15th Canadian Masonry Symposium
Ottawa, Canada
June 2-5, 2025

Seismic Assessment of Clustered Masonry Buildings: A Case Study in Castelsantangelo Sul Nera (Italy)

Margherita Fabris[i], Lorenzo Bellini[ii], Elisa Saler[iii], and Francesca da Porto[iv]

ABSTRACT

Historical centres often consist of clusters of masonry buildings, commonly arranged as urban blocks or terraced houses. Their strong irregularity and the effects of interaction among adjacent structural units often lead to an increase in seismic vulnerability. The complexity of this building type makes the assessment of the seismic response a challenging undertaking. It is therefore of great interest to identify a methodology for the seismic assessment of clusters of buildings, encompassing all stages from the knowledge process to modelling and analysis. In this context, adopted modelling strategies play a crucial role, and thus a comprehensive acknowledgement of their advantages and limitations is necessary. In this work, two modelling approaches are adopted, i.e., equivalent frame model (EFM) using 3Muri and finite element model (FEM) using Diana FEA. First, a simplified prototype case was developed. This step was essential to establish modelling strategies that ensure compatibility of the two approaches. These strategies were then extended to a real case study of terraced houses, located in Castelsantangelo sul Nera (Central Italy). The structure was affected by the 2016 Central Italy earthquake. The on-site structural, material and damage surveys carried out allow for the calibration of the implemented numerical models. The global behaviour was examined by performing nonlinear static analysis. Various configurations were simulated considering single structural units, as well as the entire cluster. The results obtained by the two modelling strategies are compared and discussed.

KEYWORDS

masonry, seismic vulnerability, historical buildings, aggregate, cluster buildings, pushover analysis.

[i] Ph.D. student, Department of Geosciences of the University of Padova, Padova, Italy, margherita.fabris.2@phd.unipd.it
[ii] Research fellow, Department of Geosciences of the University of Padova, Padova, Italy, lorenzo.bellini.1@studenti.unipd.it
[iii] Technician WCRI-Sycuri, Department of Geosciences of the University of Padova, Padova, Italy, elisa.saler@unipd.it
[iv] Full Professor, Department of Geosciences of the University of Padova, Padova, Italy, francesca.daporto@unipd.it

INTRODUCTION

Clusters of masonry buildings are a common structural type of historic built heritage around the world. Clustered buildings are composed of several adjacent structural units interacting with each other. These types of buildings are the result of a long sequence of construction phases and transformation processes over the centuries. The structural units of an aggregate may differ in geometry, materials, construction techniques, total height or inter-storey heights. The deriving strong irregularities lead to the typical high seismic vulnerability of urban aggregates.

Recent earthquakes highlighted the vulnerability of this building type and, consequently, the need to intervene in clustered buildings. In this regard, standardised methodologies have been proposed to address the knowledge process [1][2], which include critical-historical analysis, geometric, constructive and structural survey and critical survey of the damage and vulnerabilities of the aggregates of buildings. The knowledge process is complicated and demanding due to the structural complexity, heterogeneity and irregularity of this type [3]. Moreover, it is often difficult to find information on the entire cluster, which is generally composed of a large number of units. However, buildings knowledge is essential to understand the possible interactions among units and the global seismic response [4].

Numerical simulations are also influenced by the complexity of this building type. Various studies in the literature investigated masonry building clusters using different modelling strategies, often through case study approaches [3][4][5]. These include equivalent frame models (EFM), finite element models (FEM), often in a framework of parametric analyses. In many cases, EFM and FEM were employed in parallel to compare their results and assess their applicability. Parametric approaches, such as those explored by Stavroulaki [6], were also used to simulate the interaction between structural units. Nevertheless, the modelling assumptions underlying numerical simulations of clustered buildings are far to be fully disclosed.

This study investigates the use of two distinct modelling approaches, i.e., EFM (3Muri) [7] and FEM (DIANA FEA) [8], to evaluate the seismic response of buildings within a cluster. Numerical simulations were carried out on a prototype regular building to facilitate the comparison of the adopted modelling strategies reducing aleatory. Models were then implemented of a case study cluster situated in Castelsantangelo sul Nera, a historical town that was significantly impacted by the 2016 Central Italy earthquake. This cluster was object of comprehensive surveys, including geometric and structural material assessments, along with evaluations of damage, deterioration, vulnerability factors, and historical development. Nonlinear static analyses were performed to compare the results obtained from the two software packages, focusing on damage outcomes and pushover curves. For calibration purposes, the computed damage was compared with the actual damage and injuries resulting from the 2016 Central Italy earthquake. The aggregate was modelled both as a whole and as a collection of individual structural units to assess the effects of aggregation and the interactions between the units.

METHODOLOGY

This study follows a stepwise methodology aimed at analysing the seismic behaviour of historical masonry clustered buildings. The models were developed using two distinct modelling strategies and software tools: the equivalent frame model (EFM) implemented in 3Muri and the finite element model (FEM) implemented in DIANA FEA.

The 3Muri software is a widely used tool for the structural analysis of masonry buildings, specifically for seismic assessments [7]. It employs the equivalent frame model (EFM) approach, which simplifies the structure into a series of interconnected macro-elements, such as piers and spandrels, allowing for efficient non-linear analyses while maintaining a good balance between accuracy and computational cost. DIANA

FEA (Finite Element Analysis) [8] is a highly advanced finite element software designed for the structural analysis of complex constructions, including masonry buildings. DIANA FEA operates by discretising the structure into finite elements, which can be tailored to the geometry and material characteristics of the model. For masonry, this includes specialised constitutive models that account for cracking, crushing, and shear failure mechanisms.

To establish a robust modelling procedure and ensure comparability between the two different numerical approaches, the process began with the development of a simplified prototype model. The modelling strategies defined for the prototype model were then extended to the case study, which includes both individual structural units and the entire clustered building. This approach ensures that the findings from the prototype case inform the analysis of the more complex structure, facilitating a consistent comparison between the two modelling tools.

CASE STUDY: A CLUSTERED BUILDING IN CASTELSANTANGELO SUL NERA

The selected case study focuses on a clustered building located in the historic centre of Castelsantangelo sul Nera, Central Italy. This area was severely impacted by the 2016 Central Italy earthquake, particularly by the events that occurred between August 24th and October 30th, 2016. These included the strongest recorded earthquake, with a magnitude of 6.5 Mw on October 30, cantered in Norcia, and another significant event with a magnitude of 6.0 Mw, which had its epicentre in Accumuli on August 24.

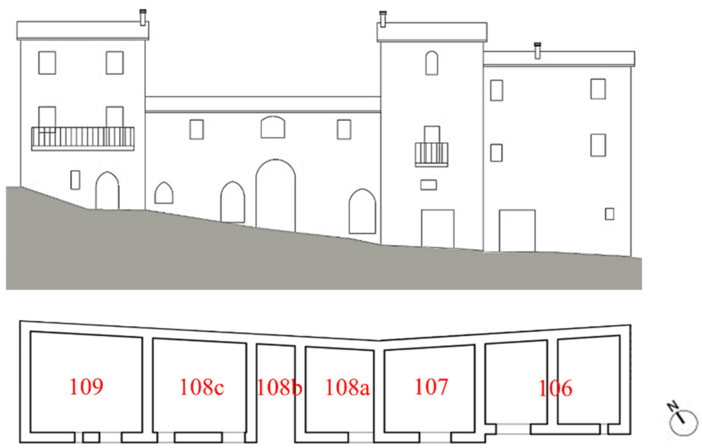

Figure 1: Plan of the first floor and main elevation of the clustered building

The cluster under examination was one of the oldest buildings in the historic centre, with the original structure dating back to the 13th century. Geometric and structural surveys were conducted, along with assessments of damage [9],[10] deterioration/state of conservation, as well as the analyses of the building's historical evolution and observable vulnerability factors, as presented in the study by Saretta (2024) [11]. Most of the walls are made of regular tuff stone, with the remaining part of random rubble, all with a thickness of 60 cm. Some external walls underwent joint repointing or injection for reinforcement. The structure features staggered floors due to the slope of the site. Reinforced concrete (r.c.) floors with clay tiles are considered as replacement of the original wooden floors. Structural units are arranged in a linear configuration and can be subdivided into four structural units: two interlocking units and two end units (Figure 1). Structural Unit 108 was formed by joining two separate buildings through the construction of a vaulted room. The case study sustained significant damage during the 2016 Central Italy earthquake sequence. As shown in Figure 2, the most severely damaged part is unit 109. In this portion of the cluster, in addition to cracks caused by shear mechanisms, the east façade at top storey collapsed due to out-ofplane overturning. Structural units 107 and 108 exhibited minor cracks due to pounding and discontinuities with adjacent units. Lastly, unit 106 displayed widespread cracks, particularly in the east wall, which caused plumbness issues due to flexural phenomena.

a) b)

Figure 2: Damage suffered by the case study following the 2016 Central Italy earthquake: a) north and east elevations of S.U. 109; b) south elevation of S.U. 108a, 107 and 106.

NUMERICAL SIMULATIONS

Prototype building

The prototype model consists of a simple two-storey building with a 5m x 5m floor plan, as shown in Figure 3. The mechanical properties of the masonry and the characteristics of the floors are detailed in Table 1 and Table 2 and are consistent with those later used in the case study. Several preliminary simulations were conducted in an effort to discern the viability of employing different modelling choices, with the objective of attaining equivalent simulations between the two modelling strategies, to fully understand possible intrinsic variations between EFM and FEM. For DIANA FEA, three masonry models were considered: *i*) an exponential model for the tensile behaviour of masonry with G_{ft} equal to 10 N/m; *ii*) a brittle model; and *iii*) a brittle masonry model without walls in the Y direction. For 3Muri, four models were analysed, combining the presence or absence of tie rods in the direction of analysis and the presence or absence of walls in the orthogonal direction. The pushover results were also compared with the shear strength estimated using the Turnšek and Čačovič criterion [12].

Pushover analyses were conducted on the prototype model, and the results obtained with 3Muri and DIANA FEA are compared in terms of global behaviour. The results of all configurations are illustrated in Figure 4. The curves clearly highlight the differences in response between the DIANA FEA and 3Muri models The DIANA FEA models (in blue) exhibit a higher load-bearing capacity compared to the 3Muri models (in green), with the ”Exponential model” achieving the highest resistance, followed by the “Brittle” and “Brittle - no transverse walls” models. For the 3Muri models, the presence of tie rods significantly enhances the load-bearing capacity, while the removal of transverse walls further reduces the resistance. Finally, the shear strength estimated using the Turnšek and Čačovič criterion (dashed line) is significantly lower than the peak capacity of the DIANA FEA models and is more comparable to the response of the 3Muri models without tie rods. The pushover curves from the two approaches that exhibit the closest behaviour are those of the 3Muri model with tie rods and the DIANA FEA brittle model without transverse walls. This suggests that the removal of transverse walls in DIANA FEA compensates for the higher stiffness typically associated with FEM modelling, bringing its response closer to that of the equivalent EFM model in 3Muri.

Based on these simulations, the final characteristics of the prototype model were established. To align the modelling strategies of the two software tools, specific adjustments were made. Consistent results in terms of base shear were obtained under the following model adjustments: *i*) in the 3Muri model, tie rods were added along the walls in the analysed direction to couple masonry panels; and *ii*) in the DIANA FEA model, orthogonal walls were disconnected, and spandrels were removed. These adjustments ensured that the structural schematisations in the two software tools were as consistent as possible.

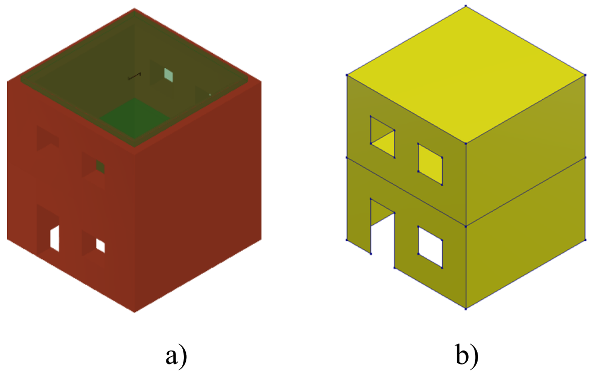

Figure 3: 3D of the prototype models: a) 3Muri, b) DIANA FEA.

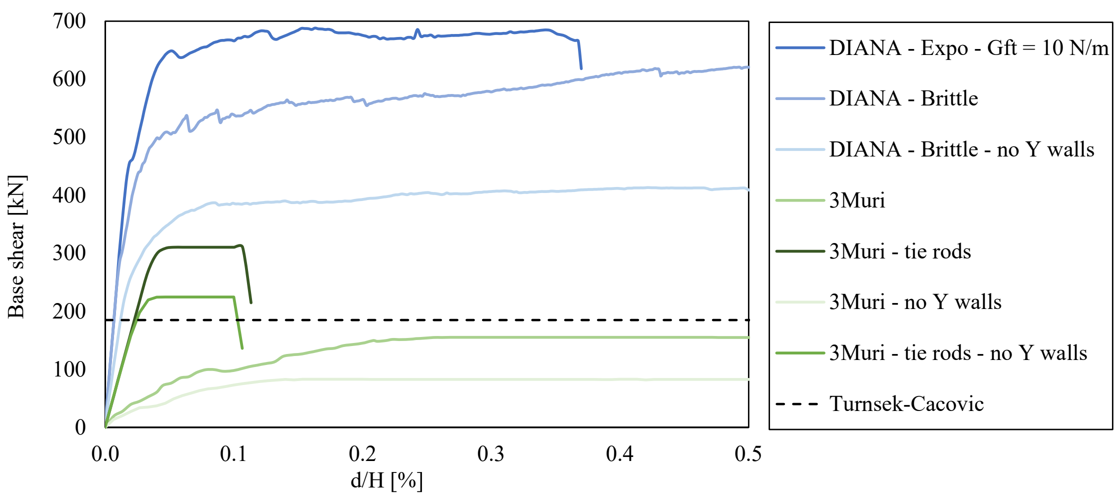

Figure 4: Pushover curves of the prototypes models

Case study building

The models of the selected case study were developed based on the findings and strategies identified through the prototype model. This ensured consistency in the modelling approach and facilitated a reliable comparison between the two software tools. The mechanical properties of tuff stone are detailed in Table 1, while the characteristics of the floors (modelled as isotropic and linear elastic) are summarised in Table 2: all floors were modelled with an equivalent structural thickness of 15 cm, a Young's modulus in both directions E=20000 N/mm^2, shear modulus G=3864 N/mm^2 and bidirectional load distribution, the latter choice being justified by the presence of a reinforced concrete topping slab. The topographic class and the soil class are respectively T2 and B [13, 14]. The Total Strain Crack model [15] was used to represent the behaviour of the masonry. This constitutive model assumes an exponential response in tension, a parabolic response in compression, and a constant behaviour in shear.

Table 1: Mechanical properties of load bearing walls

W [kg/m^3]	2100
E [N/m^2]	1676
Gft [N/mm]	0.01
ft [MPa]	0.094
fc [MPa]	3.081
ν	0.4

Table 2: Mechanical properties of floors

W [kg/m^3]	1500
t [cm]	15
E [MPa]	10000
G [MPa]	3846
ν	0.3

The geometry of the cluster is notably complex, necessitating specific modelling strategies. Due to the sloping terrain, the foundations of the structural units in the full aggregate model are not aligned, as illustrated in Figure 2. Furthermore, the slope causes a marked difference in the number of storeys visible on different elevations: the south elevation features two or three above-ground storeys, whereas the north elevation has only one or two above-ground storeys, with an additional basement level. This asymmetry was accounted for in the models by omitting the ground-floor walls of the north elevation where appropriate. In the 3Muri model, the south walls of the ground floor were treated as weightless walls and constrained at both base and top. Furthermore, the first floor was modelled as resting on a beam slightly detached from the north walls to prevent excessive restriction of ground-floor displacements due to their constraints. In the DIANA FEA models walls, floors, and roofs were represented as two-dimensional curved shell elements, discretized with a mesh of quadrilateral and triangular elements, each approximately 30 cm in size. Boundary conditions included hinges at the base of each wall panel. On the north side, where facades and floors intersect along a common edge, a 30 cm-wide strip was removed from the floor to avoid over-constraining it. This strip's free edge was then constrained to allow vertical translations only, better capturing the actual earthquake-induced damage.

Pushover analyses were performed along the x-direction using a uniform load pattern proportional to masses. The analyses in the orthogonal direction (Y) are considered less significant in terms of unit interaction. The elastic horizontal response spectrum was defined according to the spectral parameters ag (peak ground acceleration), F0 (spectral amplification factor) and T*c (corner period marking the beginning of the constant-velocity segment of the response spectrum?), for a return period (T_R) equal to 475 years, considering the Life Safety limit state (ag = 0.248 g, F0 = 2.38, and T*c = 0.33 s) [13].

RESULTS AND DISCUSSION

The results of the analyses are presented in terms of pushover curves and damage pattern. Initially, a comparison is made between the DIANA FEA and 3Muri models for each individual structural unit. Regarding the pushover analyses, the focus was placed on the longitudinal (i.e., X) direction, as the transverse one (i.e., Y) was deemed less significant for studying the behaviour of the aggregate. This choice is motivated by the fact that the building complex primarily develops along the X direction, making it the most relevant for assessing the global structural response. Figure 5 shows the pushover curves in the +X direction.

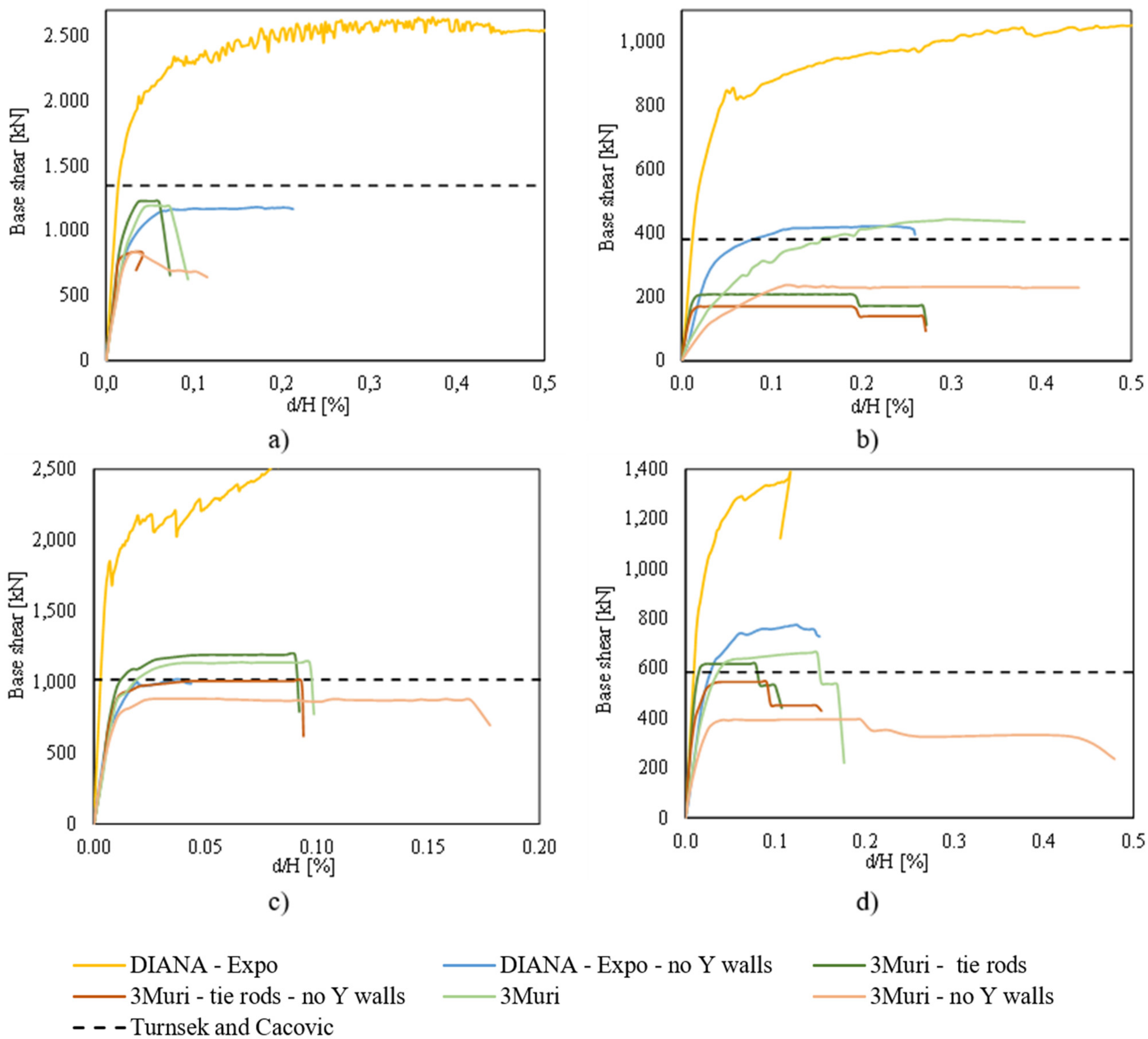

Figure 5: Pushover curves of the S.U. a) 106, b) 107, c) 108 and d) 109.

By varying the modelling approach, the pushover curves of S.U. 106, 107, 108, and 109 exhibit significant variations in terms of stiffness and strength, highlighting the influence of modelling assumptions and structural configurations. The DIANA FEA models ("Expo" and "Expo - No Y walls") exhibit a generally higher load-bearing capacity compared to the 3Muri models, with significantly greater base shear values. This behaviour is particularly evident in Units 106 and 108, where the "Expo" curve reaches considerably higher values than the other models. In the 3Muri models, the presence of Y-direction walls ("3Muri tie rods" and "3Muri") leads to a higher load-bearing capacity compared to the models without Y-direction walls ("3Muri tie rods - no Y walls" and "3Muri No Y walls"). However, this difference is not consistently significant across all units. In DIANA FEA, the absence of Y-direction walls has a noticeable impact in the initial phase, with the "Expo - No Y walls" model exhibiting a lower initial stiffness compared to "Expo". Additionally, the absence of Y-direction walls also affects the maximum base shear value attained. The S.U. 106 exhibits the highest base shear value among all cases, particularly in the DIANA FEA model

("Expo"). About the S.U. 109 in the 3Muri models, the difference between configurations with and without Y-direction walls is more pronounced, with the "3Muri No Y" model exhibiting the lowest resistance among all cases. The pushover curves highlight significant differences between the two software tools. DIANA FEA consistently predicts higher base shear values, suggesting a globally stiffer structural response. Moreover, the influence of Y-direction wall modelling is more pronounced in the DIANA FEA models than in 3Muri.

The pushover curves for the entire clustered building (Figure 6) exhibit significant differences depending on the modelling approach and the adopted assumptions. The DIANA FEA model with an exponential tensile behaviour (DIANA - Expo) shows the highest base shear capacity, followed by the DIANA model without Y-direction walls (DIANA - Expo - No Y walls), which presents a lower but still substantial base shear. This suggests that the inclusion of walls in the Y direction significantly contributes to the overall strength of the cluster. However, it is worth noting that the initial stiffness of the DIANA - Expo - No Y walls model is considerably different from that of the other models, indicating a distinct structural response in the early loading stages. The 3Muri models, regardless of the presence of tie rods or Y-direction walls, exhibit lower base shear capacities compared to DIANA FEA. Among the 3Muri configurations, the model with tie rods (3Muri - tie rods) reaches the highest base shear, indicating that tie rods play a crucial role on the behaviour of the structure. Nevertheless, comparing the two software approaches, the DIANA - Expo - No Y walls model and the 3Muri - tie rods configuration appears to be rather similar in terms of base shear capacity, even if their initial stiffness is significantly different, as well as the maximum expected drift.

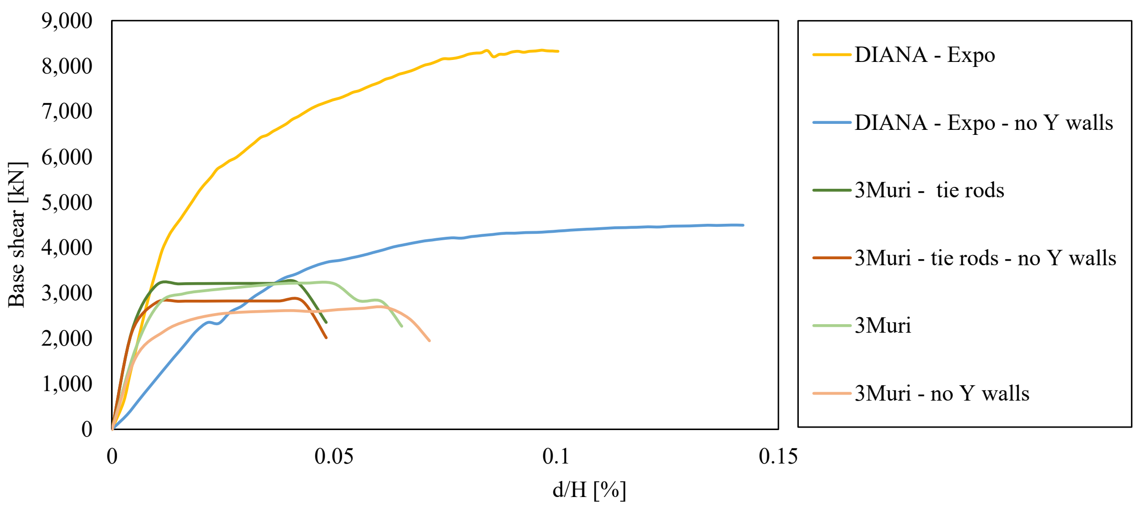

Figure 6: Pushover curves of the clustered building

Overall, the results highlight the impact of modelling choices on the predicted seismic performance of the masonry aggregate, particularly in relation to the influence of tensile behaviour assumptions, the role of tie rods, and the contribution of Y-direction walls. Finite Element Models (FEM) tend to activate all the resistance components contributing to the seismic resistance of masonry structures, including the contribution of walls orthogonal to the seismic action due to their connection with in-plane walls. Conversely, the Equivalent Frame Model inherently assumes a decoupled response of walls, which contribute to the seismic behaviour only through their in-plane shear capacity. This latter modelling strategy therefore appears to be more conservative and more consistent with analytical formulations such as Turnšek & Cacović.

Comparing the damage states of the 3Muri models for individual structural units with that of the entire cluster (Figure 7), several differences become immediately apparent. Overall, the damage appears to be more severe in the case of the individual units, yet the failure modes of the structural elements are largely consistent across almost all masonry piers. Flexural-compressive failures are predominant and are primarily concentrated on the ground floor. In the DIANA FEA models (Figure 8), similarities can be observed in terms of the localisation and typology of damage between the individual structural units and the global model. In the model of the clustered building, significant stress concentrations emerge at the contact points between structural units. Moreover, in particular in S.U. 107, higher stress levels also develop on the top floor, as also emerged from post-earthquake observations. In conclusion, by comparing the models of the clustered building with those of the individual structural units, the importance of accounting for adjacent buildings when modelling a non-isolated structure becomes evident. Regarding the comparability of the two modelling approaches, there is a clear similarity in terms of both the type and localisation of damage. The simulated damage was consistent with the on-site damage observed following the 2016 Central Italy earthquake, as illustrated in Figure 9.

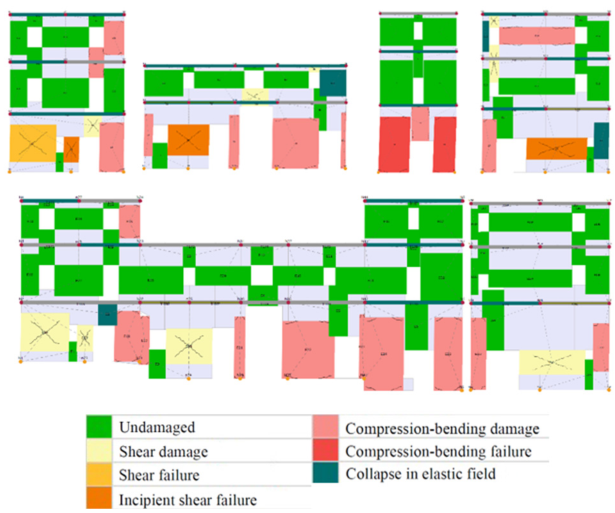

Figure 7: 3Muri damage pattern

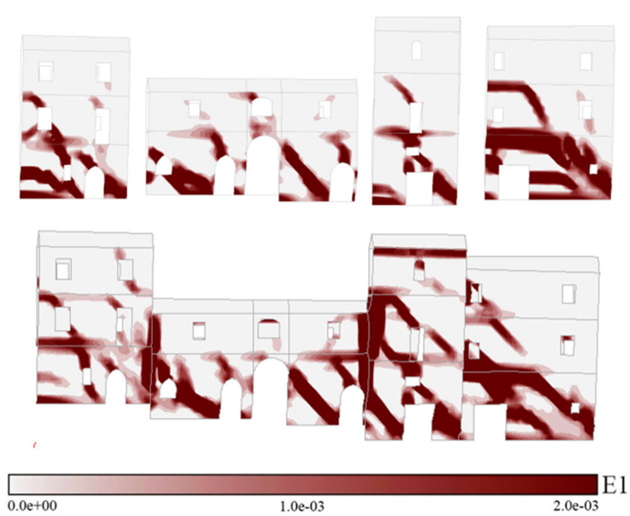

Figure 8: DIANA FEA tensile strains

Figure 9: Damage pattern after the 2016 earthquake

CONCLUSIONS

This study aimed to analyse the differences in numerical modelling between DIANA FEA and 3Muri and to identify comparable modelling strategies while also investigating the variations between the simulation of individual structural units (S.U.) and the entire clustered building.

The results highlight both the discrepancies between the two software tools and the modelling strategies to improve their consistency. FEM models capture the full interaction of masonry components, including orthogonal wall contributions, while EFM models tends to be more conservative assuming a decoupled in-plane shear response of walls. While differences were observed in terms of global response and base shear capacity, a comparable damage distribution was found, particularly in failure mechanisms.

Additionally, a significant contrast emerged when comparing the pushover behaviour of single S.U. models with that of the entire aggregate. The aggregated model exhibited a more distributed damage pattern involving upper storeys, with stress concentrations at the interfaces between adjacent units, while the single-unit models generally displayed more localised and severe damage.

These findings emphasise the need for careful consideration when selecting modelling strategies, as different assumptions and simplifications can significantly influence the outcomes. Furthermore, the modelling of masonry clustered buildings remains an open and complex issue, requiring further investigation to develop more refined and reliable methodologies.

Future research should focus on a deeper evaluation of the interactions between adjacent structural units and the influence of each unit's position within the cluster. A more detailed analysis of these aspects could enhance the understanding of structural response in historical masonry cluster and improve the accuracy of seismic vulnerability assessments.

ACKNOWLEDGEMENTS

This paper has been developed under the financial support of the Italian Department of Civil Protection (IDPC), within the ReLUIS-DPC 2022-24 and 2024-2026 Research Project (WP5 and WP10), which is gratefully acknowledged. Thanks are also due to the World Class Research Infrastructures (WCRI) programme - SYCURI: SYnergic strategies for CUltural heritage at Risk of the University of Padova.

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