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SEISMIC VULNERABILITY AND STRENGTHENING OF A MASONRY BUILDING AGGREGATE: A CASE STUDY IN PRATA (L'AQUILA)

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Abstract

Masonry building aggregates constitute a significant portion of the Italian architectural heritage. This building typology comprises adjacent structures, often constructed in different historical periods and therefore featuring significant differences in materials and construction techniques. The temporal layering of these buildings has led to structural heterogeneity, with connections between individual units that may be more or less effective, resulting in a lack of overall structural unity. This complexity makes building aggregates vulnerable to collapse mechanisms when subjected to seismic forces, especially due to irregular interactions between different parts. This study focuses on a specific case of a masonry building aggregate located in Prata (Lucoli, L'Aquila), which sustained significant damage during the 2009 L'Aquila earthquake. Following the seismic event, widespread cracks and separations between walls and inadequately anchored floors were observed, with damage particularly concentrated in the central area of the aggregate. To assess the seismic vulnerability of the structure, software 3Muri was used. Nonlinear static analyses were performed to evaluate the global load-bearing capacity of the model, as well as kinematic analyses to examine and verify local failure mechanisms. These analyses revealed significant vulnerability of the structure to horizontal loads, showing how seismic action can easily activate local collapse mechanisms in the absence of adequate structural connections. The results provided a basis for the design of targeted strengthening interventions to improve the overall structural resistance and reduce the seismic vulnerability of the aggregate.

Keywords: Building aggregate, Masonry structures, Seismic response, Simplified Model, Structural modeling.

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1 INTRODUCTION

Recent seismic events that have affected the Italian territory have highlighted the inherent vulnerability of historic centers [1, 2, 3, 4, 5, 6], which are predominantly characterized by low-quality masonry constructions and structural deficiencies. This is especially evident in small historic settlements [7]. Masonry aggregates often exhibit significant structural heterogeneity due to their historical evolution, state of preservation, and the use of different materials and construction practices. Variations in building height, number of stories, and inter-story heights further exacerbate susceptibility to the activation of local and out-of-plane collapse mechanisms [8]. Given these peculiarities, the seismic vulnerability assessment of masonry aggregates in Italian historic centers emerges as a crucial and timely issue. Understanding their potential seismic response is essential not only for risk mitigation but also to identify structural weaknesses and to implement appropriate seismic protection measures [9]. In the seismic assessment of complex historical structures, two main challenges arise: the selection of the most suitable modeling approach and the absence of a standardized procedure for seismic analysis and verification. To address the former, various models based on different theoretical approaches are applicable, including micromodels and macromodels [10, 11]. In this case study, a macro-model was developed using the equivalent frame method, a widely adopted approach for global structural analysis capable of capturing potential collapse mechanisms. The structural model was implemented in the 3Muri software, discretizing the structure into a system of one-dimensional piers and beams connected by rigid nodes [12]. Local analyses were conducted to identify potential collapse mechanisms. Additionally, global assessment, including modal and pushover analyses, was carried out to evaluate the structure’s lateral capacity and dynamic response. Based on these analyses, retrofitting strategies were proposed to enhance the building’s seismic performance. This study highlights the critical need for seismic strengthening techniques that optimize structural safety while preserving architectural integrity. This research is part of the National Recovery and Resilience Plan (PNRR) – CN1 – Spoke 5, which focuses on risk analysis at the urban scale [13, 14], ensuring that all modeling and analyses carried out in this study align with the broader objectives of urban risk assessment and mitigation.

2 CASE STUDY

The case study is a building aggregate located in the hamlet of Prata, within the municipality of Lucoli, in the province of L’Aquila. The aggregate, as illustrated in Fig. 1, spans approximately 41 m in length, 32 m in width and comprises three levels with a maximum height of 12 m. It consists of two distinct building sections: a single structural building and a section comprising three interconnected buildings. A shared wall corner serves as the structural connection between these buildings providing a partial continuity. However, variations exist among the buildings in floor count, plan configuration, and floor and roof construction. The aggregate was constructed with load-bearing masonry composed of roughly hewn, unsquared limestone blocks of medium to small dimensions, typical of the L’Aquila area. Wall thicknesses average 74 cm at the ground floor and range from 40 to 90 cm at upper levels. Roofs are primarily gabled with purlin-based primary structures. Ground floor presents barrel vaults with some replaced by steel beam and hollow brick floors. Upper-level floors are predominantly steel beam and small vault constructions. The building has already been investigated in a previous research work conducted by Sorrentino et al. [15], in which a global response analysis was performed. Though this work focuses on different interventions and research objectives—

specifically, the need to assess the greater effectiveness of a strengthening strategy involving the entire aggregate and the potential risks associated with interventions applied only to disconnected portions of the aggregate, through a comparison of macroelement models—it nevertheless constitutes a valuable resource for the investigation conducted herein, specifically it provides a preliminary support for the description of the building along with the damage it sustained in the aftermath of the 2009 L'Aquila earthquake. For the sake of completeness, documented damage is briefly reported here. Post-earthquake inspections documented roof collapses and wall damage along Via Giorgio, which was intensified by inadequate maintenance and structural deterioration. Although no disintegration of the masonry fabric was observed, extensive in-plane cracking was detected. Localized collapse, attributed to wall overturning, was identified along the walls of Via Giorgio. Additionally, detachment was observed between some horizontal structures and the façade of the small building located along the southern slope. Another damage mechanism was identified in Via dei Cicisbei, as evidenced by the presence of cracks in the lateral walls. This phenomenon, however, was partially mitigated by existing tie rods, which positively contributed to limiting damage and containing deformations. For the purpose of this research work, in-situ surveys campaign was conducted to assess the as-built condition of the building, during which non-destructive diagnostic investigations were performed. Ambient vibration measurements, thermographic surveys, and endoscopic inspections were carried out as part of the investigation campaign. For the analyses carried out in this study, a Knowledge Level 1 (LC1) was assumed for the structural assessment. Masonry mechanical properties were defined in agreement with NTC 2018 guidelines [16].

Fig. 1 Plan and front view of the masonry aggregate located in Prata (AQ). The red rectangle highlights the wall for which the kinematic analysis results of the collapse mechanisms are reported. Adapted from [15]

Fig. 2 South-east longitudinal façade of the masonry aggregate *(Image courtesy of Prof. Luigi Sorrentino, DISG, Sapienza University of Rome)*

3 ANALYSES OF OUT-OF-PLANE LOCAL COLLAPSE MECHANISMS

Local mechanisms of the aggregate were studied according to nonlinear kinematic analysis, that relies on specific assumptions, including the characterization of masonry as a material with zero tensile strength and infinite compressive strength [17]. Additionally, it is assumed that no sliding occurs between the rigid blocks involved in the collapse mechanism. These simplified assumptions enable a clear and focused evaluation of the structural behavior, providing valuable insights into the seismic vulnerability of masonry buildings [18]. In particular, simple out-of-plane overturning mechanisms of selected walls were examined, with hinges placed at the foundation level and at a height of 2.38 m, corresponding to the first floor of the building, and vertical bending mechanisms were also assessed. The nonlinear kinematic approach requires determining the horizontal action that the structure can progressively withstand as the collapse mechanism evolves. This approach derives capacity curves, depicting the relationship between the horizontal action multiplier α and the displacement of a reference point in the system. This curve can be transformed into a capacity curve for an equivalent single-degree-of-freedom (SDOF) system, from which the ultimate displacement capacity of the collapse mechanism can be determined. The seismic assessment involves verifying that the displacement demand induced by seismic actions does not exceed the displacement corresponding to the ultimate limit state [16]. Table 1 presents the results for a representative wall, which is highlighted in Fig. 1 with a red rectangle, considering different types of mechanisms. For each case, the displacement demand (d_t) of the as-built structure and the corresponding capacity displacement prior to intervention (d_{c1}) are reported, along with the related capacity-to-demand ratio (d_{c1}/ d_t). Additionally, the capacity displacement (d_{c2}) following the installation of tie rods and the updated capacity-to-demand ratio are also provided (d_{c2}/ d_t). The verification has been performed at the Life-safety Limit State (LLS).

Mechanism	d_t (m/s^2)	d_{c1} (m/s^2)	d_{c1}/d_t (-)	d_{c2} (m/s^2)	d_{c2}/d_t (-)
Overturning mechanism with hinge at the foundation level	24.29	23.15	0.95	24.57	1.01
Overturning mechanism with hinge at 2.38 m	24.29	23.08	0.95	24.57	1.01
Vertical bending	11.98	18.65	1.56	18.71	1.56

Table 1 Capacity, demand and capacity-to-demand ratio of each wall according to the nonlinear kinematic (displacement-based) procedure of the Italian Building Code [16]

Considering that out-of-plane local collapse mechanisms can be effectively mitigated by the use of tie rods, which enhance the connection between façades and orthogonal walls, a configuration involving a monolithic wall restrained by a tie rod was also analysed. For this case, a non-linear formulation of the equation of motion was employed, following the approach proposed by AlShawa et al. [19].

In the present case, tie rods designed according to the force and displacement-based procedures established by the Italian Building Code [16] are considered. The intervention involved the installation of 12 mm diameter tie rods anchored by 300×300 mm metal plates in S235 steel. This intervention is aimed at restoring the connection between the walls and preventing local collapses.

4 GLOBAL MODELING

The case study was modelled in the 3Muri software environment using the macro-element approach, which is particularly well-suited for the seismic analysis of masonry structures. The in-plane behavior of the masonry walls was represented cording to the equivalent frame model, wherein each wall is discretized into a series of piers and spandrels (two-node macro-elements) connected by rigid nodal zones. The reference model assumes a global box-type behaviour of the aggregate, represented by a three-dimensional equivalent frame configuration, with walls linked by horizontal diaphragms at each floor level [12].

4.1 Modeling Strategies

Floor and roof structures, demonstrating diverse construction styles, were modeled according to survey data. The aggregate was organized into three tiers, corresponding to elevations of 2.38 m, 5.29 m, and 8.20 m, respectively. The first level's floor layout displays a varied arrangement of flooring materials, presumably due to multiple construction phases and the necessity to accommodate distinct functional needs. Brick vaults represent a substantial component of the construction, primarily located in the center region of the aggregate. Moreover, floors constructed with steel beams and hollow clay blocks as well as timber floors have been noted, predominantly linked to the building's peripheral areas. The second level presents an alternative construction, with jack arch floor. The third level comprises floors constructed with steel beams and hollow clay blocks, in addition to jack arch floors. The roof structures are defined by horizontal components made of wooden plank decking. All the geometric information necessary for the modeling phase, along with the data for the load analysis of the slabs and the roof, were obtained from the geometric survey and the construction characteristics specified in the technical building codes [16].

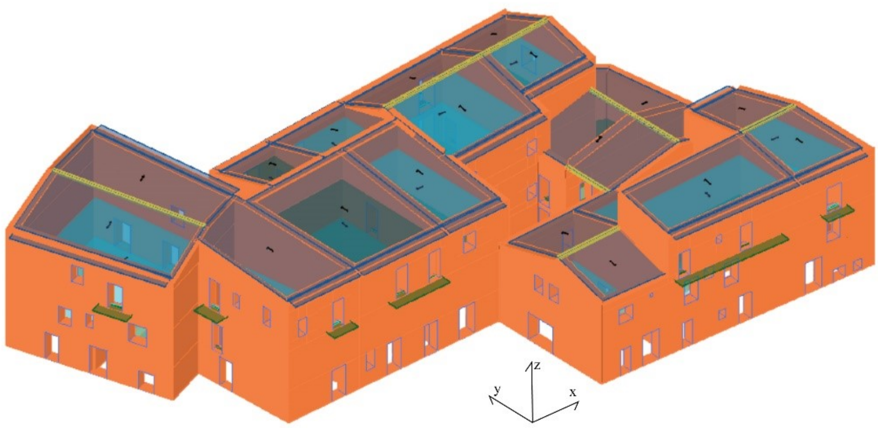

Fig. 3 3D view of the aggregate model in 3Muri software

5 AS BUILT NUMERICAL MODEL ANALYSIS

A detailed numerical analysis, utilizing either linear or nonlinear methods, was done to evaluate the seismic susceptibility of the aggregate. Modal analysis assessed dynamic characteristics (including natural frequencies, mode shapes, and participation factors), whereas pushover analysis elucidated non-linear behavior, collapse processes and overall capacity.
Global evaluations of the structure were conducted in accordance with the seismic provisions of the Italian Building Code [16].

5.1 Modal Analyses

The modal analysis of the masonry aggregate reveals a relatively stiff structural behaviour, with a first-mode period of 0.23 s, as reported in Table 2. Significant global modes are already evident within the first five modes, which excite at least 75% of the total structural mass. Specifically, the first five modes account for a cumulative mass participation of 77% in the transverse direction (y) and 78% in the longitudinal direction (x). Higher modes exhibit progressively lower mass participation, as their contribution decreases relative to the primary modes, where the mass participation exceeds 50. In light of these results and following the Italian building code [16], the criterion for applying nonlinear static analysis—normally requiring that the fundamental mode in the considered direction involve at least 75% of the total mass—can be extended to cases in which the mass participation is not less than 60%.

5.2 Pushover Analyses

A nonlinear static analysis was performed to assess the structure's seismic vulnerability. Two distinct horizontal force distributions—mass proportional and static load proportional—were separately applied along each of the two principal axes. Both loading orientations (positive and negative) and accidental eccentricities of the center of mass (positive, negative, and null) were included, resulting in 24 static load combinations. The maximum displacements (d_u) in both directions are equal to 0.42 cm, showing a symmetrical structural response along the two primary axes. The peak observed shear force is 12.22×10^3 kN in the transverse direction and 11.97×10^3 kN in the longitudinal direction, this small difference being due to the arrangement of load-bearing walls, relative stiffness, and distribution of openings. The safety index (*SI*) is

0.353 in the longitudinal direction (x) and 0.398 in the transverse direction (y). The analysis results highlight the necessity for focused measures to improve the seismic safety of both local and global collapse mechanisms.

6 SEISMIC RETROFITTING STRATEGIES

Following the linear and nonlinear structural analyses, retrofitting interventions were designed, targeted at enhancing the aggregate's seismic safety while preserving its historical and architectural integrity. Various strengthening techniques were adopted as part of the overall intervention strategy; however, only one is described in detail in this section. A global strengthening strategy using reinforced concrete plaster was implemented throughout the entire aggregate building. This consolidation technique employs a robust fiber mesh integrated into a cementitious matrix. The intervention improves the mechanical qualities of masonry by increasing its strength and enhancing its ductility. In addition, steel frames were installed around the openings, reinforcing edges and improving shear, bending, and compression resistance, thereby reducing the risk of local damage and contributing to an overall improved seismic capacity.

7 COMPARISON OF THE NUMERICAL RESULTS

Global strengthening interventions were incorporated into the 3Muri numerical model to evaluate and quantify the improvements in capacity. Post-intervention modal analysis (using reinforced plaster and steel frames) shows a modified dynamic behavior compared to the as built condition. Vibration periods decreased, indicating increased structural stiffness. Specifically, the first mode period is 0.17 s (compared to an initial period of 0.23 s), reflecting improved structural stiffness due to the interventions and enhanced overall cohesion of the masonry. The first two modes remain dominated by the x and y directions but exhibit a redistribution of the participating mass. In the first mode, the mass participation in the x direction is 56.93%, while in the second mode is 14.95% in the y direction. This indicates stronger longitudinal stiffness, likely due to interventions targeted at reducing local bending and increased lateral capacity. In the third mode, modal participation in the y direction is 56.85% (compared to 4.60% initially), indicating a significant improvement in behavior in this direction. The modal participation in the subsequent modes is more distributed, reducing the dominance of torsional behavior assessed in the previous configuration. Table 2 and Table 3 provide a detailed comparison of vibration modes for the as built model and the retrofitted model of the aggregate, respectively. These tables present the vibration period (T) and the percentage of participating masses in the x direction (M_x), y direction (M_y), and z direction (M_z).

Mode	T (s)	M_x (%)	M_y (%)	M_z (%)
1	0.23	55.47	3.90	0.00
2	0.22	3.58	64.28	0.03
3	0.21	0.51	4.60	0.02
4	0.19	12.63	1.65	0.01
5	0.18	6.38	2.73	0.00

Table 2 . Periods (T) of vibration of the first four modes and related mass participation ratios in x (M_x), y (M_y) and z (M_z) directions for the as built model.

Mode	T (s)	M_x (%)	M_y (%)	M_z (%)
1	0.17	56.93	3.08	0.00
2	0.16	0.22	14.95	0.06
3	0.15	1.11	56.85	0.00
4	0.14	1.95	0.13	0.00
5	0.14	3.96	0.60	0.01

Table 3. Periods (T) of vibration of the first four modes and related mass participation ratios in x (M_x), y (M_y) and z (M_z) directions for the retrofitted model.

The results of the pushover analysis confirm the effectiveness of the implemented strengthening measures. Fig. 4 presents the resulting pushover curves, in terms of base shear vs. lateral displacement at the control point located at the roof level. The retrofitted condition exhibits a substantial increase in base shear capacity in both principal directions when compared to the as built state. Following the interventions, the structure's load-bearing capacity significantly improves, with peak base shear values exceeding 20.00×10^3 kN in both directions. This enhancement is accompanied by an increase in elastic stiffness, consistent with the outcomes of the modal analysis. Moreover, the retrofitted models show an enhanced displacement capacity, ranging from 2.8% to 3.4%, as evidenced by the increase in maximum displacement before loss of load bearing capacity (1.38 cm in the x direction and 1.68 cm in the y direction). These findings validate the effectiveness of the combined reinforced concrete plaster and steel framing techniques in reducing seismic vulnerability. In contrast, the as built configuration exhibited a premature brittle failure mechanism, characterised by a maximum displacement of only 0.5 cm, followed by a sudden drop in load-bearing capacity immediately after reaching peak strength. The observed shift in structural response clearly indicates a transition from a brittle failure mode to a more controlled ductile global mechanism.

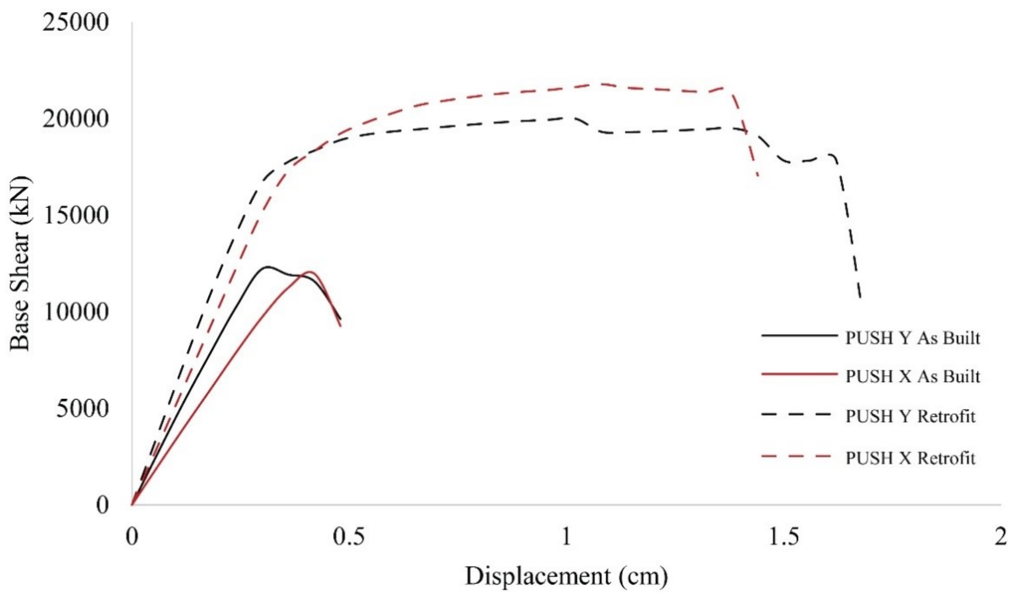

Fig. 4 Comparison between pushover curves before and after retrofit interventions.

Fig. 5 presents a radial diagram that compares the capacity-to-demand ratios at the Life-safety Limit State (LLS) of all the 24 pushover analyses for the as built and retrofitted models. A comparison of the two models reveals a substantial enhancement in structural capacity following the strengthening interventions. Specifically, the safety index for the two analysed conditions—assessed through pushover analyses in the transverse and longitudinal directions—showed an increase, with values of 1.79 and 1.08, respectively, validating the efficacy of the retrofitting methods.

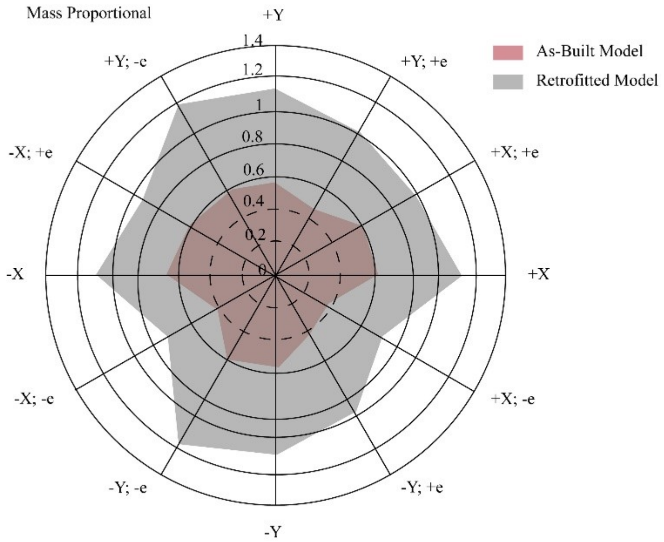

Fig. 5 Radial diagrams of the capacity-to-demand ratio for as built and retrofitted models.

8 CONCLUSIONS

This study focused on the seismic assessment and retrofitting of a masonry aggregate damaged by the 2009 L'Aquila earthquake. The definition of the numerical model was carried out following in-situ diagnostic investigations, which served to inform the structural configuration and material properties. The analyses revealed the inherent seismic vulnerability of the structure, a condition commonly observed in building aggregates within historic centres across Italy, which often exhibit widespread and severe damage during seismic events. Modal analysis enabled the identification of key dynamic properties of the aggregate, while nonlinear pushover analyses highlighted critical structural weaknesses. These insights guided the development of targeted retrofitting strategies. The proposed interventions, featuring reinforced plaster and steel framing of openings, were specifically designed to improve the seismic performance while preserving the historical and architectural character of the aggregate. Post-intervention analyses demonstrated significant enhancements in structural behaviour, including increased strength, stiffness and displacement capacity. These findings highlight the importance of a comprehensive seismic assessment and the implementation of well-conceived retrofitting measures for historic masonry aggregates. Such strategies are essential not only for mitigating seismic risk but also for ensuring the long-term preservation of cultural heritage in earthquake-prone regions.

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