Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 497-507

ECCOMAS
Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

"SCAGLIA ROSSA" EXPERIMENTAL CAMPAIGN AND MODEL UPDATING FOR NUMERICAL DAMAGE EVALUATION

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Abstract

This paper outlines the characterization of masonry walls composed of "Scaglia Rossa", a typical stone of the Apennine area between the Umbria and Marche Regions in Central Italy. The study focuses the assessment of the mechanical behavior by means of an experimental campaign carried out in the laboratory of the Polytechnic University of Marche, where the samples of "Scaglia Rossa" masonry, obtained from the controlled demolition of three school buildings, were reconstructed with the same techniques of the 1950s-'60s, and then tested in order to identify both the constituent materials, stone and mortar, and the composite masonry. The experimental tests were prior to a numerical analysis implemented by the adoption of a nonlinear model capturing the cracking behavior. The main mechanical parameters were then calibrated by means of an optimization algorithm of Levenberg-Marquardt, considering a continuous approach in macro-modelling techniques and obtaining resistance parameters not deriving directly from the experimental tests. The comparison between the results obtained from the Levenberg - Marquardt algorithm by changing the parameters of the damage model based on data given by the experimental campaign allowed to confirm the validity of the approach used.

Keywords: Central Italy Earthquake, Masonry, Experimental Tests, FE Modeling, Levenberg Marquardt Optimization Algorithm, Scaglia Rossa.

Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi:10.7712/120121.8503.19358

1 INTRODUCTION

In the recent years all over the world an elevated number of seismic events was seen, especially in the southern subregion of Europe [1]–[4]. These events caused important damages to the architectural heritage and lead to the need of in-depth investigation on the quality of materials and buildings. The features that complement a construction are, in fact, of fundamental importance in order to acquire a complete comprehension of how historical building heritage behaves under both static and dynamic loads. Italy, has been affected by diverse earthquakes (Friuli (1976), Irpinia (1980), Umbria-Marche (1996-1997), Molise (2002), L'Aquila (2009), Emilia-Romagna (2012), and Central Italy (2016-2017)) and the need to evaluate damage before a restoration project commenced was outlined. The occurred events characterized the damage and collapse of a great number of buildings demonstrating how fundamental is to assess adequately restoration works since the common ground between the various cases is made by poor quality mechanical characteristics of masonry, together with absence of connection between vertical and horizontal elements components that define the structures. The quality of masonry is determined by the features of both mortar and stone and presents in many cases the starting point of the investigation for the diagnosis, since the processes of rehabilitation and restoration are accomplished if the actual state is known. The behavior of masonry's components (mortars and stones), becomes important since masonry is a composite material that is obtained by joining artificial or natural bricks by means of mortar layers. Due to this above-mentioned reason, stiffness and resistance have great variability but can still characterize masonry materials by means of average values that are not only provided through means of codes or manuals but also experimental campaigns. In most of the Italian Regions it was seen that the seismic activity was intense through the centuries and especially in the area that defines the Apennine region between Umbria and Marche where the heritage is characterized by rural, vernacular masonry [5]. The material mostly used to define the construction techniques of the area is called "Scaglia Rossa" and is the focus of the experimental campaign and numerical non-linear modelling approach of the present paper [6], [7]. In Section 2, the methodology for the experimental campaign is presented and it is explained also the numerical approach used to identify the results of the campaign numerically. Section 3 dwells in more detail on the construction technique utilized for the components that were used during the experiments and Section 4 gives more detail on the numerical approach and damage evaluation results that were defined. In Section 5 the summarized discussion and conclusions are found.

2 METHODOLOGY

The methodology that was followed for the present work is divided in three parts. The first part contains the research done in bibliography for the identification of the construction schemes that used the "Scaglia Rossa" material in the Apennine area and the in-situ campaign that was done in order to identify visually the constructions and select the sample materials that are to be used later in the laboratory experimental tests. The second part englobes the tests that followed to identify the mechanical properties of the samples were done in the the "*Laboratorio Prove Materiali e Strutture*" of the Polytechnic University of Marche (Ancona, Italy). The test considered were divided in two categories, the first for the mortar and the second for the stone samples. In summary, these tests consisted of three-point bending tests, load bearing tests for the mortar and "Scaglia Rossa" samples individually and shear - compression tests for matrices that were constructed in the laboratory, following the double leaves technique. The third part was initiated once the results of the experimental campaign were known. It was then that the numerical modelling began and was done in order to calibrate with the Levenberg-Marquardt algorithm present in the open source software Code_Aster, the nonlinear Mazars damage model parameters onto the experimental results, [8]–[12]. This was done to see if the algorithm can calibrate the parameters and to confirm numerically with a macro-model approach the evolution of the damage seen in the experimental campaign.

3 CASE STUDY

In the Apennine area, after the II World war, the zones between Marche and Umbria were built with a relatively new, compared to the older techniques, local material that was easily available and abundant called "Scaglia Rossa". This material monopolized the market in the years between the 50's and 60's instead of bricks, tuff and concrete blocks that were also later introduced. Coming into more recent years and specifically concentrating attention on the 2016-2017 seismic sequence and the damages it caused in Central Italy, the examinations of engineers reported that the structures consisting of this limestone were considerably damaged. The damage reports consider at the end of the seismic sequence cases of disintegration of the masonry, and out-of-plane mechanisms were rare compared to frequent cracks encountered on the examined panel planes.

The experimental campaign was carried out in the "*Laboratorio Prove Materiali e Strutture*" of the Polytechnic University of Marche (Ancona, Italy), where the samples of "Scaglia Rossa" masonry were accumulated. The samples derived from three school buildings [13]–[15], were controlled demolitions were done. The samples then were assembled using the construction technique of 1950's – 60's and were tested in order to identify the mechanical properties of the constituent materials, stone and mortar, and the composite masonry. Initially, load bearing tests were carried out for the selected "Scaglia Rossa" specimens and tested to measure the compressive resistance of the limestones. Afterwards, four matrices were assembled with a cement mortar mixture with percentages that were found in literature to near the construction technique of the initial period (1950's – 60's). Mortar samples were extracted and tested with three-point bearing and load bearing tests (on the remaining portions), after 28 days of curing.

Diverse FE models were developed to reproduce the data acquired by the experimental campaign and a calibration process was executed with the Levenberg – Marquardt algorithm present in open source software Code Aster, developed by EDF (Eletricité de France), in order to obtain the parameters that characterize the non-linear evolution and could not be directly measured from the experimental tests.

4 SPECIMENS SETUP AND MECHANICAL CHARACTERIZATION

The constructed walls for the masonry mechanical parameters evaluation are four in number and are made with samples of different sizes and shapes utilizing a double leaves technique (Figure 1). Two different kind of tests were performed: a load bearing test in order to establish the behavior under vertical static loads on one wall and load-bearing tests in order to establish the resistance to horizontal loads acting in the plane for all three walls. The dimensions of the four constructed walls are reported in Table 1.

Wall N.	Base (mm)	Length (mm)	Height (mm)
Wall matrix n.1	760	846	500
Wall matrix n.2	750	862	500
Wall matrix n.3	720	860	500
Wall matrix n.4	740	857	500

Table 1: Wall specimens' geometrical properties

Figure 1: Construction process followed for the wall specimens with "Scaglia Rossa" limestone applying the double leaves technique.

The load bearing test for the wall matrix follows the Italian legislation and is provided by UNI EN 1052-1:2001. This experiment aimed to understand the level of axial force that ca be supported by the composite specimen and to provide indications in presence of only vertical forces. The force-displacement curve was obtained by using two LVDT between the frame and the steel plate in the top of the specimen to gain the displacement (Figure 2).

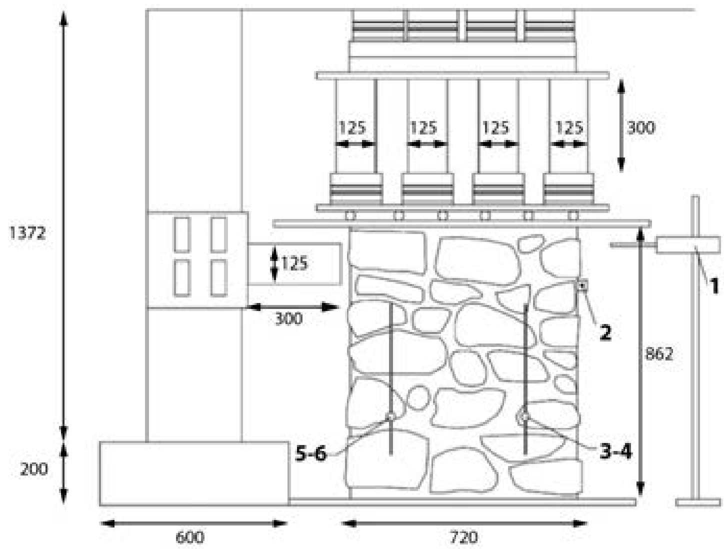

Figure 2: Load-bearing - shear apparatus with example of one matrix specimen. The numbers indicate the dimensions of the apparatus and the positioning of the strain gauges used to measure displacements (measures in mm).

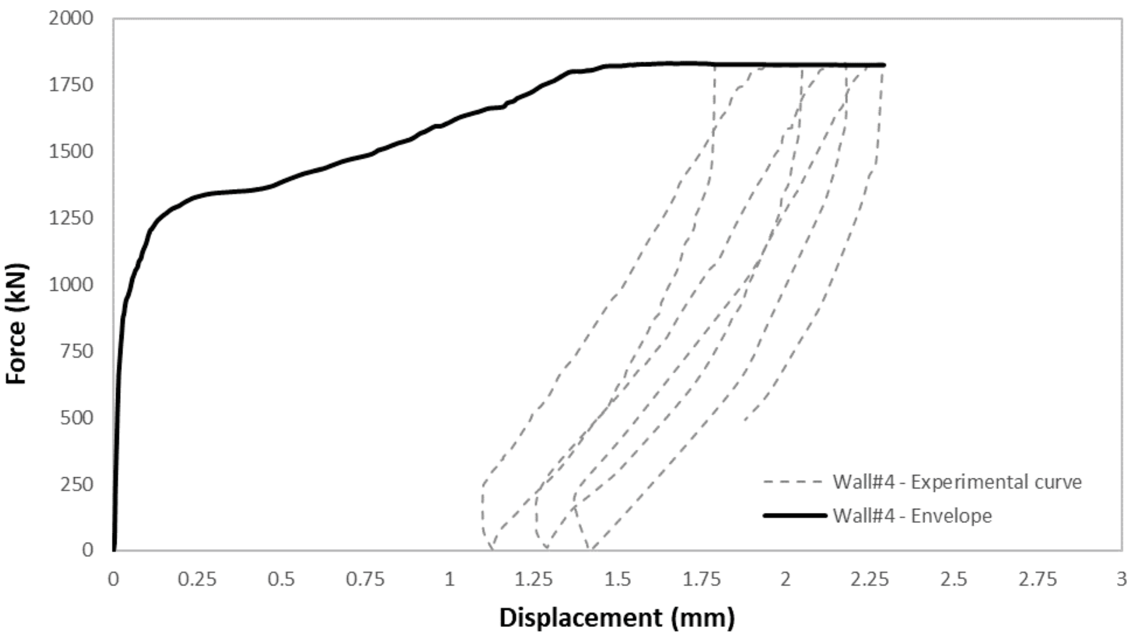

Figure 3: Force - Displacement (kN - mm) evolution curve with the enveloped curve of the Wall#4 that was subjected to load-bearing test.

The results indicate that the range between 0 – 800 kN the displacement values are almost null, while the in the range between 900 – 1200 kN there is augmented displacement. The peak of the curves is found in the 1800 kN range where a clear plateau is visible (Figure 3). Once the horizontal evolution was observed, three ulterior cycles were applied to evaluate residual displacements and possible accumulated damage. The wall had reached its ultimate limit and is able to withstand numbers of cycles without a decrease in stiffness (Figure 4).

(a) (b) (c)

Figure 4: (a) Installed displacement transducers on the wall matrix, (b, c) damage on the specimen caused by the load - bearing test.

For the shear-compression tests a constant precompression load of 400 kN was applied and kept constant during the entirety of the procedure. Afterwards, the hydraulic actuators are activated once the stabilization of the vertical force has occurred. The resulting shear force-displacement curves of the three specimens are shown in Figure 5.

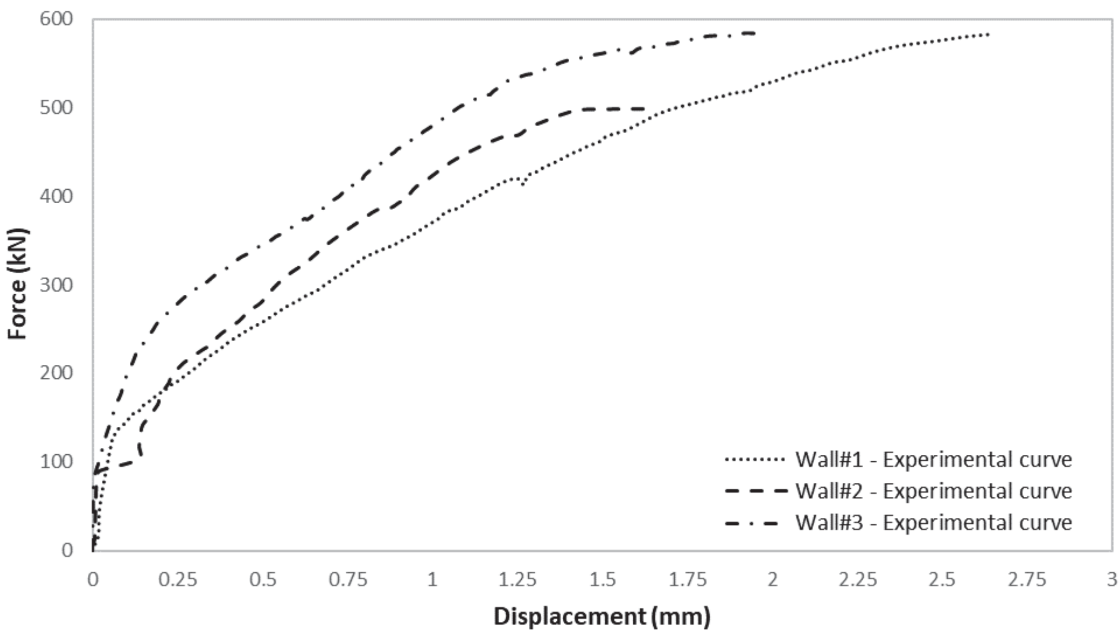

Figure 5: Summary of the horizontal force (kN -mm) curves of the specimens subjected to load-bearing-shear tests

All the performed tests showed homogeneity in their behavior, with a maximum resistance standing above 500 kN except for local criticalities. In more detail, Wall#1 retains the maximum force applied at 580 kN with the displacement arriving at 2.6 mm or the drift is 0.31%. For Wall#2, the maximum force stands at 500kN for a drift of 0.18% and Wall#3 a maximum force of 580kN is observed for a drift of 0.22%. The drift values are comparable with values encountered in National Standards for nonlinear analysis of masonry's walls. The absence of plateau is given to the highly fragile behavior of the specimens once the maximum force is reached. The damage observed indicates in all the specimens a diagonal rupture due to compression and shearing and in some cases panel disintegration when the maximum force applied was reached (Figure 6).

Figure 6: Damaged specimens at the end of the load-bearing-shear test for Wall#1, Wall#2 and Wall#3.

The non-monolithic behavior of such matrix is well represented and does confirm the behavior found commonly in stone walls made by substantially joined faces with diatones providing connections transversally.

5 NUMERICAL METHODOLOGICAL ANALYSIS AND RESULTS

Once the experimental campaign was concluded, with the geometrical information received, diverse Finite Element models were developed for each test of the campaign. To consider the material non linearities, Mazars damage model was considered, and a calibrations process was followed. The process had as its objective the calibration of Mazars damage model parameters (Isotropic scalar damage model), with the Levenberg – Marquardt algorithm,[16], in order to capture the force – displacement curves course and to visualize and evaluate the resulting damage coming of the specimens at the end of the experimental campaign on macro – models, [17]–[21].

The model for the analysis and calibration of Mazars damage model was constituted by 3887 nodes and 16930 tetrahedral elements. For the load-bearing model, the nodes number arrives at 4231 while the tetrahedral elements are 16445. The left side panel substitutes the place of the two hydraulic heads with an equivalent plate. The decision to model this part was to reduce possible errors of the calculation by mesh incompatibilities. The loading was given at the top and left face of the equivalent steel plates of the model while the bottom side is fixed (Figure 7).

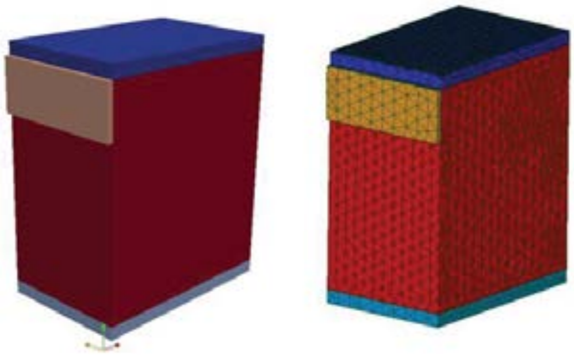

Figure 7: Macromodel geometry and mesh representation

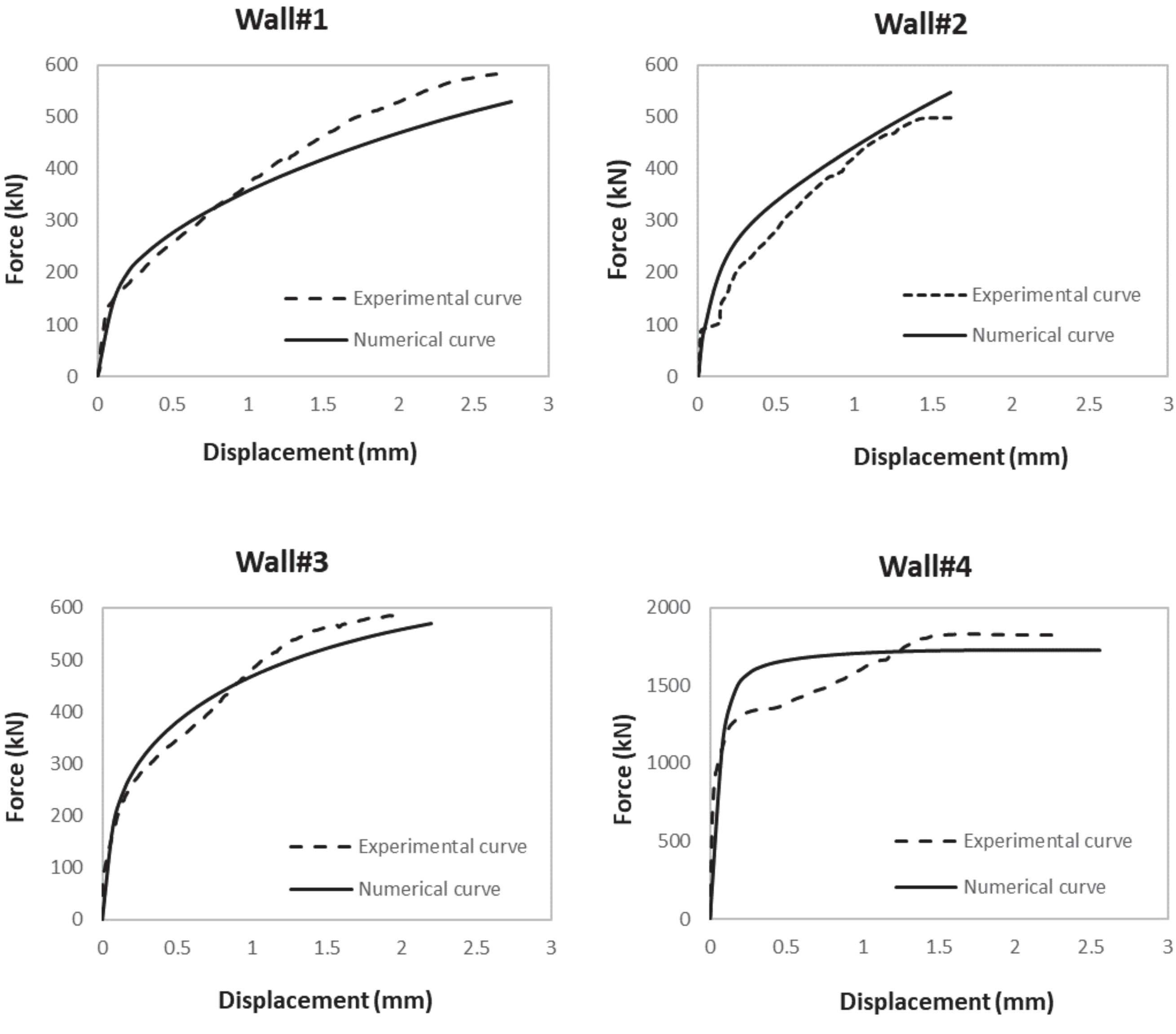

Figure 7: Comparison between the experimental and numerical force - displacement curves (kN - mm), results of the macro-modelling approach.

The results of the calibration by the Levenberg – Marquardt algorithm, obtained under the form of force – displacement curves and the fit with the experimental curves is shown in Figure 8 and the values product of the optimization process in Table 2. In all cases, it was possible to capture the progress of the compression – shearing with discrepancies shown for Wall#2 and Wall#3 that was caused by progressive disaggregation of the materials during the experimental tests.

Wall #	E (MPa)	ν	A_t	A_c	B_t	B_c	k	E_0 (10^{-5})	Error (%)
(1)	4049.3	0.243	1.120	0.158	5020	99.3	0.808	5.66	1.56
(2)	3000.0	0.400	1.170	0.843	6800	0.10	1.090	0.108	3.69
(3)	4843.8	0.150	0.460	0.223	7260	104.0	0.700	0.0276	3.94
(4)	8000.0	0.400	0.191	0.017	14000	136.0	0.258	40.40	13.21

Table 2: Calibration results of Mazars damage model parameters

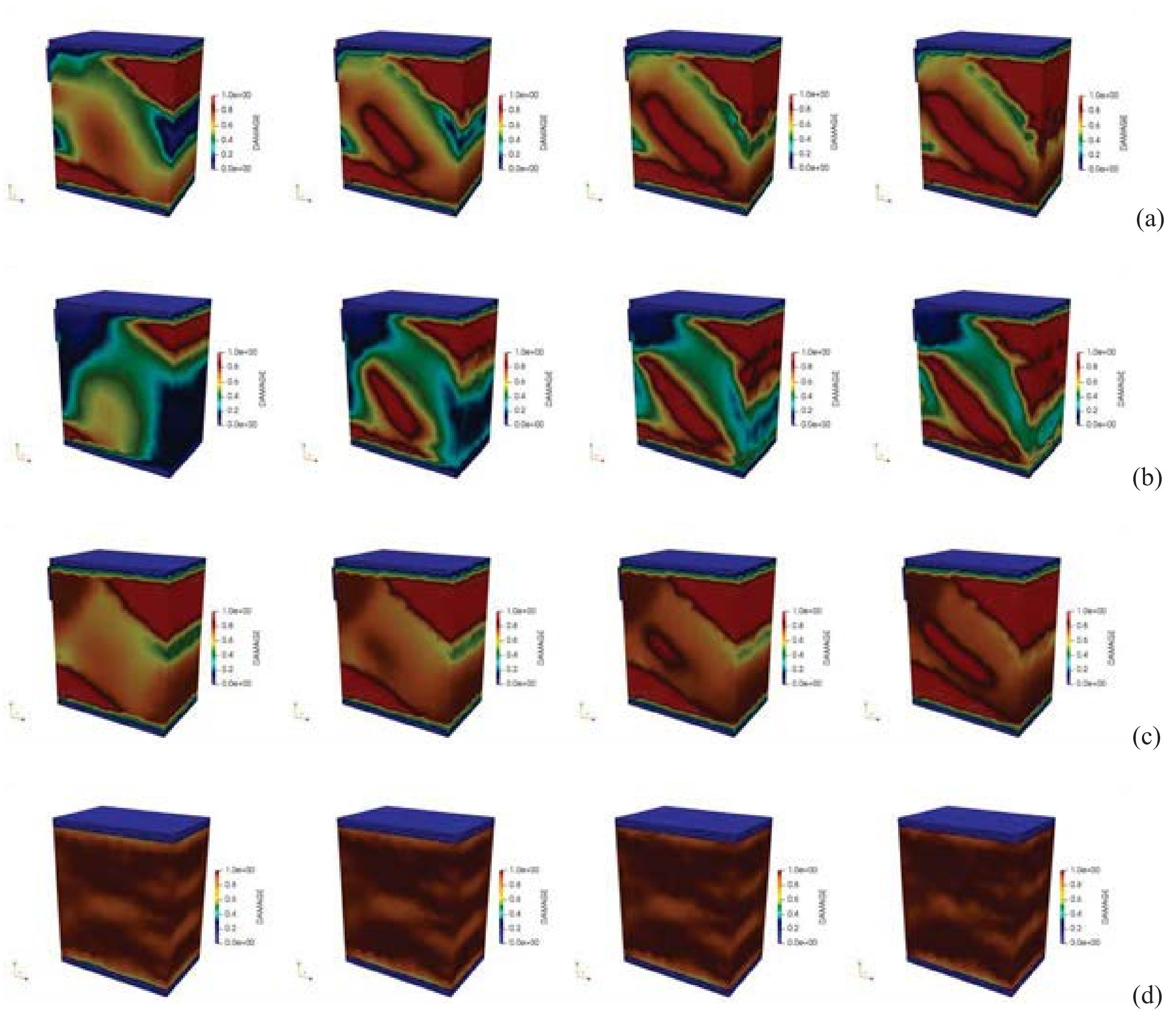

Figure 8: Numerical damage evolution for (a) Wall#1, (b) Wall#2, (c) Wall#3, (d) Wall#4.

The damage of the numerical models is concentrated to the upper-right and lower-left sides of the specimens and evolves later in the middle part of the specimens where the diagonal damage is evident. In comparison to the actual damaged state of the specimens, visually the damage is found to evolve diagonally and at the base of the specimen, so the numerical propagation in this point seems to be visually in good correspondence as can be seen in Figure 8. The damage evolution is initially concentrated in the inverse diagonal in respect to the experimental schemes. While the shearing process continues so does the damage in the correct diagonal direction and it is at that point that it corresponds to the results of the campaign.

6 CONCLUSIONS

The studies of the present work are carried out to assess the mechanical behavior of masonry walls build utilizing the “Scaglia Rossa” stone, a material typical of the area that encircles the Apennine regions between Umbria and Marche in Central Italy. Diverse experimental tests and numerical analyses by finite element method were performed with the aim to provide quantitative indications for the professionals that are involved in the reconstruction and rehabilitation works in the area affected by the renowned earthquake of Central Italy in 2016. The experimental campaign involved several tests on the constructed masonry composite that was reconstructed using techniques adopted in 1950’s and 1960’s. The specimens, in presence of shear loading, demonstrated an evident fragile behavior connected with the diagonal failure due to compression and shearing deformations. This characteristic mechanism was observed in all investigated cases. Also, several finite element models were developed aiming to reproduce the resulting data of the experimental campaign. This work was assisted by a calibration process by the Levenberg – Marquardt algorithm to fit the numerical process on the experimental results and validate if Mazars damage model can reproduce the specimen’s evolution of damage. The results obtain under the form of force – displacement curves on a macro – modelling approach and reproduced the experimental behavior visually. The summary of both experimental and numerical approaches appear to be of importance in order to define the nonlinear and numerical behavior of the material “Scaglia Rossa” masonry, in order to be utilized under design orders for specific restoration projects whose focus is based on structural fragilities featuring the recent seismic activities.

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