



Evolution of Modal Properties in Masonry Buildings: Influence of Damage and Retrofit Strategies

M. Banicek¹, M. Shaqfa² and J. Atalic³

ABSTRACT

Historic unreinforced masonry (URM) buildings are highly vulnerable to seismic action, particularly to out-of-plane (OOP) failure mechanisms. This study investigates the evolution of modal properties of a representative four-story URM building in the historic center of Zagreb, Croatia, under progressive damage and reversible retrofit strategies. A 3D finite element model was developed in Abaqus, where masonry walls were represented by solid elements using the Concrete Damage Plasticity (CDP) model, and timber floors by orthotropic shell elements. Weak wall-to-wall connections and stiffness degradation were explicitly modeled. Multiple scenarios, including as-built, damaged, and retrofitted configurations (with timber diaphragm stiffening and tensioned anchors), were analyzed through linear modal and nonlinear time-history analyses. Results show that earthquake-induced damage leads to significant period elongation, redistribution of modal mass participation ratios (PMR), and increased torsional effects. Damage concentrates on wall intersections and spandrels, causing stiffness loss and modal shape changes. Retrofit measures reduce damage localization and stabilize modal properties, highlighting their effectiveness in improving seismic performance and preserving heritage structures.

Introduction

Unreinforced masonry (URM) buildings represent much of the building stock in many historic European city centers, including Zagreb, Croatia. These structures, built before the advent of seismic design, exhibit brittle behavior, poor wall-to-wall and floor-to-wall connections, and are highly vulnerable to out-of-plane failure during earthquakes [1].

The 2020 Zagreb (Mw 5.4) and Petrinja (Mw 6.4) earthquakes revealed extensive damage to URM structures, including gable collapses, façade detachment, spandrel cracking, and partition wall failures [1–3]. Such mechanisms highlight the importance of understanding how structural degradation influences dynamic behavior. Modal parameters, such as natural frequencies, mode shapes, and PMRs, provide valuable insights into structural health and seismic vulnerability [4, 5].

This study aims to quantify how progressive damage and reversible retrofit strategies affect the dynamic characteristics of a representative URM building. Special emphasis is placed on linking changes in modal properties to the distribution and intensity of earthquake-induced damage using the Zagreb 2020 earthquake record.

¹ Postdoctoral researcher, Croatian Centre for Earthquake Engineering, Faculty of Civil Engineering, University of Zagreb, Kaciceva Street, Zagreb, Croatia (email: maja.banicek@grad.unizg.hr)

² Postdoctoral researcher, Seminar for Applied Mathematics, Department of Mathematics, ETH Zurich, Rämistrasse 10, 8092 Zurich, Switzerland

³ Professor, Department of Engineering Mechanics, Faculty of Civil Engineering, University of Zagreb, Kaciceva Street 26, 10000 Zagreb, Croatia

Numerical Model and Analysis Setup

The selected case study is a representative four-story URM building typical of Zagreb's early 20th-century construction, following the modeling strategy previously presented in [6]. Masonry walls were represented by 3D solid elements employing the CDP model implemented in Abaqus [7, 8], while timber diaphragms were modeled using orthotropic shell elements. The adopted continuum-based CDP approach enables the simulation of stiffness degradation, tensile cracking, and compressive crushing within a computationally efficient finite-element framework. The key masonry parameters included density $\rho = 2000 \text{ kg/m}^3$, Young's modulus $E = 1500 \text{ MPa}$, compressive strength $f_c = 3.5 \text{ MPa}$, and tensile strength $f_t = 0.15 \text{ MPa}$. The adopted parameters were selected based on available experimental data for Zagreb masonry and commonly used literature values. Timber floors were modeled as orthotropic shell elements to capture the variation of in-plane stiffness in two orthogonal directions and the shear stiffness of the diaphragm. Weak wall-to-wall and floor-to-wall connections were explicitly simulated. Cases A–E included a static loading step followed by modal analysis, while Cases F and G included nonlinear time-history analysis followed by modal analysis of the damaged state (Table 1). The nonlinear time-history analyses were performed using the recorded horizontal components of the March 22, 2020 Zagreb earthquake. The record was applied without spectral scaling or filtering in order to preserve the original frequency content representative of downtown Zagreb site conditions.

Table 1. Cases used for the study (summary of model variations).

Case	Connection Wall B–ACD	Wooden floor	Partition walls	Modal/Time History
A	Good	Single	Yes	Modal
B	Weak	Single	Yes	Modal
C	Good	Double	Yes	Modal
D	Good	Single	No	Modal
E	Good	Double	No	Modal
F	Good	Single	No	Time History then Modal
G	Good	Double	No	Time History then Modal

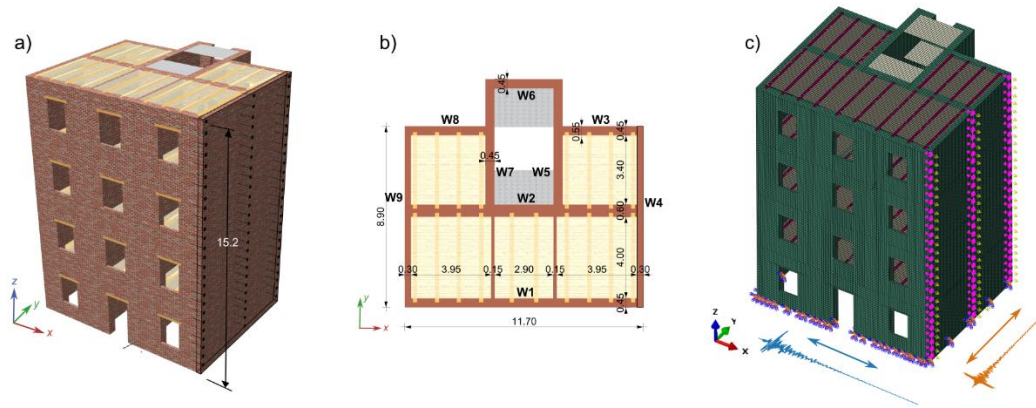


Figure 1. Building geometry and numerical model (dimensions in meters).

Results and Discussion

Evolution of Modal Properties

The analysis of fundamental periods and modal participation ratios (PMRs) across all scenarios (Cases A–G) (see Fig. 2. and 3.) highlights how structural configuration, connection quality, and damage govern dynamic behavior. In the as-built model (Case A), the first translational modes occur at about 0.33 s with $\text{PMR}_x \approx 73 \%$ and $\text{PMR}_y \approx 68 \%$, and the torsional mode contributes $\sim 39 \%$. Introducing weak wall-to-wall connections (Case B) slightly lengthens periods and reduces PMR_x , indicating partial decoupling of longitudinal and transverse walls. Diaphragm stiffening (Case C) shortens periods by $\sim 2\text{--}3 \%$, improving load transfer, while removal of partition walls (Case D) slightly increases periods and enhances torsional effects.

The combined strategy (Case E) results in a more balanced PMR distribution and improved load transfer between orthogonal wall systems.

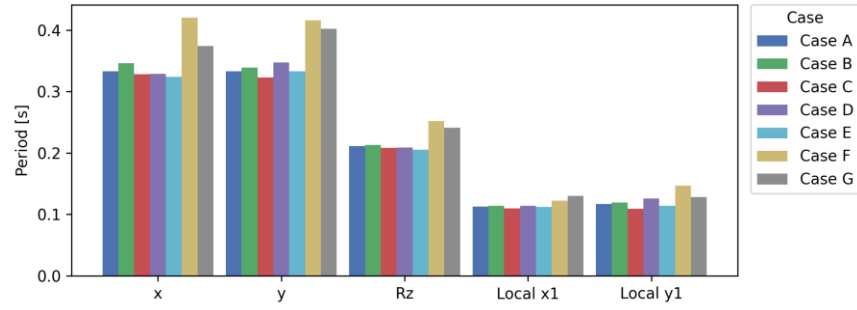


Figure 2. Fundamental periods of selected global and local modes for each modal shape.

Post-seismic results show the most significant changes. In the damaged configuration (Case F), fundamental periods increase substantially, translational PMRs drop, and rotational effects become more significant due to stiffness degradation and cracking, while translational modes still govern the global response. Retrofit implementation (Case G) mitigates these effects: periods remain longer than in the undamaged state but are much shorter than in Case F, and PMRs are more balanced, demonstrating improved global connectivity and a more stable seismic response.

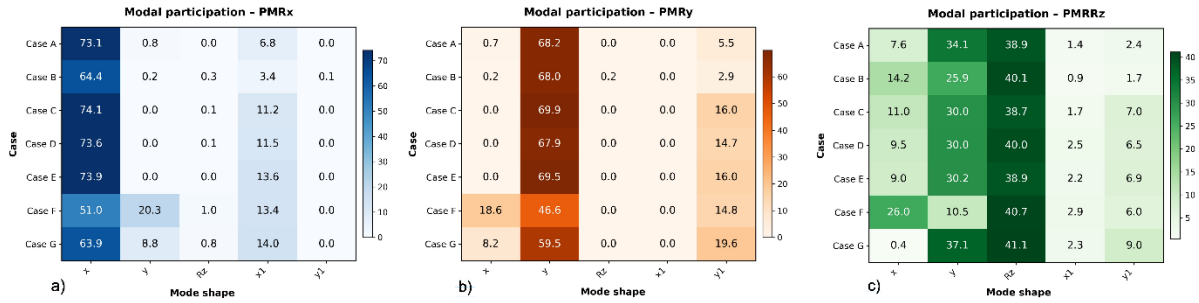


Figure 3. Effective modal mass participation ratios (PMR) for all analyzed cases (A–G).

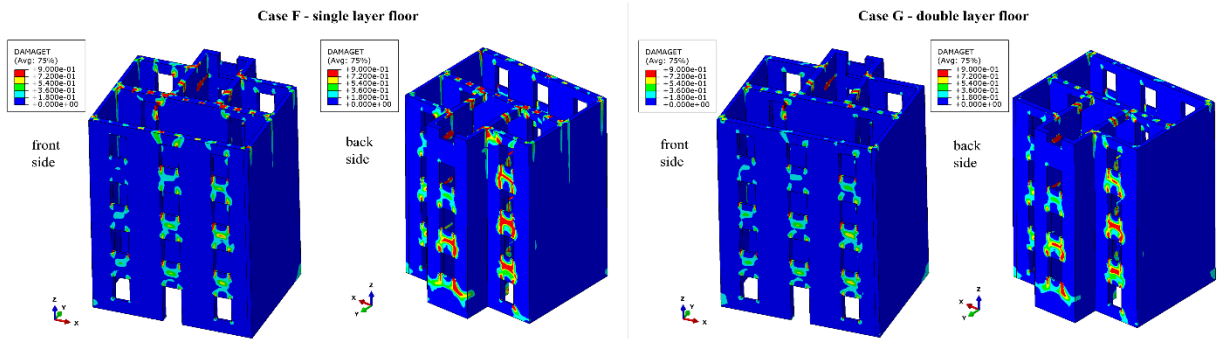


Figure 4. Tensile damage parameter distribution (DAMAGET) for Cases F and G: F – damage concentration at wall connections; G – more uniform damage distribution.

Damage Distribution and Its Influence on Dynamic Behavior

The spatial distribution of damage (Fig. 4) shows severe cracking and tensile failure at wall-to-wall intersections and spandrel regions in Case F. These zones coincide with modal shape distortions and increased torsional participation, demonstrating a direct link between localized damage and modal parameter shifts. Enhanced diaphragm stiffness reduces damage localization and alters the dynamic response mechanism. Rather than concentrating deformation in isolated walls, the structure engages a larger number of walls in both

directions, reducing torsional modes and stabilizing modal properties.

Conclusions

This study demonstrates the strong coupling between earthquake-induced damage, damage distribution patterns, and modal properties of URM buildings. Key conclusions are:

- Progressive damage causes significant period elongation, PMR redistribution, and increased torsional response.
- Localized damage, especially at wall junctions and spandrels, directly governs shifts in modal shapes and dynamic characteristics.
- Reversible retrofit measures (e.g., timber diaphragm stiffening) reduce damage concentration, promote global wall engagement, and stabilize modal properties.
- Modal analysis represents a useful supporting tool for assessing global damage evolution and retrofit efficiency.

The results obtained indicate that reversible, heritage-compatible retrofit techniques can significantly improve the seismic stability and resilience of historic masonry buildings in downtown Zagreb and similar historic urban environments. The presented results should be interpreted as trend-based observations for a representative URM typology, while future work should include validation against additional monitored and experimentally characterized structures.

Acknowledgments

This research was funded by the Croatian Centre for Earthquake Engineering under grant number A679117 – HPC – Research project in the field of Earthquake Engineering, and supported by the Croatian Science Foundation through the project “Development of an Earthquake Risk Model for Schools in the Republic of Croatia” (EARS, UIP-2025-02-3985).

References

1. Atalić J, Šavor Novak M, Uroš M, et al. The Mw5.4 Zagreb (Croatia) earthquake of March 22, 2020: impacts and response. *Bulletin of Earthquake Engineering* 2021; 19(9): 3461–3489.
2. Atalić J, Demšić M, Baniček M, Uroš M, Dasović I, Prevolnik S, Kadić A, Šavor Novak M, Nastev M. The December 2020 magnitude (Mw) 6.4 Petrinja earthquake, Croatia: Seismological aspects, emergency response and impacts. *Bulletin of Earthquake Engineering* 2023; 21: 5767–5808.
3. World Bank Group. Croatia earthquake – rapid damage and needs assessment 2020. Washington, D.C., 2020.
4. Michel C, Lestuzzi P, and Lacave P. Seismic vulnerability assessment to decision-making support for building retrofit strategies. *Earthquake Engineering & Structural Dynamics*, 47(1):239–259, 2018.
5. Meoni A, D'Alessandro A, Mattiacci M, García-Macías E, Saviano F, Parisi F, Lignola GP, Ubertini F. Structural performance assessment of full-scale masonry wall systems using operational modal analysis: Laboratory testing and numerical simulations. *Engineering Structures* 2024; 304: 117663.
6. Baniček M, Shaqfa M, Atalić J, Vaing S. Predicting modal parameters of damage stages and retrofit methods of a URM masonry building. Proceedings of 3rd Croatian Conference on Earthquake Engineering (3CroCEE). Split, Croatia, 2025.
7. Lubliner J, Oliver J, Oller S, Oñate E. A plastic-damage model for concrete. *International Journal of Solids and Structures* 1989; 25: 299–326.
8. Dassault Systèmes. *SIMULIA Abaqus User Assistance 2023*. Dassault Systèmes: Providence, RI, 2023.