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Effects of earthquakes with different nature on the seismic performance of masonry vaults

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Abstract

Past seismic events showed that earthquakes can cause severe damages in masonry vaulted structures, which can lead to significant damage, including fatalities, and heritage and economic losses. Although seismic guidelines suggest the implementation of specific modern strengthening techniques to prevent those seismic losses, many masonry vaulted structures are unreinforced and they are one of the most vulnerable structural elements in monumental buildings, such as churches and palaces. Thus, the present paper focuses on the seismic performance of a numerical model, which simulates an experimental reduced-scale dry-joints vault, through the nonlinear dynamic analysis, by applying several earthquakes of different nature. The numerical model was built based on the discrete element method, where it is possible to simulate the detailed geometrical properties: the interlocking between the blocks, the cuts along the diagonals, the offset of the units and the boundary conditions. Moreover, the model was calibrated based on results obtained from shake table tests. The results of this sensitivity analysis, obtained from the different inputs, are compared in terms of damage patterns.

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Keywords: Groin vault; earthquake; discrete element method; nonlinear analysis.

1. Introduction

Masonry vaults represents one of the most widespread horizontal structural elements in historical buildings. Systematic post-earthquake damage surveys in churches and historical constructions have proved the vulnerability of vaults towards dynamic actions. Although understanding the 3D seismic behaviour of vaults is of primary importance for preserving our cultural heritage, the research in this field is still limited. Most of the works in

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literature were focused on the 2D analysis of vaults modelled as a sequence of arches, under both static and dynamic actions. Few researchers analysed the 3D behaviour of vaults by simulating seismic actions as differential displacements applied to supports using both numerical and experimental approaches (Block, Ciblac, and Ochsendorf 2006; Milani and Tralli 2012; Torres et al. 2019). The main aim of this paper is to investigate the seismic behaviour of a groin vault with asymmetric boundary conditions: a typical configuration found for instance in vaults covering the lateral aisles of the churches or the cloisters of palaces.

During seismic events, especially when the action is mainly acting along the longitudinal direction, the lower stiffness of the central nave's colonnade, compared to the external walls can lead to differential displacements along the longitudinal direction and, consequently, to the development of a shear damage mechanism in the horizontal structural elements (Fig. 1). This failure is mainly identified by typical diagonal crack occurrence, as shown in Fig. 1 (a) that is recurrently observed during post-earthquake surveys. This is due to the lower stiffness of the central nave's colonnade compared to the external walls can lead to differential displacements along the longitudinal direction and, consequently, the development of a shear damage mechanism in the horizontal structural elements (Bianchini et al. 2019).

This paper describes the numerical simulations which followed a wide experimental campaign on 1:5 scale model of a groin vault (Fig. 1b) tested on the shaking table at the LNEC (National Laboratory for Civil Engineering, Lisbon, Portugal) within SERA-(Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe) Transnational Access Project. The shake table tests' results are compared with the numerical results of the nonlinear time history analysis, build in DEM environment, where the in-plane shear response of the small-scale model was investigated by applying differential displacements on the abutments. During the shake table tests, the response of the mock-ups was evaluated as function of an increasing intensity earthquake testing protocol, in which an artificial pre-processed strong ground motion designed for Emilia Romagna region was used.

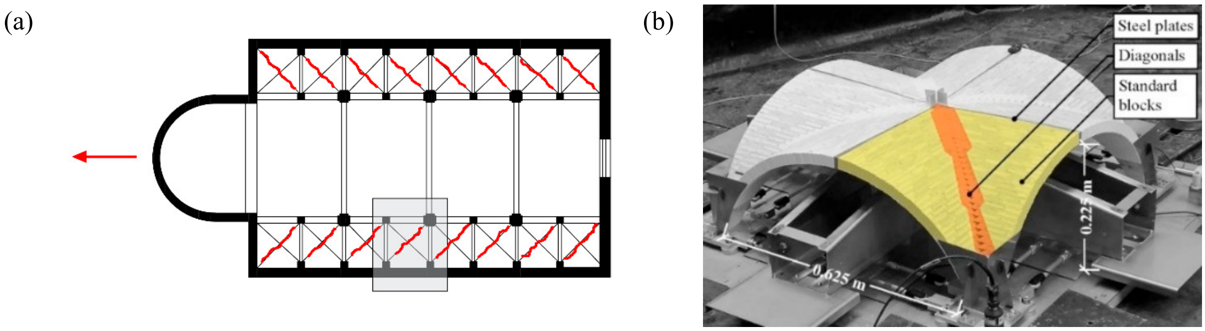

Fig. 1. Plan view of the three-naves church (a) in red the typical shear failure of the lateral nave vaults (Bianchini et al. 2019), (b) 1:5 scale model vault at the end of the construction.

2. Experimental testing

2.1. Setup and modal parameters

The characteristics of the scaled mock-up used in the experimental tests are here summarized (Rossi, Calderini, and Lagomarsino 2016; Milani et al. 2016; Bianchini et al. 2022). The geometry of the mock-up is a low-rise single-leaf dry joints groin vault with a square base, a span l of 0.625 m and a rise r of 0.225 m. The block thickness t_b is approximately 0.012 m, the width w_b is 0.024 m, while the length lb is variable. The pattern is radial (Fig. 1b) and the diagonals are made by special blocks with complex stereometry. Finally, the abutments of the vault are made with single larger blocks, shaped to be fixed on aluminium bases and accommodate the base blocks of each cap.

The blocks were produced through 3D printing technology, made of vinyl polymer and carbohydrate plastic powder. The standard blocks (in yellow in Fig. 1b) have a cavity on their upper side, where a steel plate is inserted to increase the weight. The blocks along the diagonals (in orange in Fig. 1b) do not have the cavity and the steel insertion and thus they are fully made of plastic. In particular, the mean homogenized density ρ of standard blocks with the metal insertion is 2.70 ± 0.05 g/cm^3, while for the diagonals is 0.55 ± 0.02 g/cm^3. The Young's modulus E was measured by compression tests on masonry pillars constituted by six standard blocks and its mean value was equal to 123.00 MPa, while the mean friction coefficient μ between blocks is equal to 0.56, corresponding to the friction angle of 29.60° ± 2.50°, measured through tilting table tests.

The main aim of the experimental research, which are here numerically simulated, was to investigate the seismic response of masonry cross vaults under shaking table tests (STT), inducing the pure shear failure (Fig. 1a), which very often occurs in churches and palaces during seismic actions (Bianchini et al. 2022).

To reproduce this mechanism, boundary conditions and the setup during the SST were designed as here described (Fig. 2). First, the abutments of the vault are fixed on aluminium bases linked together by means of couples of aluminium bars with rod ends and hollow section with internal and external radius of 8 and 10 mm, respectively. In this way, the distance between the abutments cannot vary and their rotation along the vertical axis is prevented.

Two piers of the vault are fixed to the steel base ($p_1 - p_2$), while the other two piers ($p_3 - p_4$) are free in the horizontal plane. Thanks to the shaking table, the vault is subjected to horizontal accelerations applied at its base along the North-South direction. Due to the tiny dimensions of the test specimen, specific instrumentation was also implemented; namely one linear variable displacement transducer ($LDVT_1$) located at the N-W corner; six piezoelectric accelerometers (Acc_{1x}, Acc_{1y}, Acc_{1z}, Acc_{2x}, Acc_{2y}, Acc_{2z} in Fig. 2) were placed at the bottom of the vault to measure the response of the fixed plated, while five variable capacitance unidirectional accelerometers (Acc_{3y}, Acc_{4x}, Acc_{5z}, Acc_{6x}, Acc_{7y}) were placed on the vault. Moreover, two optical cameras were used to record the response of the key of the western arch and the movable piers using automatic tracking, respectively, along the plane xy (OP_{1xy}) and yz (OP_{2yz}).

Two video cameras were used to record the tests: one exactly at the top of the test specimen, using scaffolding, and another located in front of the East elevation on a tripod outside of the shake table.

Modal parameters were be obtained through dynamic identification tests: the first natural frequency of the mock-up was obtained equal to 4.00 Hz, corresponding to a shear behaviour mode shape.

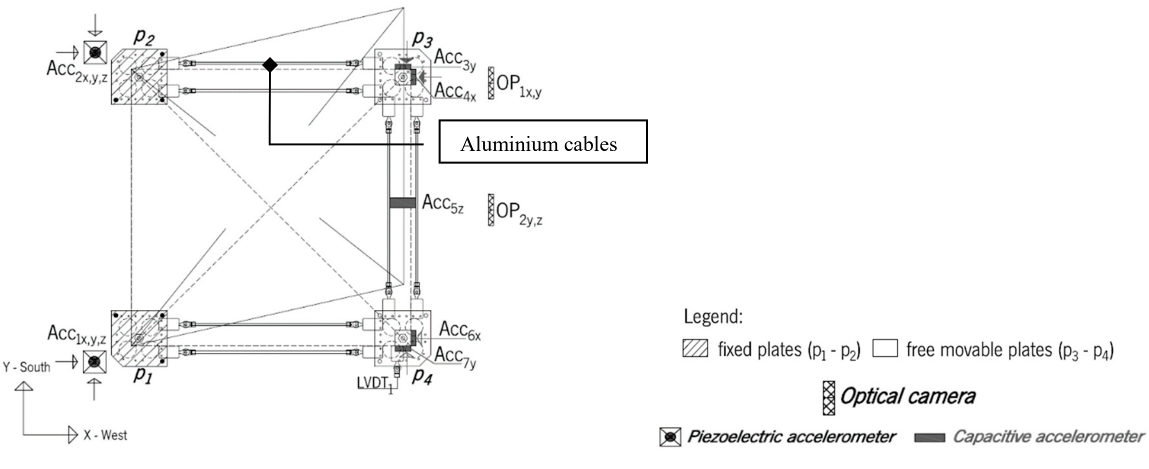

Fig. 2. Setup of the experimental campaign to reproduce the shear failure with corresponding instrumentation (Bianchini et al. 2022).

2.2. Seismic results

Regarding the ground motion, during the experimental campaign, an artificial seismic input was selected to be applied in the shaking table tests and it was properly scaled according to the Cauchy-Froude similitude law, linked to the scale effect, for a total duration of 8.93 s (Bianchini et al. 2022). This artificial input is compatible with the elastic response spectrum defined in the Italian Code (Ministero delle Infrastrutture e Trasporti 2018b, 2018a), for the municipality of Mirandola (Italy) and rock type of soil, location of the Emilia 2012 earthquake's epicentre.

It is stressed that only the longitudinal component (North-South direction) was examined, which corresponds to the y direction of the mock-up (Fig. 2), aiming at inducing the shear failure on the mock-up. The testing sequence of the vault is presented in Table 1, while the time history of the accelerations, velocities and displacements are shown in Fig. 3.

Table 1. List of shaking table tests carried out on the reduced scale vault (chronological order). *Value of first frequency obtained after the seismic shaking table tests.

Input		Column B (t)
% of action		Frequency [Hz] *
50 %		4.00
75 %	→	4.00
100 %		3.90
125 %		3.71
150 %		3.35

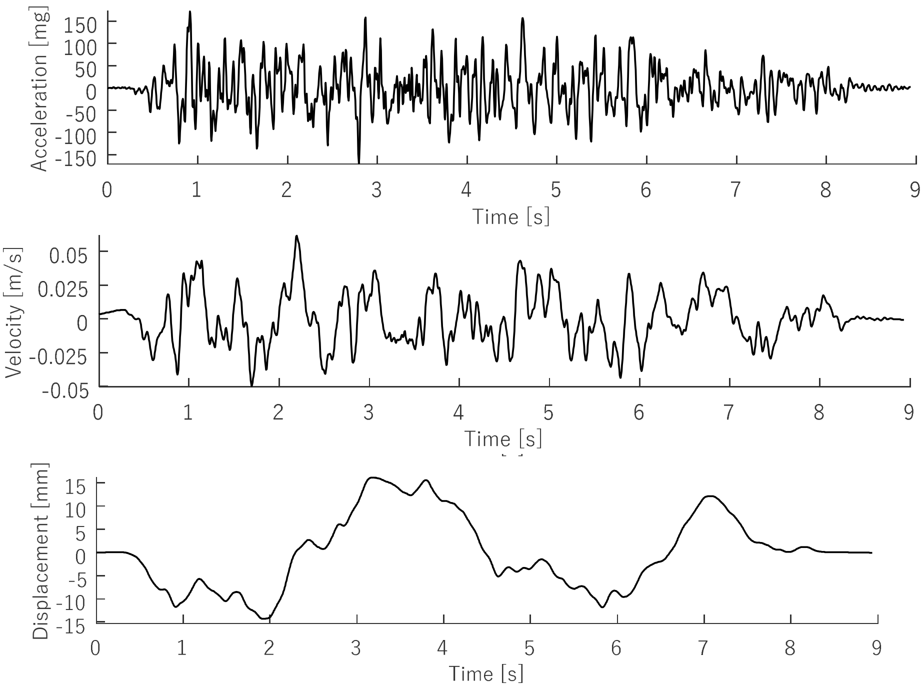

Fig. 3. Time histories of accelerations velocities and displacements measured at the shaking table's level.

3. Discrete element model

The typology of the mock-up and the multiple test conditions allows to assess the performance of a DEM model (Fig. 4) in 3DEC 5.2 environment (Itasca Consulting Group 2016), in terms of collapse mechanism, displacement capacity, and computational effort, reproducing the sequence of the shaking table tests and investigating the response by applying very different earthquakes.

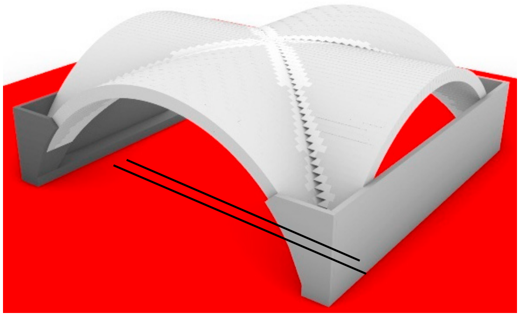

Fig. 4. Geometry of the simulated groin vault: 3DEC 5.2 model (in red the block that simulates a rigid base).

The DEM rigid block model assumes that deformations and nonlinear behaviour are lumped at the joints; this means that the displacement capacity of the structure is controlled by the contact stiffnesses and contact inelastic parameters, namely cohesion (c) and friction angle (θ).

Between the steel plate and the solid of the shaking table, and only under the movable piers (p_3 and p_4), a very low shear stiffness and shear capacity joint was applied (K_s=2.0e0 KN/m^3, friction angle θ =2.0°), allowing movement along the horizontal directions to recreate the required shear behaviour. On the other hand, under the fixed piers, the steel plate is completely connected to the shaking table through a perfect connection. The aluminium cables have been inserted to reproduce the tie-rods and to induce the pure shear behaviour. For those cables, Young's modulus E_c=69 GPa was adopted, based on their technical specifications.

The natural frequency of the first mode shape associated with the shear behaviour, obtained through dynamic identification tests was used to calibrate the numerical model by performing eigenvalue analysis. The modal analysis results showcase a first numerical frequency equal to 4.10 Hz, presenting an error equal to 2.5% in comparison with the experimental results. This value was got with a normal stiffness and shear stiffness equal to K_n=3.5e05 KN/m^3 and K_s=1.50e05 KN/m^3, respectively, (respectively 0.35 MPa/mm and 0.15 MPa/mm), assuming K_s=0.4×Kn (Ptaszkowska and Oliveira 2014). Regarding the dilatancy angle ψ, according to Angelillo et al. (2014), a zero value is recommended and it was adopted. Table 2 summarizes the final material properties adopted in DEM and FEM models.

Table 2. Linear elastic properties of the blocks (units) and mechanical properties for the joints.

	Young's modulus [MPa]		Poisson's ratio [-]		Specific mass [kg/m3]
Standard blocks	123.0		0.20		2700.0
Diagonal blocks	2.50		0.20		550.0
Steel elements	210.0e+06		0.30		7800.0
Aluminium cables	69.0e+06		0.30		2700.0
	Normal stiffness Kn	Shear stiffness Ks	Friction angle μ	Dilatancy angle ψ	Cohesion
Joints	3.50e+05	1.50e+05	0.57	0	0.00

3.1. Setup and modal parameters

Several time history analyses were conducted using Incremental Dynamic Analysis (IDA), following the experimental tests sequence (Table 1), and finally analysed according to qualitative (damage and failure mechanism). However, only the set of amplitude 150% was selected in this section. As it is possible to observe from Fig. 5, the fall of the central blocks of the key of the vault is meticulously replicated by DEM model, mainly due to the verticality of the joints, which is accentuated at the top of the vault.

Another important aspect, which underlines the quality of the results obtained by DEM model, is the evolution of the damage that occurs during the analysis: the fall of the blocks coincides in terms of location and time with the experiments. In addition, close to the steel plate corners, concentrations of sliding of the blocks are notable.

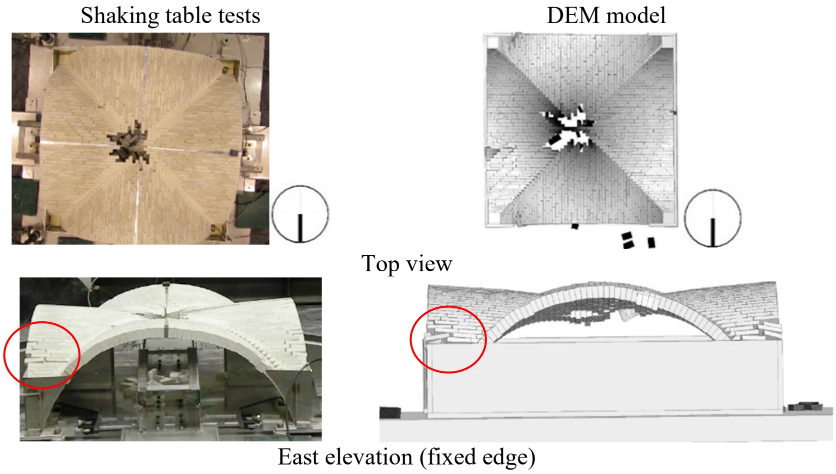

Fig. 5. DEM deformed shapes compared with the experimental results at the end of 150% seismic sequence.

4. Natural ground motion influence

For sake of completeness, as suggested by Guide for the Probabilistic Assessment of the Seismic Safety of Existing Buildings (CNR national research council of Italy 2014), while considering historic structures it is fundamental to investigate the seismic behaviour taking into consideration different set of inputs, especially impulsive ones. Thus, in this section a probabilistic analysis was conducted in order to identify a set of ground motions within 40 different earthquakes, recorded all over the world between 1935 and 2017. The purpose of this additional research is to investigate if the collapse mechanism of the model and the seismic parameters at the collapse change, based on the content of different ground motions. For each ground motion, a series of ground motion parameters were selected and then collected according to a normalised bell distribution.

Those parameters are: the effective duration of the earthquake, Arias Intensity, root mean square of the accelerations (RMSA), of the velocities (RMSV) and displacements (RMSD), the specific input energy (IEs), the Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), development length of a velocity (LDV) and the Impulsivity Index (IP). All of them were normalised based on the PGA and the time step was properly scaled according to the Cauchy similitude law. Thus, six ground motions were then chosen (Fig. 6), selecting the most recurrent inputs belonging to three specific ranges of the normalised bell distributions. Those ranges are identified as follows: lower bound (0; μ-σ), central range (μ-ε; μ+ε), upper bound (μ+σ;1) with μ equal to the mean value, σ the standard deviation and ε standard error.

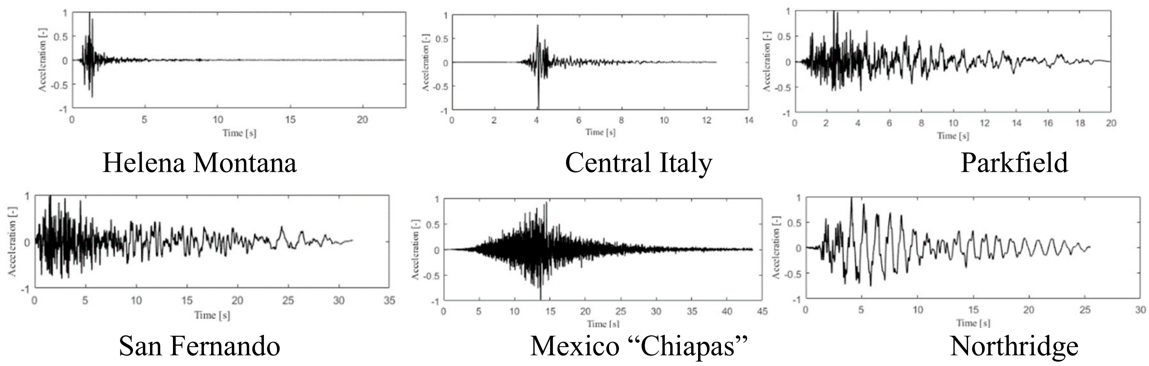

Fig. 6. List of the selected ground motion for the nonlinear time history analyses

For each seismic event, several incremental dynamic analyses were conducted in order to obtain the collapse of the model. From Table 3 is it possible to observe the variety of PGA, PGV and PGD at the level of the collapse.

Table 3. Ground motion parameters at the collapse of the selected inputs.

Event name	Range	Collapse PGA [m/s^2]	Collapse PGV [m/s]	Collapse PGD [mm]	Type of collapse
Helena Montana	Lower	7.50	0.28	28.81	
Central Italy	Lower	7.00	0.36	12.01	
Parkfield	Central	1.50	0.18	45.96	4 hinges along the fixed edge side (East)
Mexico “Chiapas”	Upper	2.50	0.26	206.48	
San Fernando	Central	1.25	0.30	225.98	
Northridge	Upper	1.00	0.12	22.27	
μ		7.07	0.25	90.25	
σ		6.40	0.09	98.40	
ε		2.61	0.04	40.17	

As it is possible to highlight the PGV scatter is the more stable with lower values of σ and ε. However, beside the differences in terms of ground motion contents, the collapse of the model still showcases the failure of the fixed edge (East elevation) due to the formation of the four hinges, as it was observed during the experimental campaign (Fig. 7).

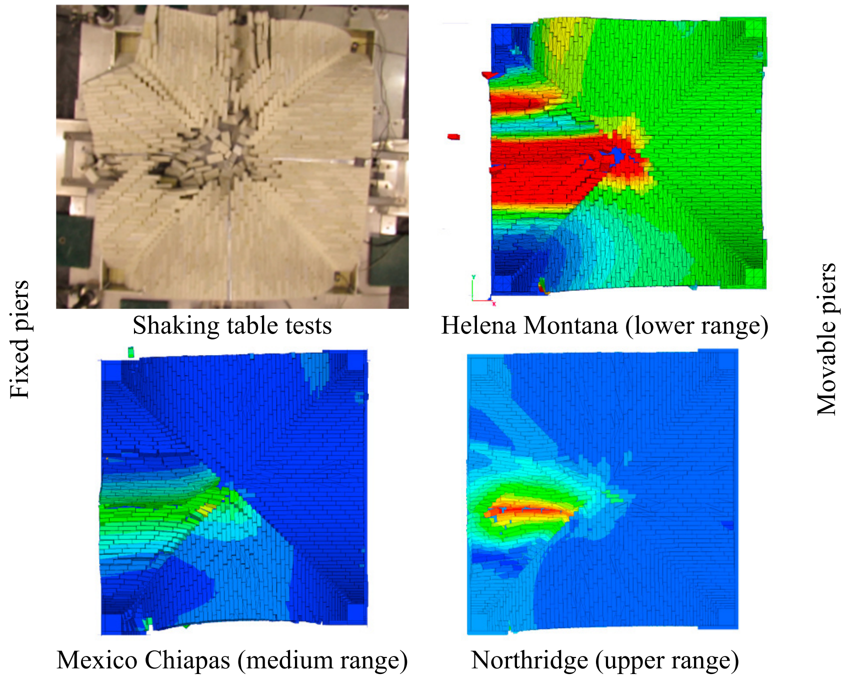

Fig. 7. Deformed shapes before the collapse of three selected earthquakes.

5. Conclusions

This paper presents the numerical simulation developed through DEM approach to simulate an experimental campaign on the shake table tests and a sensitivity analysis with six different ground motions, representing a step forward on the modelling of vaulted structures under dynamic conditions.

The main conclusions are summarised as follows:

- DEM model is generally capable of reproducing the large displacements and replicate the collapse mechanism observed during the shaking table tests;
- DEM model reproduces well the loading history and its corresponding damage in the mock-up during time;
- Different ground motions cause a similar damage mechanism, happening for different values of PGA and PGD;
- PGV values are more representative of the collapse and generally coherent between the several ground motions.

References

Angelillo, Maurizio, Paulo B. Lourenço, and Gabriele Milani. 2014. Masonry Behaviour and Modelling. CISM International Centre for Mechanical Sciences, Courses and Lectures 551: 1–26. https://doi.org/10.1007/978-3-7091-1774-3_1.

Bianchini, Nicoletta, Nuno Mendes, Paulo Xavier Candeias, Chiara Calderini, Michela Rossi, and Paulo B. Lourenço. 2022. Seismic Response of a Small-Scale Masonry Groin Vault : Experimental Investigation by Performing Quasi-Static and Shake Table Tests. Bulletin of Earthquake Engineering, 1–23. https://doi.org/10.1007/s10518-021-01280-0.

Bianchini, Nicoletta, Nuno Mendes, Paulo B. Lourenço, Chiara Calderini, and Michela Rossi. 2019. Seismic Assessment of Masonry Cross Vaults through Numerical Nonlinear Static and Dynamic Analysis. In COMPDYN 2019 7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, edited by M. Papadrakakis and M. Fragiadakis, 600–612. Crete, Greece. https://doi.org/10.7712/120119.6942.18709.

Block, Philippe, Thierry Ciblac, and John A. Ochsendorf. 2006. Real-Time Limit Analysis of Vaulted Masonry Buildings. Computers and Structures 84 (29–30): 1841–52. https://doi.org/10.1016/j.compstruc.2006.08.002.

CNR national research council of Italy. 2014. CNR-DT 212/2013: Guide for the Probabilistic Assessment of the Seismic Safety of Existing Buildings, 188.

Itasca Consulting Group, Inc. 2016. 3DEC 5.2. Three Dimensional Distinct Element Code.

Milani, Gabriele, Michela Rossi, Chiara Calderini, and Sergio Lagomarsino. 2016. Tilting Plane Tests on a Small-Scale Masonry Cross Vault: Experimental Results and Numerical Simulations through a Heterogeneous Approach. Engineering Structures 123: 300–312. https://doi.org/10.1016/j.engstruct.2016.05.017.

Milani, Gabriele, and Antonio Tralli. 2012. A Simple Meso-Macro Model Based on SQP for the Non-Linear Analysis of Masonry Double Curvature Structures. International Journal of Solids and Structures 49 (5): 808–34. https://doi.org/10.1016/j.ijsolstr.2011.12.001.

Ministero delle Infrastrutture e Trasporti. 2018a. Bozza circolare esplicativa Norme Tecniche per le Costruzioni, issued 2018.

———. 2018b. NTC 2018 - 1, issued 2018.

Ptaszkowska, Joanna, and Daniel Vitorino de Castro Oliveira. 2014. Numerical Modeling of Masonry Vaults Strengthened with Transversal Diaphragms. In SAHC2014 - 9th International Conference on Structural Analysis of Historical Constructions, edited by F. Peña and M. Chávez. Mexico City, Mexico.

Rossi, Michela, Chiara Calderini, and Sergio Lagomarsino. 2016. Experimental Testing of the Seismic In-Plane Displacement Capacity of Masonry Cross Vaults through a Scale Model. Bulletin of Earthquake Engineering 14 (1): 261–81. https://doi.org/10.1007/s10518-015-9815-1.

Torres, Benjamín, Elisa Bertolesi, Juan J. Moragues, Pedro A Calderón, and Jose M. Adam. 2019. Experimental Investigation of a Full-Scale Timbrel Masonry Cross Vault Subjected to Vertical Settlement. Construction and Building Materials 221: 421–32. https://doi.org/10.1016/j.conbuildmat.2019.06.015.