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SEISMIC VULNERABILITY ASSESSMENT OF 1960S REINFORCED CONCRETE FRAME BUILDINGS WITH INFILL MASONRY WALLS

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Abstract

This study investigates the seismic performance of low-rise and mid-rise reinforced concrete (RC) structures with and without masonry infills through nonlinear static and dynamic analyses. The research emphasizes the role of confined masonry in enhancing structural stiffness and strength, as well as its contribution to the overall seismic resilience of buildings. Field testing, including ambient vibration measurements, and historical records were integrated to calibrate the numerical models and refine capacity curves. Results indicate that masonry infills significantly improve base shear capacity and limit state performance, particularly in terms of Damage Limitation (DL) and Significant Damage (SD). In the absence of infills, structures exhibited increased vulnerability to seismic forces, leading to potential collapse. The influence of material properties, such as masonry strength and concrete grade, was evaluated through parametric studies. The findings highlight the necessity of accurate material characterization and proper assessment methodologies, aligning with the guidelines of Eurocode 8 and recent advances in seismic engineering. Additionally, the importance of ambient vibration testing for model calibration is underscored, offering a non-invasive approach to assess the dynamic properties of existing buildings. This research contributes to the ongoing efforts to improve the seismic assessment and retrofitting of vulnerable structures in earthquake-prone regions.

Keywords: Reinforced concrete frame, Seismic performance, Material testing, Model calibration, Retrofitting.

1. Introduction

Kosova lies in a moderate seismic vulnerable zone. The records from different sources shows that there are a number of magnitude VI or VII that occurred in Kosovo in the last 500 years. In this paper, for the stock of buildings selected, the building codes at the time of their construction did not prioritize seismic activity as much as they do today. The selected buildings were constructed during the period from 1960 to 1970. These structures were built using in situ concrete and prefabricated slab decks, consisting of a concrete frame structure combined with masonry walls, with materials categorized according to the standards of that time. Currently, the design of buildings complies with Euro norms, and earthquake intensity is measured in terms of PGA. In Kosovo, the peak ground acceleration ranges from 0.05 to 0.20 ag/g. Concrete frame structures, often with infilled masonry, were first constructed in Kosovo during the 1950s and 1960s. These buildings were typically not high-rise structures but rather 4- to 6-story buildings. In such cases, although earthquakes affect the structure, their impact may not be as significant as it would be on 10- to 14-story buildings [1]. Nevertheless, a proper risk assessment requires foreseeing any possible risk that may arise during the lifetime of the building, and one of them is also seismic activity [2][3].

A building's inadequate seismic response is mainly caused by poor execution of key structural elements, connections, and assembly, as well as the use of materials such as smooth rebar, low-quality concrete, and outdated design principles. Consequently, in European seismic-prone countries, the

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assessment of existing structures is a priority since most residential buildings were designed using old versions of seismic codes or without applying the codes. In many of these buildings, there are significant uncertainties regarding their nonlinear behavior [4]. The seismic vulnerability of existing reinforced concrete (RC) structures infilled with masonry walls is evident from the observed damages to failed structures across Europe after earthquakes. The infills in a building can enhance its performance; however, in some cases, they may also have a negative impact. Infills can induce different failure mechanisms. For instance, infill from the first floor upward could affect the global structure and, under seismic loading, create a soft-story mechanism. They may also cause short-column mechanisms or result in localized failure mechanisms [5]. Several studies have highlighted the impact of masonry infills on building performance, as masonry walls can exhibit shear strength [6][7].

A full-scale test on a three-story building strengthened with infill brick walls showed that the addition of these walls prevented slab collapse and increased both the strength and stiffness of the original frame structure [8]. Similarly, Dolsek and Fajfar observed that infill walls enhance the stiffness and strength of a structure, provided the seismic demand does not exceed the deformation capacity of the infill walls [9]. To mitigate the devastating effects of seismic events, it is crucial to evaluate the vulnerability of buildings to plan effective mitigation policies and structural strengthening interventions. Assessing the performance of a building involves a combination of in situ tests, laboratory tests, and numerical analysis. These methods allow for an analysis of the structure's behavior under permanent, transient, and seismic loads. Numerical analysis alone is insufficient, as the influence of infill walls on building performance cannot be neglected for this type of structure. Additionally, not all walls may affect the structure's behavior under seismic loads. To address this, material testing and ambient vibration tests were conducted to evaluate the material properties and the dynamic characteristics of the buildings [10].

Ambient vibration testing records real-time vibrations of the structure, typically caused by environmental factors such as wind, occupants, or other micro-vibrations [11]. Based on the in situ data, a validated structural model was developed to simulate and calibrate the building’s behavior. In this study, an existing concrete frame structure with masonry infill was analyzed. The 3D numerical model was created using software such as CSI and Seismosoft package [12][13]. This model was calibrated with results obtained from ambient vibration tests. A parametric study was conducted to evaluate the influence of the infills on the structure and to determine how the mechanical properties of materials affect global behavior. Non-linear static analysis was performed to assess the seismic vulnerability of the building [14].

2. Description of structure

2.1. General Description

A large neighborhood, known for its replicated buildings, has been selected for this study. The buildings in this neighborhood share the same year of construction, materials, construction technology, and structural system. The selected building is a 6-story reinforced concrete structure with infilled walls, located in Prishtina, the capital city of Kosovo. A view of the location is presented in Fig. 1.

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Figure 1. Series of replicated buildings

The buildings are aligned with joints between the individual group of apartments with the same geometry and other parameters. The selected building has 2 bays in "Y" direction and 5 bays in "X" direction. The maximum span between columns is 3.85 m in "X" direction and 5.60 m in "Y" direction , with rectangular section and designed with characteristic resistance f_{ck}=22.0 N/mm^2 in basement and other floors , except third and fourth floor with lower value. All columns are reinforced with 4Ø16 mm main bars in the basement, ground, first and second floor and 4Ø14 mm bars on the third and fourth floor. The stirrups are Ø6/25 cm are in general for all columns. In scope of the construction methodology during the built are used the horizontal RC beams, reinforced with Ø8/10 cm and characteristics of concrete f_{ck}=20.0 N/mm^2. The typical floor plan is presented in fig.2 and section in fig.3.

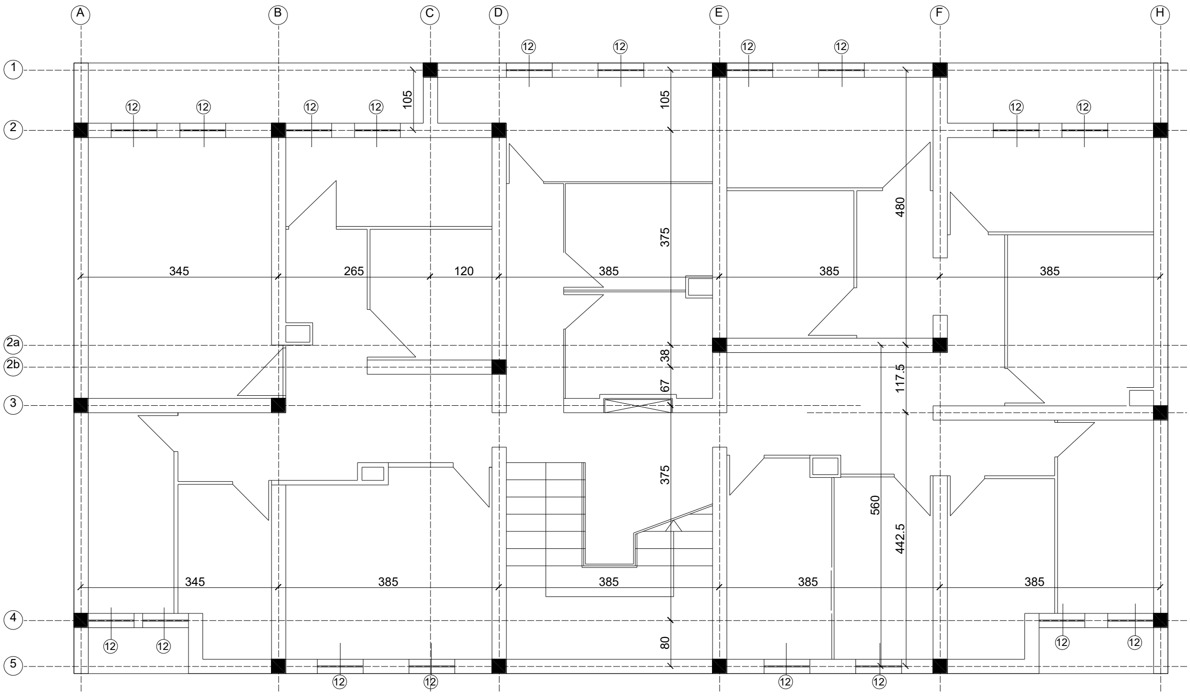

Figure 2. Geometry of typical floor plan

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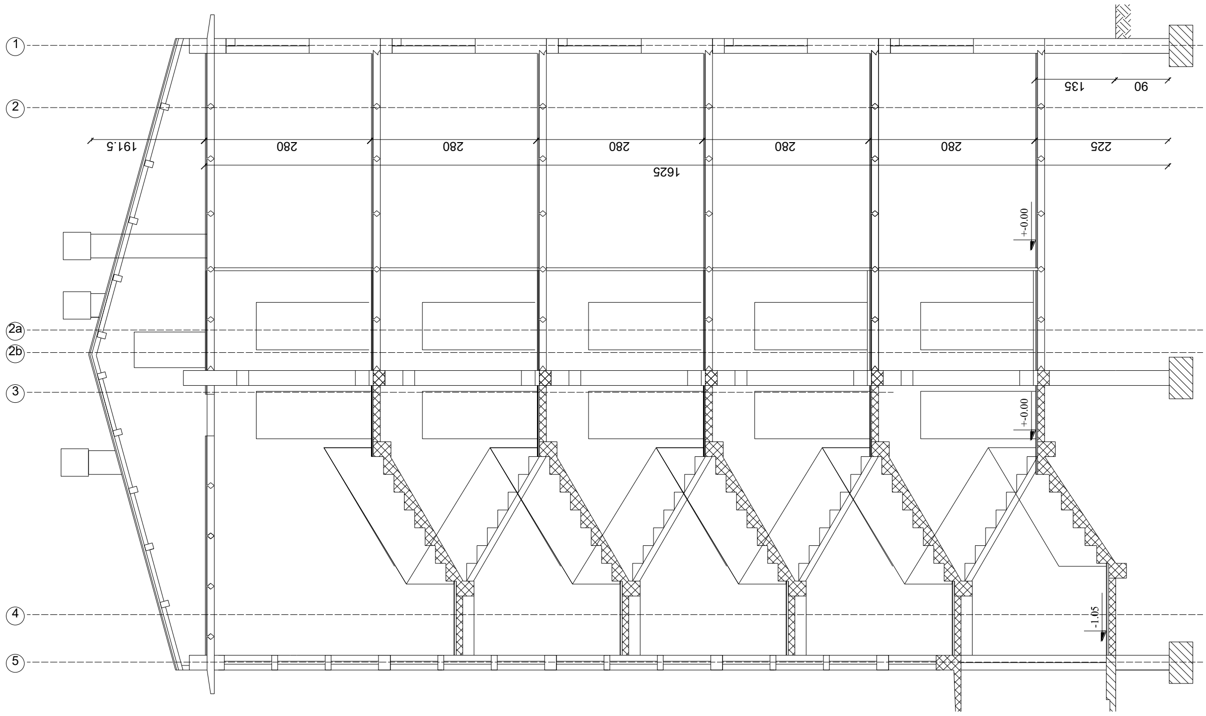

Figure 3. Vertical cross section

2.2. Testing of structural elements

2.2.1. Description the proposed Methodology

The proposed methodology for assessing the seismic vulnerability of existing reinforced concrete (RC) structures with masonry infills is structured into the following systematic steps:

1. **Collection of Technical Information**: Comprehensive data collection is undertaken to enhance the structural knowledge of the building. This includes archival research, construction drawings, and field investigations to identify critical design parameters and material properties.
2. **Estimation of Structural Capacity**: The structural system's capacity is evaluated with respect to the Life Safety (LS) performance limit state. This step involves analyzing the structural integrity under seismic loads to ensure compliance with LS criteria.
3. **Demand Evaluation (PGAc)**: The seismic demand is assessed by determining the Peak Ground Acceleration (PGA) corresponding to the building's location and seismic zone. This evaluation considers regional seismic hazard data and site-specific factors.
4. **Identification of Vulnerability Class**: Based on the assessed capacity and demand, the vulnerability class of the structure is identified. This classification aids in prioritizing retrofitting measures and informs risk mitigation strategies.

2.2.1.1. In situ testing - Characteristic value of concrete quality – Schmidt hammer test

As part of the evaluation, the quality of concrete in the structural elements was assessed using the non-destructive Schmidt Hammer Test. The testing procedure adhered to the requirements of Standards EN 12504-2, ensuring consistency and reliability in the results. Table 1 summarizes the findings obtained from different structural positions.

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Table 1. Non-destructive testing results for different positions

Position	Age (days)	Mean reading	Calibrated Strength	fck (N/mm²)
Column	>28	42	37.87	30
Foundation	>28	36	24.5.6	20
Horizontal Beams	>28	44	38.8	30

A comparative analysis of these results against the original design specifications and in situ tests revealed that the concrete has not experienced significant chemical degradation over time. Consequently, the material properties have remained stable, ensuring structural reliability.

2.2.2. Laboratory tests - Testing the masonry unit-clay bricks

Samples of masonry units were carefully extracted from the building for detailed compression strength testing in the laboratory of the Faculty of Civil Engineering. A total of six clay bricks, each with standardized dimensions of 250 × 120 × 62 mm, were selected and grouped into three representative testing samples. The structural behavior of wall elements is intrinsically linked to the mechanical properties of the masonry units, which play a pivotal role in the overall seismic and load-bearing performance of the infill walls.

In this context, the infill walls of the studied building were partially constructed using clay bricks. Compression strength tests were carried out in strict compliance with Standards EN 772, ensuring the reliability and accuracy of the obtained results. These tests provided valuable insights into the mechanical characteristics of the masonry units, including their ability to withstand compressive forces under operational conditions. The findings are summarized in Table 2, which presents a detailed overview of the compression properties of the sampled materials.

Table 2. Testing results of clay bricks

Sample	Load (kN)	Mean value (N/mm²)	Shape factor	f_b (N/mm²)
S”1”	770	24.3		
S”2”	706	23.5	0.75	16
S”3”	460	16.0		

2.3. In situ testing - Ambient Vibration Test

Ambient vibration testing is a non-destructive technique utilized to evaluate the dynamic properties of structures by examining their responses to natural environmental excitations, such as wind, traffic-induced vibrations, or human activity. This approach is widely applied to determine critical parameters including natural frequencies, mode shapes, and damping ratios of the structural system [15].
Measurement points were strategically located according to the prescribed measurement protocol, ensuring that the selected positions were free from steady-state vibrations caused by eccentric machinery or other rotary influences. In instances where transient frequencies were identified, they were carefully filtered out during the signal processing phase to ensure the accuracy of the results [16].
The testing process employed standard equipment for structural analysis, which included accelerometers, advanced data acquisition systems, signal processing software, and controlled excitation sources. Key considerations during the procedure involved minimizing environmental interference, optimizing sensor placement, and maintaining high data quality. This method offers several advantages, including its non-invasive nature, speed, and simplicity, allowing it to be performed

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on active structures without disrupting their normal operations. Since the vibration amplitudes in such tests are small, ambient vibration testing effectively captures the linear behavior of structures. Previous studies have demonstrated that results obtained from ambient vibration tests are consistent with those from forced vibration experiments conducted within the linear excitation range [17].
Data acquisition involved the conversion of analog signals from the sensing devices into digital formats, followed by permanent storage for subsequent analysis. Rigorous checks were performed to address potential errors arising from quantization, aliasing, filtering, and signal leakage. These steps were essential to ensure the integrity of the data and to derive accurate parameter estimates [18]. The detailed layout of the measurement points and the testing plan for each floor are illustrated in Fig. 4.

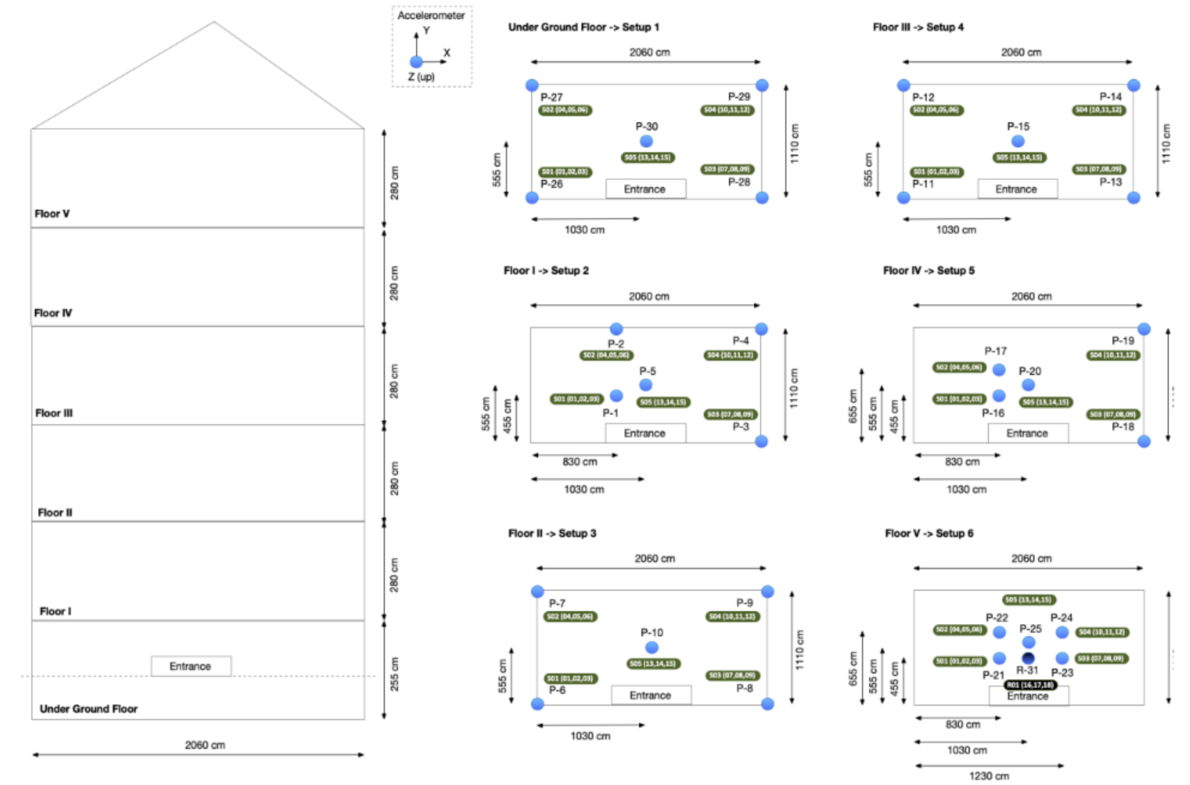

Figure 4. Layout of locations the accelerometers

2.3.1. Testing results

The measurements were conducted on April 20, 2024, starting from 9:30 a.m. and concluding at 1:00 p.m. Each measurement lasted a total of 300 seconds, equivalent to 5 minutes. Given the analysis of multiple measurement series, the calculated singular values were averaged to display the curves effectively. Additionally, the identified mode shapes, along with their corresponding direction, frequency (f), and period (T), are summarized in Table 3. Fig. 5 present singular values of spectral densities.[15].

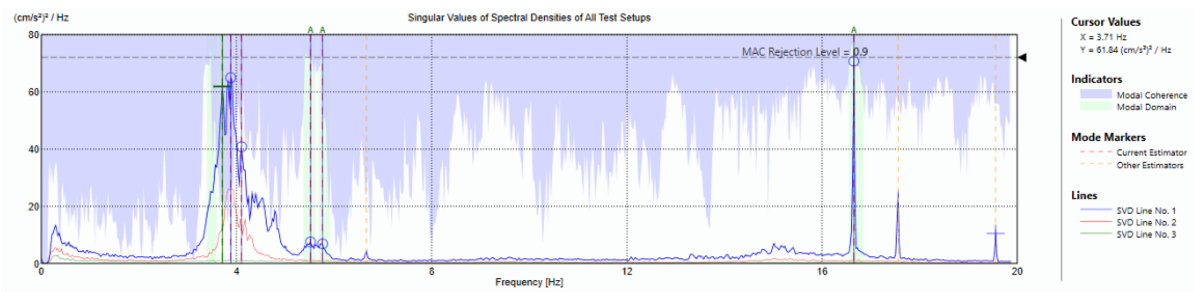

Figure 5. EFDD singular values of spectral density for all setups[14]

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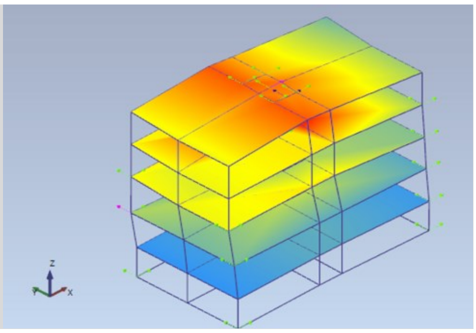
The analysis identified a total of 8 mode shapes, among which 4 can be considered global mode shapes with frequencies f1=3.711 Hz, f2=4.102 Hz, f3=5.518 Hz and f4=5.762 Hz. The remaining mode shapes are local, signifying independent oscillations of individual or adjacent. structural elements [15].

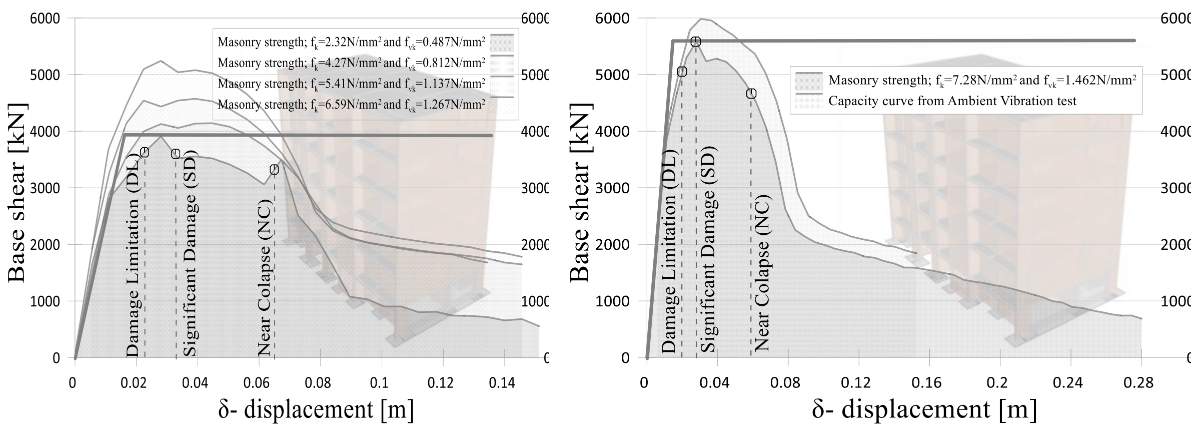
Table 3. Identified dynamic properties of study case

Mode shape	Description	f(Hz)	T(sec)
1	Translations in Y direction slight rotation	3.711	0.269
2	Translations in X direction slight rotation	4.102	0.244
3	Torsion	5.5.18	0.181



3. Parametric study

Infill walls significantly influence the global and local behavior of structures. Globally, they enhance stiffness and strength, improving seismic performance and dynamic characteristics. Locally, they affect load distribution and may induce failure mechanisms like soft-story or short-column effects. To study these impacts, a nonlinear static analysis was conducted, calibrated with in situ test data. This method, essential for assessing buildings in seismic regions, involves pushover analyses under constant gravity loads (1.00G + 0.30Q) and incremental lateral forces to simulate seismic inertia. Self-weight and additional slab loads are included in the 3D model, with two vertical load patterns: uniform (simulating soft-story mechanisms) and modal (aligned with the fundamental mode shape). Analyses consider both positive and negative lateral directions, with accidental eccentricities to address mass and seismic motion uncertainties. Each pushover analysis produces a capacity curve (base shear vs. horizontal displacement at a control node). Comparing capacity with demand from a 5% damped Linear Response Spectrum determines Limit States (Near Collapse, Significant Damage, or Damage Limitation). Structural demands, verified against Eurocode 8 - Part 3, account for brittle and ductile behaviors, material nonlinearity, and section interaction effects.



(a) (b)

Figure 6. Calibration of capacity curves: (a) Influence of masonry properties on structural dynamic behavior; (b) Field-test-based comparison

The initial model assumes masonry with moderate mechanical performance, simulating a scenario where lower-cost, lower-performance masonry products are used. This assumption leads to discrepancies in modal periods and frequencies compared to the calibrated model. Despite this moderate

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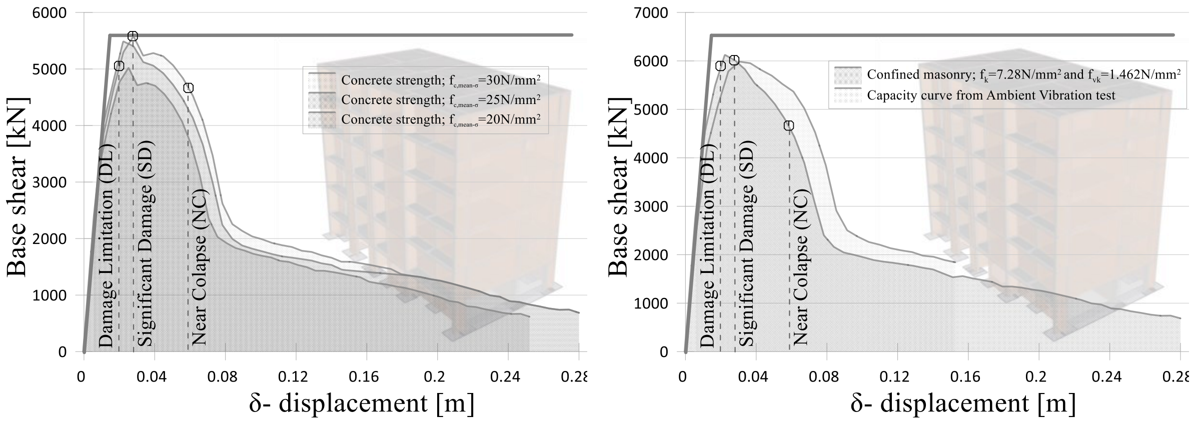
characterization, the overall influence of the masonry on the structure's behavior is relatively high, with a notable 25% difference observed in the DL state between the initial and calibrated model (fig. 6(a)).

Experimental tests on the masonry units demonstrated performance exceeding the characteristic strength determined in laboratory conditions. However, while the structure includes confined masonry, the initial modeling treated all masonry as unconfined, introducing inconsistencies in the calibration of the final model, which incorporates test-based properties as represented in fig. 6(b). As the project documentation does not explicitly identify the confined masonry elements, further field investigations are needed to refine the capacity curves and address these uncertainties.

To account for the influence of confined masonry, assumptions were made based on the construction techniques likely employed during the building's execution. Masonry along the perimeter and near the main corridor was presumed to be confined. As illustrated in Fig. 7(b), incorporating these assumptions reduces the discrepancy in base shear, bringing the differences in DL and SD states to below 10%. However, additional destructive and non-destructive testing is essential to verify the locations and properties of the confined masonry.



(a) (b)

Figure 7. Calibration process of capacity curves; (a)impact of concrete strength, (b)calibration considering confined masonry

Field testing of concrete mechanical properties revealed that the in-situ performance of the concrete exceeds the specifications outlined in the project documentation. The observed mechanical properties suggest a higher concrete strength class than initially assumed in the design phase. This discrepancy highlights the potential for underestimation of the concrete's structural contribution in the original project specifications.

To evaluate the impact of concrete strength on structural behavior, a series of parametric study cases was conducted, each representing different levels of concrete strength. These cases examine variations in stiffness, load-bearing capacity, and overall structural performance under seismic and gravitational loads. The results, as illustrated in Fig. 7(a), provide a comparative analysis of how variations in concrete strength influence the capacity curve, particularly in terms of base shear and displacement thresholds. This analysis demonstrates the critical role of accurate characterization of material properties in structural modeling and the potential benefits of higher-than-expected concrete performance for improving the building's seismic resilience.

4. Results

The analysis presented in this study further highlights the critical role of historical records in understanding and improving the structural knowledge of the analyzed building. Data collected from the city archive was instrumental in defining the structural layout and characteristics, enabling accurate modeling and assessment. Detailed structural analysis revealed that the building's capacity is sufficient to withstand the Peak Ground Acceleration (PGA) for the designated seismic zone, primarily due to the stabilizing effect of the infill walls. However, the absence of these infills significantly compromises the structural integrity, making it prone to severe damage and potential unusability. Additionally, the displacement associated with the limit states is reduced as masonry strength increases, indicating better overall structural integrity under seismic loads. For higher masonry strength, the range between DL and SD states narrows, suggesting a stiffer response and a reduced likelihood of intermediate damage during seismic events. These findings emphasize the critical role of masonry strength and infill walls in determining the structure's seismic performance. Accurate material characterization, combined with historical data, proves essential for reliable predictions and improved structural resilience, underlining the importance of integrating both engineering analysis and historical research in the assessment of heritage structures.

The results in Fig. 6(a) demonstrate a significant influence of masonry strength on the structural response. Variations in masonry strength impact both the base shear capacity and the displacement thresholds corresponding to the DL, SD, and NC states. Specifically, masonry with higher strength (f_m=6.59 N/mm^2) exhibits a notable increase in peak base shear capacity, approximately 35–40% higher than that of the lowest strength masonry (f_m=2.32 N/mm^2). This improvement reflects the enhanced stiffness and strength provided by higher-performance masonry materials, which contribute to greater resistance against lateral forces.

Variations in concrete strength as depicted in fig. 7(a) directly affect the base shear capacity and displacement thresholds corresponding to the DL, SD, and NC states. Structures with higher concrete strength exhibit an approximately 10–15% increase in peak base shear capacity compared to those with lower strength, reflecting their enhanced resistance to lateral forces. Additionally, higher-strength concrete reduces displacements at all limit states, indicating improved structural stiffness and overall seismic resilience.

As illustrated in fig. 7(b) The results underscore the critical role of confined masonry in enhancing structural performance under seismic loading. The incorporation of confined masonry with properties of significantly improves the capacity curve, as evidenced by increased base shear capacity and better alignment with the capacity curve derived from Ambient Vibration tests. Confined masonry contributes to higher stiffness and strength, which delays the transition between the Damage Limitation (DL), Significant Damage (SD), and Near Collapse (NC) states.

The enhanced confinement effects narrow the gap between numerical predictions and field-test results, reducing discrepancies in both displacement and base shear. These findings highlight the necessity of accurate field validation and appropriate modeling of confined masonry to capture its stabilizing effects. Confined masonry, particularly near the building perimeter and structural corridors, plays a pivotal role in ensuring seismic resilience and must be prioritized in assessment and retrofitting strategies.

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