Influence of the Structural Condition on the Dynamic Characteristics of a Building

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Abstract

Over time, the technical condition of buildings deteriorates due to material fatigue, environmental effects, and structural damage. These processes lead to a decrease in stiffness, which directly affects the dynamic characteristics of the structure. This study investigates the influence of stiffness degradation on the natural frequencies and mode shapes of a single-storey masonry building located on the campus of the Cracow University of Technology. Two numerical models were developed using the Finite Element Method (FEM): an intact model and a weakened model with locally reduced stiffness simulating wall cracks and material losses. The modal analysis revealed that a 20% reduction in the Young's modulus of masonry resulted in a 3–8% decrease in the natural frequencies. Moreover, the weakened model exhibited a visible modification of vibration mode shapes, with higher local displacement amplitudes in the cracked zones. These results confirm that the dynamic response of a building is highly sensitive to local stiffness changes. From a practical perspective, the observed decrease in natural frequencies can be used as a quantitative diagnostic indicator of the structural condition. Tracking changes in modal parameters over time allows early detection of stiffness degradation and supports preventive maintenance strategies. The study confirms that modal analysis, combined with numerical modelling, provides an effective, non-destructive method for assessing the technical state and dynamic stability of existing and renovated masonry buildings.

Keywords: *dynamic analysis; natural frequencies; mode shapes; stiffness degradation; masonry buildings; structural diagnostics; FEM*

1. Introduction

The dynamic characteristics of a building describe its behaviour under dynamic loading and constitute a set of the structure's inherent parameters, independent of the type and magnitude of external excitation. They include, above all, the natural frequencies, mode shapes, and damping ratio [1]. These quantities are closely related to the material properties of the structural elements, their geometry, spatial configuration, and boundary and connection conditions. Any variation in these factors — for instance, due to material degradation, cracking, or deformation — leads to a modification of the building's dynamic characteristics. In engineering practice, the analysis of dynamic characteristics is an important diagnostic tool, as it enables the detection of stiffness reduction or local damage in load-bearing elements without the need for invasive methods [2–3]. A decrease in natural frequencies may serve as one of the first indicators of the loss of structural integrity [4]. Dynamic investigations are also essential for assessing the vibration comfort of building occupants, since excessive vibration amplitudes or accelerations can adversely affect the well-being and health of people inside the structure [5–6]. In recent years, the development of numerical methods — particularly the Finite Element Method (FEM) — has gained increasing importance in diagnostic analyses, enabling an accurate representation of the geometry, material heterogeneity, and boundary conditions of a structure. Modal analysis performed within the FEM framework allows the determination of the natural frequencies and mode shapes of a building. Comparing these parameters for different structural conditions makes it possible to assess the influence of degradation on its dynamic behaviour. The results of such analyses can also be applied to vibration comfort assessment in accordance with national and international standards, such as PN-B-02171:2017-06 [7] and ISO 2631-2:2003 [8]. The subject of this study is a masonry building located on the campus of the Cracow University of Technology at 24 Warszawska Street in Kraków, Poland. Erected at the end of the 19th century and subjected to long-term use and multiple refurbishments, the structure represents a suitable case for examining the influence of changes in stiffness of materials and connections on its dynamic characteristics.

The aim of the study is to determine the effect of the building's technical condition on its dynamic characteristics by comparing the results of modal analyses of two numerical models: an intact structure and a model with local structural degradations representing cracks and material losses in load-bearing walls. Additionally, the study includes an assessment of human vibration comfort using the Vibration Perception Index (WODL), allowing a comprehensive analysis of the relationship between the structural condition and its dynamic impact on occupants.

2. Dynamic analysis of the building

The analysed building, located in the northern part of the Cracow University of Technology campus at 24 Warszawska Street in Kraków, is a single-storey masonry structure with load-bearing walls made of two layers of solid brick bonded with lime mortar. The building, constructed in the late 19th century, has plan dimensions of 20.22 × 16.39 m and a height of 4.97 m. Due to its age and

long-term service, local cracks and material losses can be observed in some of the load-bearing walls, which may affect the global stiffness of the structure [Fig. 1].

Fig. 1. View of the analysed building and local wall damage

In 2024, a comprehensive renovation was carried out, including thermal insulation of the external walls, replacement of windows, and renewal of the façade finish (see Fig.2). The renovation improved the building's energy performance and appearance, while preserving its original geometric form and structural system. The refurbishment works were performed without altering the load-bearing elements, ensuring that the building retained its essential dynamic properties and could still serve as a valid subject for vibration analysis.

Fig. 2. View of the building after renovation.

To assess the influence of these degradations on the building's dynamic behaviour, a three-dimensional numerical model was developed using the Finite Element Method (FEM) [9]. The analysis was performed in Autodesk Robot Structural Analysis Professional 2025. The model reproduces the geometry and boundary conditions of the actual structure, including the masonry walls, reinforced concrete floor slab, and elastic foundation supports (Fig. 3).

a)

b)

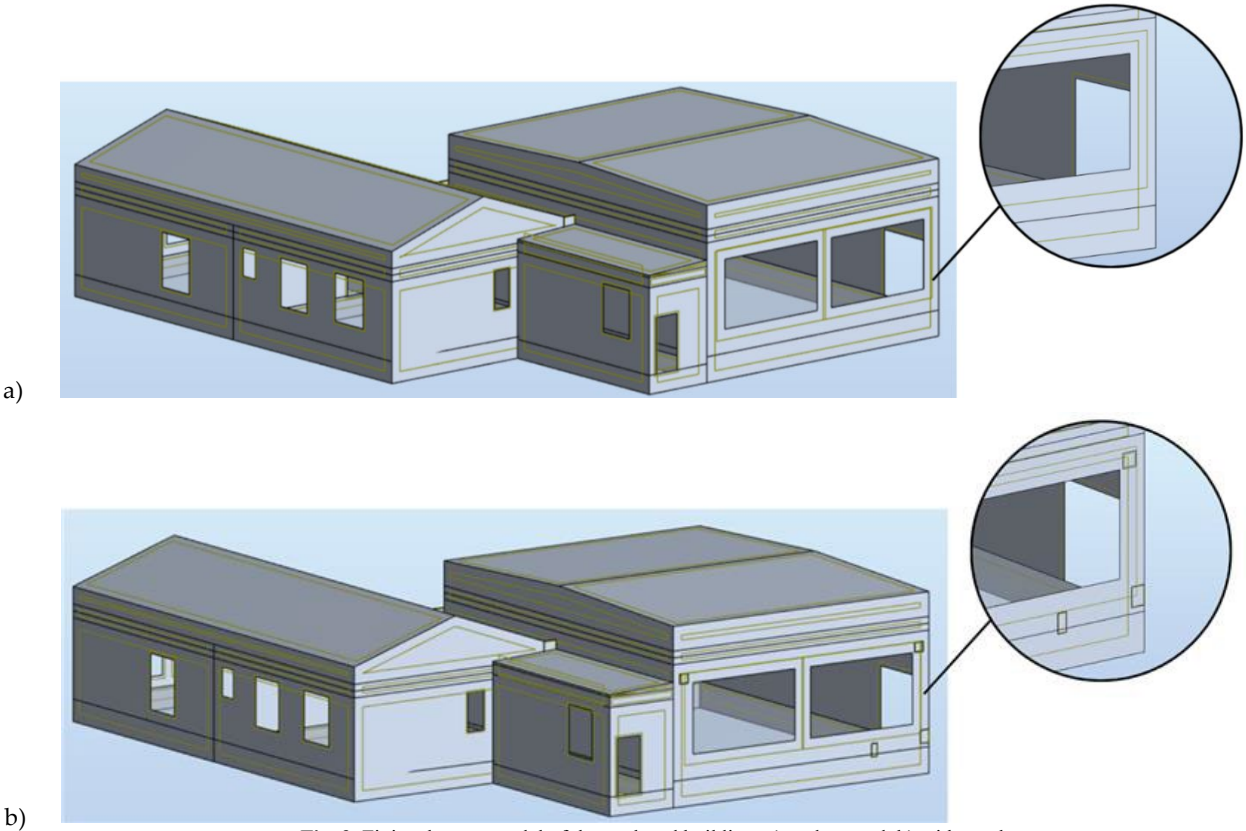

Fig. 3. Finite element model of the analysed building: a) undamaged, b) with cracks

Two models were considered:

a) an intact model, representing the undamaged structure, and
b) a weakened model, in which local stiffness reductions were introduced in wall panels to simulate the observed damage.

In the weakened model, the Young's modulus was reduced by 20% in the affected regions, while the Poisson's ratio was slightly increased to represent reduced shear stiffness. The walls were modelled as shell elements, and the floor slab as a double-reinforced concrete plate. The building was supported on elastic foundation springs located along the bottom wall edges at −0.6 m below ground level. Both models were subjected to modal analysis, aimed at determining the natural frequencies and mode shapes of the structure. The results were compared to evaluate the influence of stiffness degradation on the dynamic response. The differences between the two models ranged from 3% to 8%, depending on the vibration mode [Table 1].

Tab. 1. Comparison of natural vibration frequencies between the intact and weakened models

Model variant		Intact	Damaged	Difference
Mode [Hz]	1	5.31	5.06	4.94%
	2	8.28	7.93	4.41%
	3	8.82	8.42	4.75%
	4	9.31	8.61	8.13%
	5	9.44	9.02	4.66%
	6	9.86	9.30	6.02%
	7	10.86	10.32	5.23%
	8	11.08	10.77	2.88%
	9	11.62	11.23	3.47%
	10	12.38	11.93	3.77%

Several parameters affect the natural frequencies of buildings. The most important include the stiffness (Young's modulus), mass, boundary conditions, and geometric proportions of the structure. An increase in stiffness leads to higher natural frequencies, while an increase in mass causes them to decrease. Stiffer boundary supports and a more compact geometry also result in higher frequency values [10].

The first three vibration modes of the intact building are presented in Figures 4–6, showing typical global deformations associated with the fundamental translational and torsional responses.

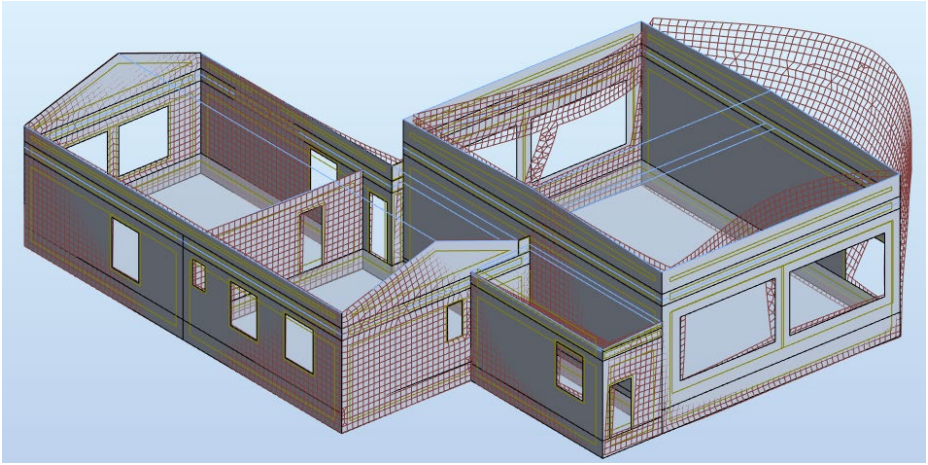

Fig. 4. The first natural mode of vibration of the intact building

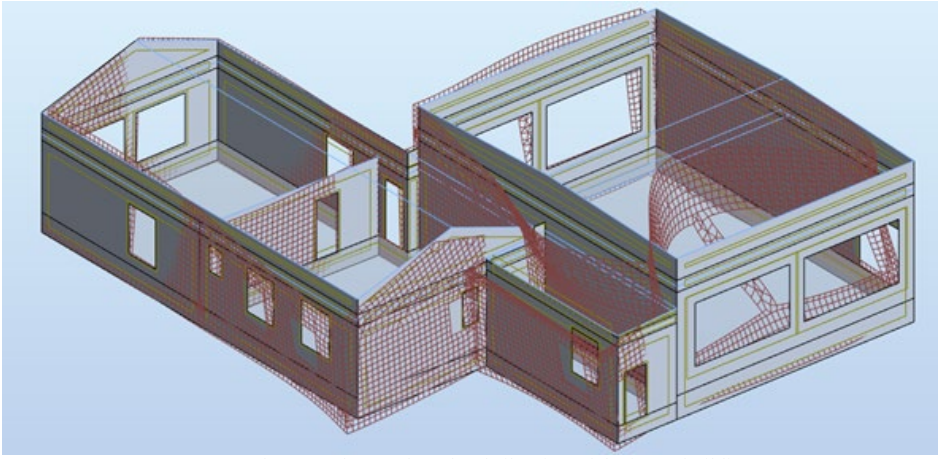

Fig. 5. The second natural mode of vibration of the intact building

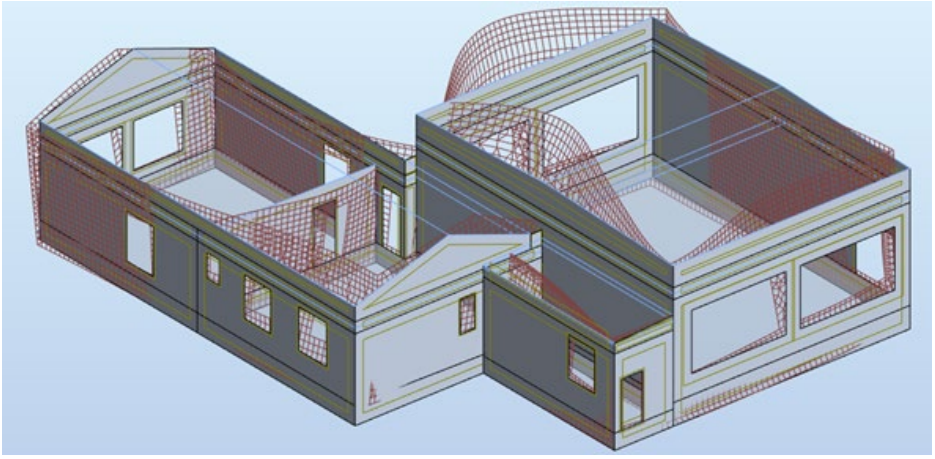

Fig. 6. The third natural mode of vibration of the intact building

The obtained results confirm that material degradation and local wall damage reduce the global stiffness of the building, leading to a noticeable decrease in natural frequencies. This reduction, although moderate (3–8%), indicates a potential increase in the building's susceptibility to resonance or amplified vibrations under external dynamic loads such as traffic or wind.

3. Discussion and perspective

The conducted analyses confirmed that both the natural frequencies and the mode shapes of the building are sensitive indicators of changes in structural stiffness. Even though the overall decrease in frequency between the intact and weakened models did not exceed 8%, a noticeable modification in the deformation patterns of the vibration modes was observed.

In the undamaged model, the first mode was dominated by translational motion of the entire structure in the longitudinal direction, while the second and third modes represented transverse translation and torsional behaviour, respectively. In contrast, the weakened model exhibited a visible shift in the deformation distribution — the areas corresponding to simulated wall cracks showed higher local amplitudes of displacement, indicating a concentration of dynamic response in the weakened zones. This confirms that even

small stiffness reductions can significantly alter the global vibration mode shapes, leading to potential redistribution of internal forces under dynamic loading.

Such changes in the mode shapes are of particular diagnostic importance, as they can serve as qualitative indicators of local damage. By comparing mode shape curvatures or modal strain energy distributions, it is possible to identify the regions where stiffness degradation has occurred. This approach, known from modal-based damage detection, could be further developed in future work to improve the sensitivity of numerical diagnostics for masonry structures.

The results also highlight that in irregular buildings, such as the analysed structure, torsional modes may appear already at low frequencies due to the asymmetry of mass and stiffness distribution. This coupling between translational and torsional modes can amplify the response under non-uniform excitations, such as wind or nearby traffic. Therefore, identifying these mixed-mode behaviours is crucial for assessing both the structural safety and vibration comfort of the occupants.

From a practical perspective, the analysis demonstrates that modal analysis is a powerful tool for structural assessment, capable of revealing early signs of deterioration that may not yet be visible through traditional inspection methods. The moderate but systematic reduction in natural frequencies and the localized changes in mode shapes observed in this study emphasize the need for periodic dynamic testing of aging masonry buildings.

Future research should focus on validating the numerical results through experimental modal analysis (EMA), allowing direct comparison between measured and simulated mode shapes. The application of model updating techniques, where numerical parameters are iteratively adjusted to fit experimental data, would enhance the reliability of stiffness estimation. Additionally, combining modal analysis with vibration-based structural health monitoring (SHM) systems would enable long-term observation of changes in both frequency and mode shape patterns, supporting predictive maintenance strategies.

Ultimately, integrating these numerical and experimental methods would provide a comprehensive framework for the diagnosis and preservation of historical masonry buildings, ensuring both structural safety and human vibration comfort. The present study thus underlines the dual diagnostic value of natural frequencies and mode shapes as fundamental parameters for assessing the dynamic condition of existing structures.

The summary presented in Table 2 illustrates the qualitative characteristics of the first three vibration modes. It confirms that each mode carries distinct diagnostic information, with torsional behaviour being particularly sensitive to irregularities in stiffness distribution. Such comparative evaluation of mode shapes can support vibration-based damage identification methods in existing masonry buildings.

Tab. 2. Summary of observed mode characteristics and diagnostic interpretation

Mode no.	Dominant behaviour	Characteristic deformation zone	Diagnostic significance
1	Longitudinal translation	Uniform displacement along the main axis of the building	Represents the global stiffness of the structure; useful as a reference for detecting general stiffness degradation
2	Transverse translation	Slight asymmetry due to wall openings and irregular geometry	Sensitive to lateral stiffness loss; may indicate uneven material degradation between wall segments
3	Torsional mode	Concentration of rotation near building corners and weakened wall areas	Reveals irregular stiffness distribution and coupling between translational and torsional modes; valuable for identifying local damage

4. Conclusion

The study confirmed that the technical condition of a masonry building significantly affects its dynamic characteristics. The comparison of the intact and weakened numerical models showed that a local reduction in material stiffness by approximately 20% caused a 3–8% decrease in natural frequencies. This relationship demonstrates that even moderate structural degradation leads to a measurable reduction in the building's dynamic stiffness.

The analysis of mode shapes revealed changes in deformation patterns, with increased local displacements in the weakened zones corresponding to simulated wall cracks. These qualitative changes confirm that the dynamic response of a structure is sensitive not only to material degradation but also to the spatial distribution of stiffness within the system.

From a practical engineering perspective, the observed decrease in natural frequencies can be considered a quantitative diagnostic indicator of the building's technical condition. Monitoring the evolution of these frequencies over time allows early detection of stiffness loss and structural weakening, even before visible cracks or damage appear. Such an approach can be effectively applied in the vibration-based assessment and maintenance of masonry and historical buildings.

The results also demonstrated that the Finite Element Method (FEM) provides an efficient tool for reproducing the dynamic behaviour of real structures when the geometry, material parameters, and boundary conditions are properly defined. Moreover, the analysis confirmed that renovation works, such as façade insulation or window replacement, did not alter the building's fundamental dynamic response, as its original load-bearing system remained unchanged.

In conclusion, tracking reductions in natural frequencies and observing changes in mode shapes should be incorporated into the diagnostic procedures of existing masonry buildings. Regular dynamic testing, supported by numerical simulations and experimental modal analysis, can form the basis of structural health monitoring (SHM) systems, enabling preventive maintenance and long-term safety evaluation of renovated and aging structures.

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