Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.44

INTEGRATION OF THE OMA AND FEMU FOR ESTIMATION MODULUS OF ELASTICITY IN MASONRY STRUCTURES

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Abstract

The recent seismic activity in Croatia has inflicted significant damage on numerous buildings, with masonry structures being especially vulnerable. For the effective rehabilitation and restoration of these structures, it is critical to assess key mechanical properties such as the modulus of elasticity, compressive strength, tensile strength, and shear strength. Conventional methods for determining these properties often involve labour-intensive field tests and laboratory analysis of masonry samples. This paper introduces an innovative methodology that integrates Operational Modal Analysis (OMA) with Finite Element Model Updating (FEMU) to estimate the modulus of elasticity in masonry structures. By leveraging dynamic parameters, including natural frequencies and mode shapes derived from OMA, the methodology allows for the updating of a numerical sub-model of the masonry. This integrated approach was applied to a real structure, with results compared to those obtained using traditional testing methods. The findings indicate that the proposed method is not only more efficient but also yields highly accurate estimations of mechanical properties, particularly the modulus of elasticity, with minimal disruption to the structure. The reduced need for invasive testing, coupled with its precision, positions this approach as a compelling alternative to traditional methods for assessing the structural integrity of masonry structures following seismic events.

Keywords: Operational modal analysis (OMA), Finite element model updating (FEMU), Modulus of elasticity, masonry structures, seismic activity

1. Introduction

Recent seismic events in Croatia, particularly those affecting Zagreb and Petrinja, have resulted in extensive damage to numerous buildings, with masonry structures being especially susceptible. The necessity of rehabilitating and reconstructing these buildings to ensure their load-bearing capacity and functional integrity has underscored the importance of comprehensive structural assessments. Consequently, experimental investigations and structural condition evaluations have become indispensable components of the rehabilitation process. The restoration and retrofitting of earthquake-damaged structures is a complex and time-consuming endeavour, requiring thorough preliminary investigations and in-depth material testing to ensure compliance with current regulatory standards. Traditionally, these investigations involve a range of testing methods to determine key mechanical properties. These are modulus of elasticity, compressive strength, tensile strength, and shear strength of masonry materials [1]. Investigation methods can be categorized into destructive, semi-destructive, and non-destructive approaches [2]. Destructive testing methods, such as core extraction [3] and flat-jack testing [4]–[6], are commonly used in laboratory analyses. However, these approaches are often limited by the availability of representative masonry samples and the challenges associated with establishing reliable correlations between material hardness and strength. Semi-destructive methods, including rebound hammer testing [7]–[9] and endoscopy [10], are frequently employed to provide information

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.44

about the hardness of brick and mortar as well as the internal condition of walls. Despite their utility, these techniques are constrained by localized application and potential subjective interpretation by investigators. Non-destructive testing methods, such as ground-penetrating radar [10]–[12] ultrasonic testing [13], and infrared thermography [14], offer the advantage of damage detection without significantly compromising the integrity of the structure. While these methods yield valuable insights into the condition of masonry elements, they require considerable expertise for accurate result interpretation. Additionally, acoustic emission [15] techniques are employed to monitor crack propagation over extended periods, but their primary limitation lies in the time-intensive nature of the monitoring process.

Beyond field testing, numerical modelling plays a critical role in the rehabilitation process [16][17]. Numerical analysis aims to predict the actual behavior of structures by considering their geometry, mechanical properties, and boundary conditions. The development of robust numerical models, commonly referred to as "digital twins" is crucial for assessing load-bearing capacity and formulating effective restoration strategies that align with current building codes.

This paper presents an integrated approach for estimating the mechanical properties of materials of masonry structures that combines experimental investigations with numerical modelling. Specifically, it leverages the integration of Operational Modal Analysis (OMA) [18] and Finite Element Model Updating (FEMU)[19]. The methodology begins with dynamic testing to perform modal identification, from which natural frequencies and mode shapes are extracted. A finite element model of a representative masonry wall segment is then developed and calibrated using the OMA results to estimate the modulus of elasticity accurately. The proposed methodology was applied to the case study of the earthquake-damaged School of Medicine, University of Zagreb. Dynamic testing and modal identification were conducted on a representative masonry wall sample, and a corresponding local model of the wall was calibrated using FEMU. Additionally, traditional testing methods were performed on the same wall to determine mechanical properties, and the results from both approaches were compared. The findings demonstrate that the integrated approach, which minimizes structural disruption, is more efficient and yields accurate estimations of mechanical properties compared to conventional methods.

The paper is organized as follows: Section 2 describes the experimental campaign and its results. Section 3 outlines the finite element model updating process for the representative wall segment. Section 4 discusses the iterative FEMU results, while Section 5 provides concluding remarks on the methodology's efficiency and accuracy.

2. Experimental campaign

2.1. Description of the structure

The Building at Šalata 3 is a key facility of the School of Medicine, University of Zagreb supported by auxiliary structures. The building has an irregular footprint, with a basement, ground floor, two upper floors, and an attic. Its footprint dimensions are approximately 58.92 x 68.49 meters, with a cornice height of 17.78 meters and an overall height of 28.45 meters. The gross floor area is 8,452 square meters. Load-bearing walls are constructed of solid brick, from 45 to 94 cm thick, with inter-floor slabs made of 10 cm reinforced concrete supported by a T-beam grid system. A T-beam system also supports the floors and ceilings in the large auditorium and central corridor. In the ground-floor foyer and part of the left wing's first floor, a three-flight staircase features masonry vaults, with a 10 cm reinforced concrete slab above them. Vertical access is provided by two double- and triple-flight staircases, likely of precast reinforced concrete on steel supports. The building lacks vertical and horizontal ties, and the wooden roof is gabled and tiled.

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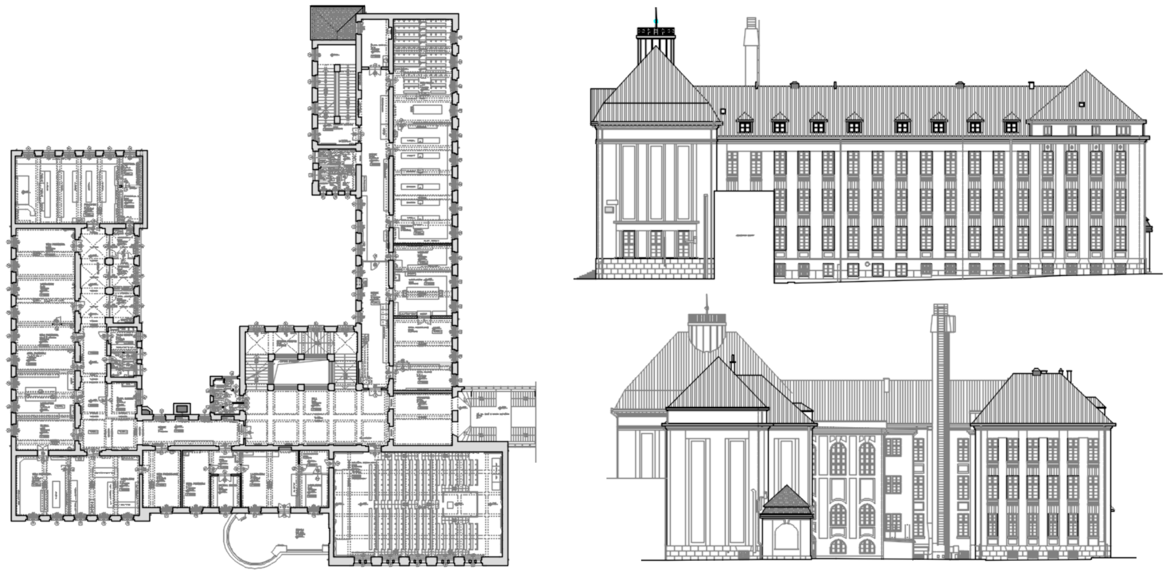

(a) (b)

Figure 1. Documentation of the current condition of the School of Medicine, University of Zagreb building: (a) ground floor plan, (b) west and north façades of the building

2.2. On site - determination of mechanical properties

On the building previously described, a series of investigation works were carried out to assess the structural condition and determine the quality of the materials used (Figure 2.). These includes the flat jack and shear test.

(a) (b) (c)

Figure 2. Determination of the mechanical properties (a) vertical stress (b) modulus of elasticity (c) shear strength of masonry wall on the first floor of the School of Medicine, University of Zagreb

Based on the performed test using flat jack and a small hydraulic press the values of different important mechanical properties are obtained (Table 1). The obtained results are used to compare the one obtained using the proposed method.

Table 1. Determined values of mechanical properties of materials of wall at the School of Medicine, University of Zagreb

Mechanical property	**Experimentally determined value**
Vertical Stress, σ_0, MPa	0.35
Modulus of elasticity, E, MPa	1393
Shear strength, f_{v0}, MPa	0.15
Coefficient of friction, μ	0.30

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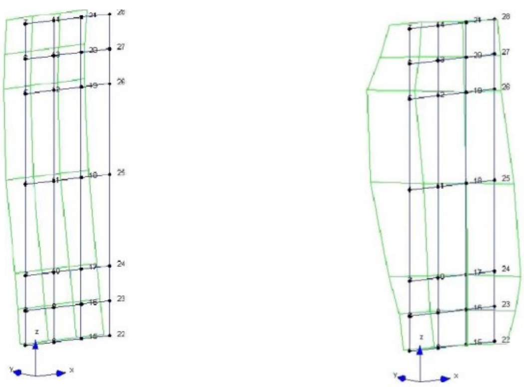
2.3. Operational modal analysis of the representative wall

Within the experimental analysis of the School of Medicine, University of Zagreb building by classical operational modal analysis the dynamic properties (natural frequencies and mode shapes) of the representative wall were determined. The location of the cut was strategically selected close to the door opening in the load-bearing wall, ensuring that the structural behavior around the opening could be effectively evaluated while minimizing the influence of boundary conditions on the sides; the cut itself was made with a width of 5 mm (red line, Figure 3 a)). The OMA was conducted by roving four accelerometers (Figure 3 b)) in several points on the wall on which the connection between the wall and accelerometer was made using the round metal plate (Figure 3 b)). One accelerometer was used as a referent (orange point, Figure 3.c)). Frequency domain decomposition (FDD) was used to estimate the values on natural frequency and mode shapes (Figure 4.).

Figure 3. Operational modal analysis set up (a) arrangement of the measurement points (b) accelerometer Brüel & Kjær Type 4508 (c) round metal plate on used during the measurement to place the accelerometers on the wall



29.2 Hz 92.4 Hz

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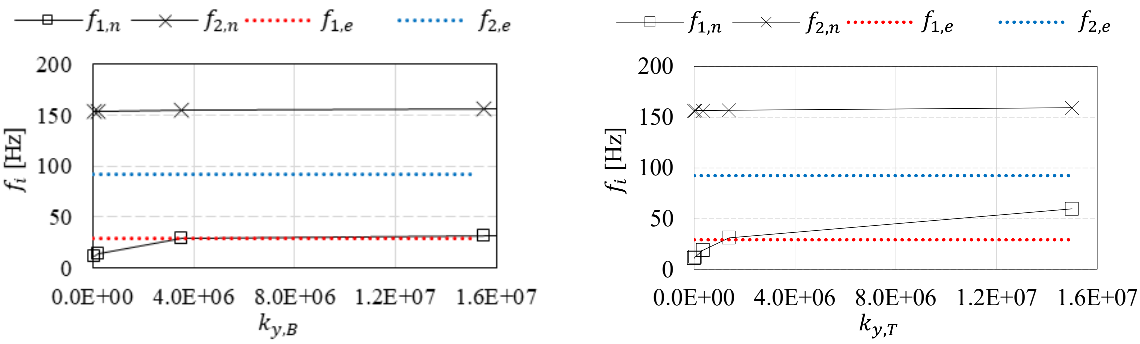
Figure 4. Results of the modal identification of the representative wall on the first floor of the School of Medicine, University of Zagreb

3. Finite element modelling and updating

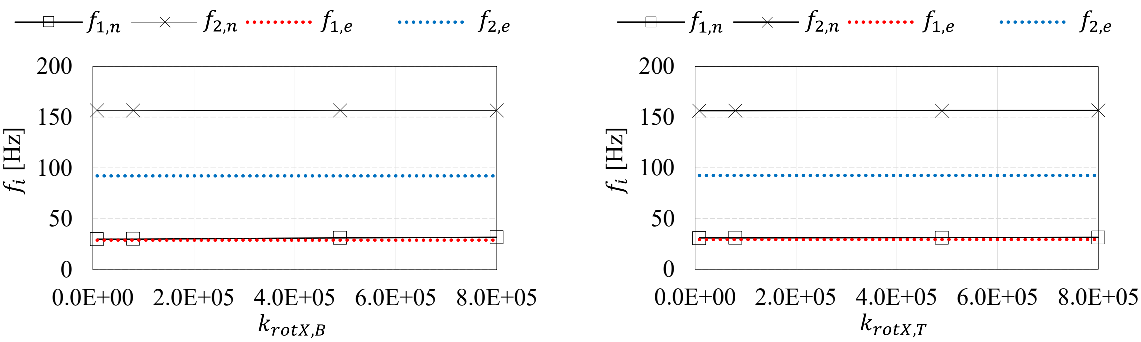
3.1. Initial numerical model and manual calibration

The experimentally obtained results were used to update the local numerical model of the wall. Numerical modelling of the wall was performed using commercial FE package Ansys and personal computer with the processor 3.59 Hz and 16 GB RAM memory. FE model was developed using (i) four node shell elements with six degrees of freedom, SHELL 181, and (ii) COMBIN14 for modelling support with lateral and rotational spring elements. It is assumed that the vertical displacement was constrained. The developed model was meshed using 108 elements. The initial values of the mechanical properties of numerical model were assumed as follows. The modulus of elasticity was proposed as: E_x = 1393 MPa and E_y = 1393 MPa, the material density, ρ = 1700 kg/m3, shear modulus G_{xy} = 557.2 MPa and G_{xz} = 557.2 MPa, Poisson ratio= 0.25. The boundary conditions were determined based on the iteration of the spring stiffness until matching between mode shapes are not reached (Figure 5. and Figure 6.).



(a) (b)

Figure 5. Dependence of the change in numerically obtained first $(f_{1,n})$ and second $(f_{2,n})$ natural frequency on the change in stiffness of the translational spring in the y direction at (a) the bottom of the wall $(k_{y,B})$ (b) the top of the wall $(k_{y,T})$ with the highlighted values of the experimentally determined first $(f_{1,e})$ and second $(f_{2,e})$ natural frequency



(a) (b)

Figure 6. Dependence of the change in numerically obtained first $(f_{1,n})$ and second $(f_{2,n})$ natural frequency on the change in stiffness of the rotation spring around the x axis at (a) the bottom of the wall $(k_{rotX,B})$ (b) the top of the wall $(k_{rotX,T})$ with the highlighted values of the experimentally determined first $(f_{1,e})$ and second $(f_{2,e})$ natural frequency

The obtained stiffness of the spring elements was determined based on the values that results in the highest values of MAC factors (0.959 for the first and 0.791 for the second mode). These values are: $k_{y,B}$= $1.55 \cdot 10^7 N/m$; $k_{rotX,B}$ = $4.90 \cdot 10^5\ Nm/rad$ for the bottom of the wall and $k_{y,T}$= $1.38 \cdot$

$10^6\ N/m$; $k_{rotX,T} = 4.90 \cdot 10^5\ Nm/rad$ for the top of the wall. For the determined values of the spring stiffness, the calculated values of first two natural frequencies were $f_{1,num}$= 31.13 Hz for the first and $f_{2,num}$= 156.63 Hz for the second mode. Despite the good correlation of the manually optimized numerical model with springs of different stiffness values, the residual of the natural frequency for the second mode remains high (48.32%). To reduce the residual, automated FEMU is applied using Harmony search optimization algorithm [20] in the following.

3.2.Harmony search based finite element model updating

The automated process of the finite element model updating start with the manually calibrated initial finite element model from the previous section. In the first step, numerical model is automated calibrated by updating the spring stiffness values. Based on the manually performed FEMU the obtained values of spring stiffness were: $k_{y,B} = 4.42 \cdot 10^6$; $k_{rotX,B} = 1.78 \cdot 10^5$ for the bottom of the wall and $k_{y,T} = 1.06 \cdot 10^6$; $k_{rotX,T} = 5.32 \cdot 10^4$ for the top. The calculated values of the spring stiffness result in the MAC factor 0.982 for the first and 0.784 for the second mode shape and they correspond to the 28.39 Hz for the first and 154.86 Hz for the second mode. To decrease the changes in natural frequencies updated numerical model is updated in the second step by changing the values of the mechanical properties of materials. This was done by iterating the modulus of the elasticity of masonry between the interval $[40 - 1400]$ MPa while it has been concluded that vertical stress does not affect much the natural frequency value (Figure 7 a)).

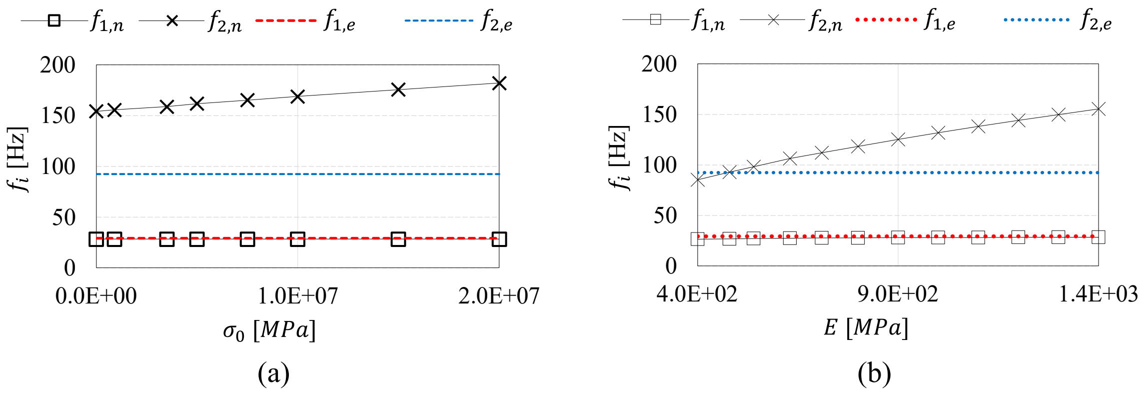


Figure 7. Changing in first $(f_{1,n})$ and second $(f_{2,n})$ numerically obtained natural frequency depending on the change in (a) vertical stress (σ_0) (b) modulus of the elasticity of the masonry (E) with the highlighted values of the experimentally determined first $(f_{1,e})$ and second $(f_{2,e})$ natural frequency

4. Discussion

In the following figure (Figure 8.), the trend of changes in natural frequency values across iterations is presented. The initial models, based on different traditional boundary conditions, did not demonstrate satisfactory agreement between experimentally and numerically obtained frequency and mode shape values. Thus, updating FEM of masonry wall was performed using an automated Harmony Search optimization algorithm.

The first iteration focused on updating the stiffness of translational springs in the y-direction at the top and bottom of the wall, as well as the rotational springs around x axis at the same points, to more accurately simulate the actual boundary conditions. From the graphical representations of natural frequency variations relative to spring stiffness, it can be concluded that the translational springs in the y-direction have the greatest influence on frequency changes. The differences between experimentally and numerically obtained frequencies were 0.27% for the first mode shape and 3.70% for the second, indicating satisfactory results that justified the use of the developed model in the next iteration step. The second iteration examined the effect of varying the vertical stress on the masonry wall natural frequencies. Results showed that the natural frequency was not significantly affected by changes in vertical stress. Consequently, the vertical stress level was set to the values for which was shown that it minimize the residual between the second experimental and numerical natural frequencies. The third

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iteration involved the final assessment of the masonry elasticity modulus, utilizing experimentally obtained modal characteristics. The differences between the experimental and numerical natural frequencies were 1.39% for the first and 0.83% for the second mode, with an elasticity modulus value of 1310 MPa. The difference between the adopted elasticity modulus, determined by calibrating the numerical model based on experimental results, and the modulus obtained through flat-jack testing was 6.33%.

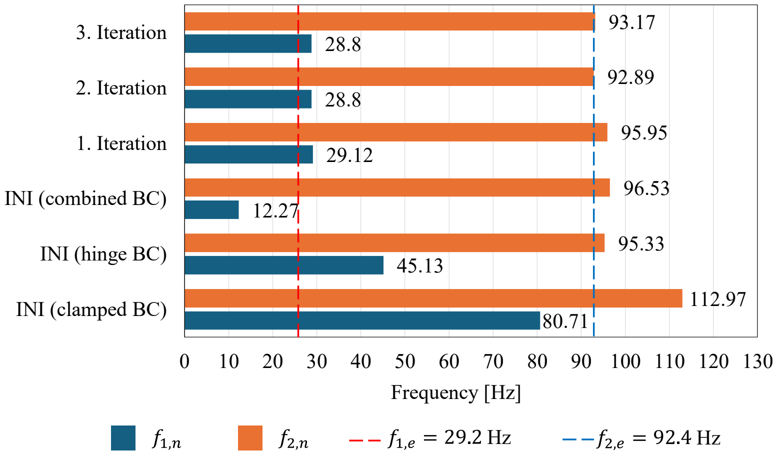

Figure 8. Changing in first $(f_{1,n})$ and second $(f_{2,n})$ numerically obtained natural frequency trough the performed iterations steps with the highlighted values of the experimentally determined first $(f_{1,e})$ and second $(f_{2,e})$ natural frequency

5. Conclusion

This paper presented an innovative approach for estimating the modulus of elasticity in masonry structures by integrating Operational Modal Analysis (OMA) with Finite Element Model Updating (FEMU). The methodology leverages dynamic parameters, such as natural frequencies and mode shapes obtained from OMA, to accurately update a numerical model of the masonry wall. The application of this approach to a real structure demonstrated that it is not only more efficient but also highly accurate, significantly reducing the need for invasive testing that could potentially damage the structure. Results from the optimization process, conducted using the Harmony Search algorithm, revealed that changes in the stiffness of translational springs in the y-direction had the most substantial impact on frequency variations. Although variations in vertical stress had a lesser effect on natural frequencies, the iterative calibration process effectively refined the mechanical property estimates. The modulus of elasticity obtained using the proposed approach differs only slightly from the value determined through the flat-jack method, demonstrating that this approach enables highly accurate estimation of the modulus of elasticity. The method offers a significant advantage in terms of precision and minimal structural impact, establishing itself as a robust alternative to conventional techniques for assessing the mechanical properties of earthquake-damaged masonry buildings.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No [101151734].

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