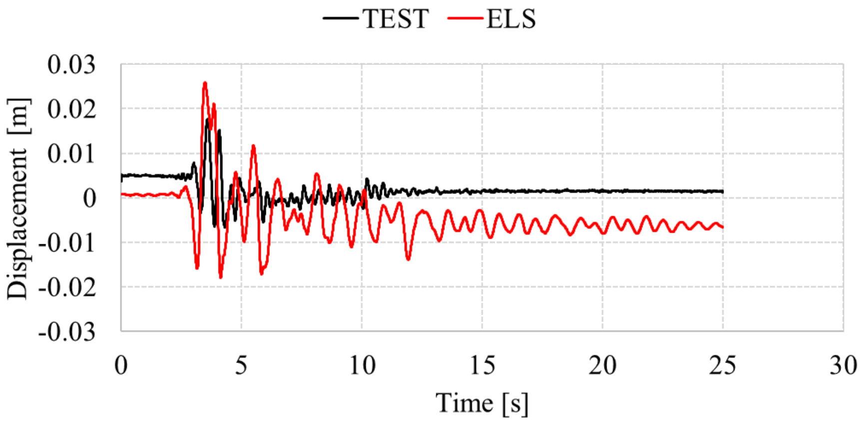
In this section the main results of the sequence of the NLTHAs are shown, focusing on damage pattern and displacement and peak acceleration responses.

The crack pattern illustrated in Figure 8 shows that numerical results are consistent to the experimental ones; the most evident correspondence is achieved for cracks along the diagonal joints, typical for in-plane shear mechanism. The hinge formation along the nails is also well caught. Discrepancies on the displacement responses are present, as shown in Figure 9, with a difference variation from 16% to 39%; on the contrary, the acceleration time series recorded during numerical simulation are more consistent, with a difference variation from 1% to 35%.

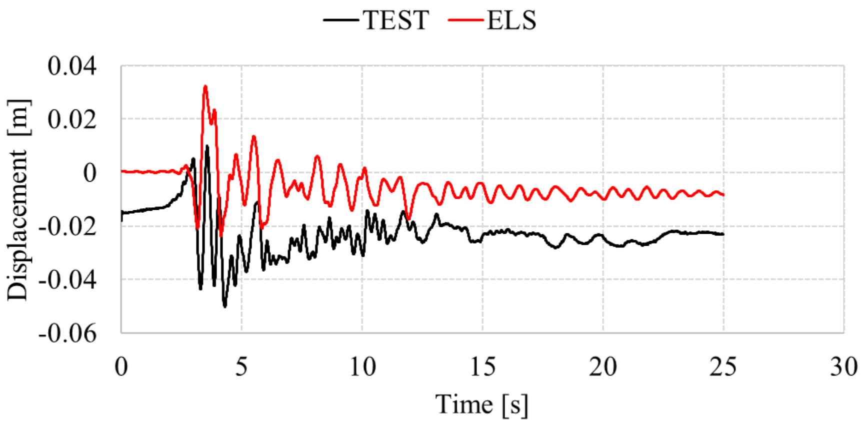


(a) (b)

Figure 8: Comparison of experimental [7] (a) and numerical (b) crack patterns at the end of 75% of AQA signal.

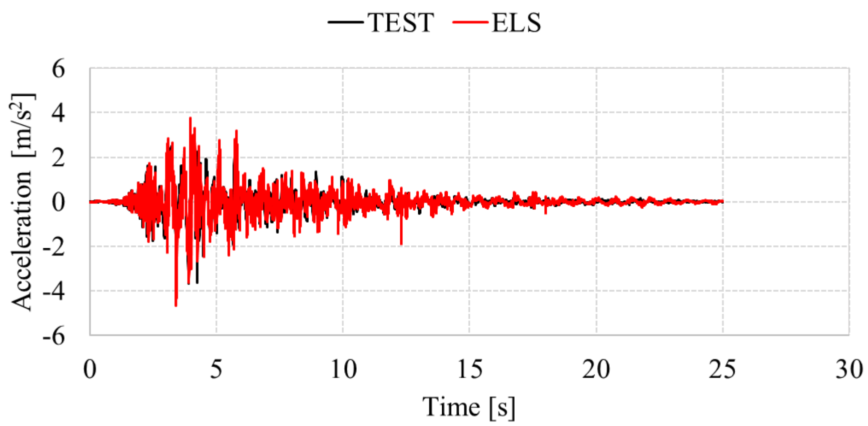


OC1-y

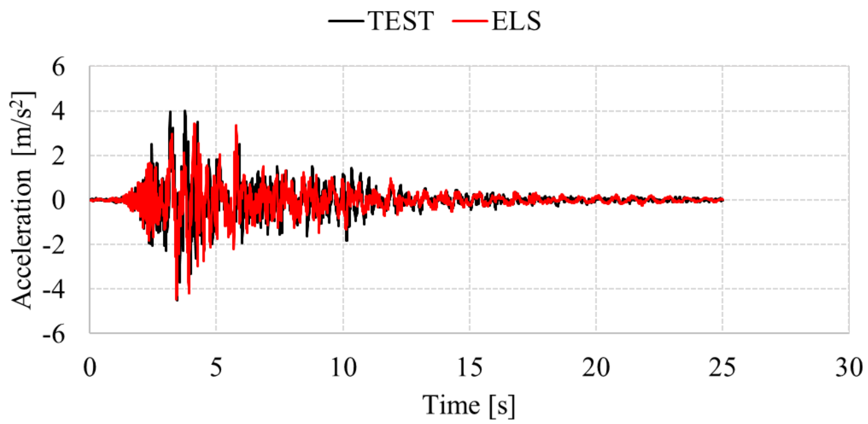


OC2-y

Figure 9: Comparison of experimental and numerical displacement responses related to the 75% of AQA signal.



OC1-y



OC2-y

Figure 10: Comparison of experimental and numerical acceleration responses related to the 75% of AQA signal.

7 CONCLUSIONS

In this work, a series of Nonlinear Time History Analyses has been carried out reproducing the shaking table tests of a brick masonry cross-vault. Preliminary analysis, static and dynamic, have shown that the AEM is able to reproduce both mechanical and dynamic properties of masonry cross-vault, which are consistent with those obtained from experimental tests. The adopted modeling strategy allows the analyst to study the behavior of the vault from the initial elastic range up to severe damage, with the possibility to evaluate how cracks are evolving during the analyses. NLTHA results have highlighted the great correspondence with the experimental seismic tests, showing that the in-plane shear mechanism is predominant, even though a few discrepancies are still present. The overall results may be summarized as follow:

- A good agreement has been reached comparing the natural frequency and the first shape mode of AEM model and tests results, showing that this methodology is capable to reproduce the dynamic characteristics of the specimen;
- For the unstrengthened specimen, the damage pattern is well caught from the numerical analysis as well as the acceleration recorded at measure points, with a relative error range from 1% to 35%. The displacement time series differ more than the acceleration with a higher average error up to 39%.

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