Comparison of Dynamic Characteristics of a Residential Building Using Ambient Vibration Testing and Finite Element Modal Analysis

Asadulla Khotamov[1], Sardor Rashidov[1], Sirojiddin Kholbekov[1], Fitrat Abdikhalilov[1] and Jörg Röder[2]
[1]Tashkent University of Architecture and Civil Engineering, Yangi Shahar Str. 9, 100194 Tashkent, Uzbekistan
[2]Potsdam University of Applied Sciences, Kiepenheuerallee 5, 14469 Potsdam, Germany
a.xotamov@taqu.uz, s.rashidov@taqu.uz, s.xolbekov@taqu.uz, abdixalilovfitrat@gmail.com, joerg.roeder@fh-potsdam.de

Keywords: Building, Structure, Technical Condition, Earthquake Resistance, Structural Health Monitoring (SHM), Seismic Sensors, Ambient Vibration, Triaxial Accelerometer.

Abstract: This study compares the dynamic characteristics of a six-storey residential building in Tashkent, Uzbekistan, using ambient vibration testing and finite element modal analysis. The building is located in a high seismic hazard zone, which makes reliable evaluation of its dynamic behavior essential for seismic safety assessment. The research combines in-situ microseismic measurements with numerical simulation to examine the consistency between experimentally identified and analytically predicted vibration parameters. Ambient vibration data were recorded using PCB Piezotronics 393B05 triaxial accelerometers and an 80-channel data acquisition system, and the signals were processed in MATLAB to determine the fundamental natural frequencies and periods of the structure in the principal directions. The measured values were 2.89 Hz and 0.34 s along the X-axis, and 2.95 Hz and 0.33 s along the Y-axis. In parallel, a three-dimensional structural model was developed in LIRA-SAPR 2022 to perform modal and seismic response analysis under permanent, live, and seismic loads. The numerical modal analysis produced a fundamental frequency of approximately 2.89 Hz, which was close to the experimentally identified values of 2.89 Hz and 2.95 Hz along the principal structural axes. The calculated displacements also remained within the allowable limits specified by KMK 2.01.03-19. Comparison of the experimental and numerical results showed close agreement, with only minor differences between the identified dynamic parameters. The findings confirm that ambient vibration testing is an effective tool for validating FEM-based models of existing buildings and can significantly improve the reliability of seismic performance assessment in earthquake-prone regions.

1 INTRODUCTION

In recent years, the Government of Uzbekistan has adopted a series of decisions [1], [2], leading to the formation of roadmaps for the development of the sector and the systematic implementation of measures aimed at improving the operational reliability of buildings and structures, especially multi-apartment residential buildings. Technical inspection and monitoring of existing buildings should also be organized in accordance with standardized procedures for assessing structural condition [3].

In particular, with the aim of introducing modern scientific and technical approaches to ensuring seismic safety, further enhancing the earthquake resistance of buildings and structures, developing advanced methods for predicting strong earthquakes, and establishing an effective modern system for preparedness, the Decree of the President of the Republic of Uzbekistan No. PF-184 dated October 20, 2025, “On measures to further improve state control and management in ensuring the earthquake resistance and seismic safety of buildings and structures” was signed [1]. Within this framework, a research study was conducted on one of the multi-apartment residential buildings in Tashkent to assess its seismic reliability, applying both conventional methods and one of the modern approaches.

Various technical instruments and methods are used to evaluate the seismic condition of building and structural systems. Modern structural health monitoring also includes data-driven damage-detection methods; for example, convolutional neural networks have been applied to automated crack identification from structural images [4]. Such image-based approaches complement vibration-based monitoring by providing information on visible surface damage. Traditional analytical approaches, such as finite element modeling (FEM), provide computational estimates of structural response under seismic loading. Digital simulation models are widely used to assess earthquake-related structural behaviour and potential damage scenarios [5]. However, numerical models may rely on idealized material properties and simplifying assumptions that do not fully reproduce the actual condition of an existing structure. For instance, the actual geometric parameters of an existing building may deviate from the idealized computational scheme because of construction tolerances and geometric imperfections permitted within standardized construction requirements [6].

If these deviations exceed the permissible construction tolerances defined by the relevant standards, the stress-strain state of the numerical model may change substantially [6].

In contrast to purely numerical approaches, ambient vibration testing and microtremor-based analysis enable the dynamic characteristics of a structure to be estimated from low-amplitude vibration records [7]. Operational modal analysis under ambient excitation is implemented using highly sensitive instrumentation capable of recording micro-vibrations induced by microseisms, wind, traffic, and human activity. The reliability of sensor-based structural health monitoring also depends on accelerometer calibration, measurement uncertainty, and the metrological stability of the acquisition system, particularly in seismic monitoring applications [8]. Modern structural health monitoring architectures may additionally incorporate distributed sensing and IoT-based data acquisition to support continuous collection, transmission, and integration of structural-response information [9]. Such measurements provide a direct, in-situ evaluation of vibration parameters while accounting for the actual geometric, physical, and mechanical properties of the structure during testing.

The primary objective of this study is to assess the seismic vulnerability of buildings within a 6-story residential complex in Tashkent. The assessment integrates microseismic ambient vibration measurements with numerical simulations based on the finite element method (FEM). By comparing the lowest natural frequencies and corresponding mode shapes obtained experimentally and numerically, the reliability, accuracy, and limitations of the two approaches are evaluated.

The results provide important insights into the potential of microseismic monitoring (ambient vibration-based operational modal analysis) as a highly effective supplementary tool for seismic vulnerability assessment in high-seismic-risk regions. The investigated six-storey residential complex and its location in Tashkent are shown in Figure 1.

2 METHODOLOGY AND RESULTS

To determine the dynamic characteristics of the research object, high-sensitivity triaxial seismic accelerometers manufactured by PCB Piezotronics (Amphenol Company), Model 393B05, were employed (Fig. 2). The accelerometer is capable of detecting extremely low-level structural vibrations in the frequency range of 0.7 to 450 Hz with a sensitivity of 10 V/g (1.02 V/(m/s²)) and converting them into electrical signals. These signals are very weak, contaminated with noise, and cannot be directly interpreted by a computer in their raw form.

Therefore, in accordance with the digital data acquisition methodology, the signals are amplified and converted from analog to digital format using an 80-channel mobile engineering data acquisition system (Fig. 3) produced by Pacific Instruments, Inc., USA, and then transmitted to a personal computer (PC).

Subsequently, using AcqLogger Software Ver. 1.0.0.0 (developed in the LabVIEW programming environment), the recorded acceleration time histories are processed and the resulting frequency-domain signals (power spectral densities, transfer functions, etc.) are visualized in graphical form on the computer monitor (Fig. 4 and 5).

Figure 1: Overall appearance and location of the residential complex on which the study was carried out.

Figure 2: High-sensitivity triaxial accelerometer.

Figure 3: 80-channel mobile engineering data acquisition system.

Brief description of the digital data acquisition methodology used for ambient vibration measurements:

The seismic sensor (transducer) detects building vibrations (e.g., micro-vibrations caused by earthquakes, traffic, or wind excitation) and converts them into electrical signals. These signals are typically very weak.

Amplifiers (signal conditioners / preamplifiers) are used to amplify the weak signals to a level suitable for subsequent processing stages. At this stage, noise is reduced and signal quality is improved.

ADC (Analog-to-Digital Converter) converts the amplified analog signals into digital format. This process transforms the signal into numerical values (e.g., sequences of binary data) compatible with computer processing.

PC (personal computer) receives and stores the digital data. Here, the data is recorded and archived. The PC serves as the central station, controlling all components of the acquisition system.

MATLAB is the software environment used for post-processing the recorded data. In MATLAB, the signals undergo filtering, graphical visualization, frequency-domain analysis, and other mathematical computations to determine the vibration characteristics (e.g., natural frequencies, mode shapes, amplitudes, damping ratios).

The static and dynamic analysis of a 6-storey frame building under the combination of main and special loads was performed using the LIRA-SAPR 2022 software package, employing a spatial (3D) structural model. Numerical methods are widely used to evaluate the seismic response and deformation behaviour of building structures. Related seismic-zone studies have also demonstrated the applicability of nonlinear structural analysis for identifying deformation and capacity characteristics under earthquake loading [10].

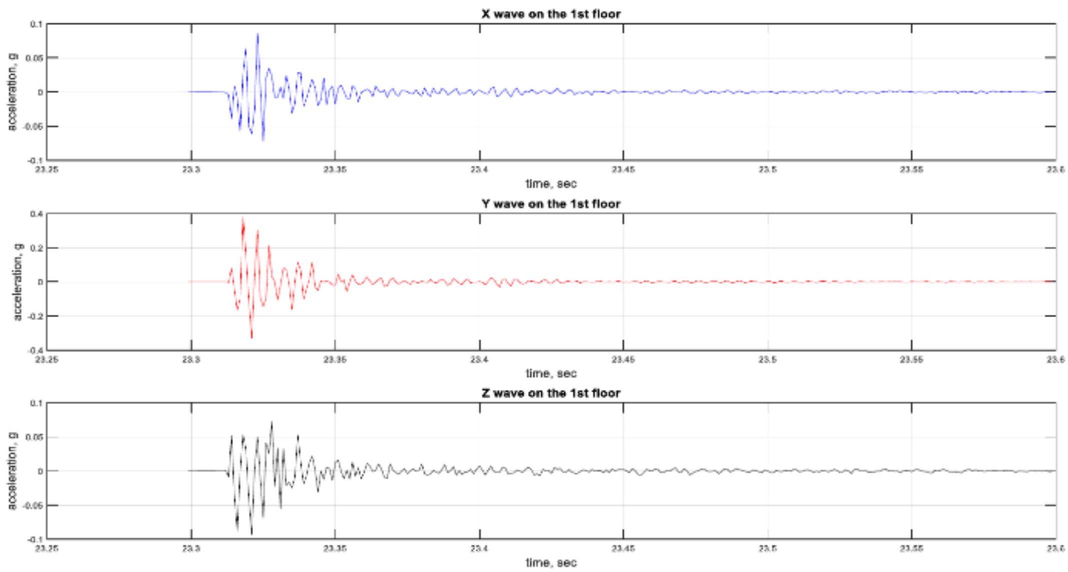

Figure 4: Measured acceleration records at the first-floor level, g (m/s²).

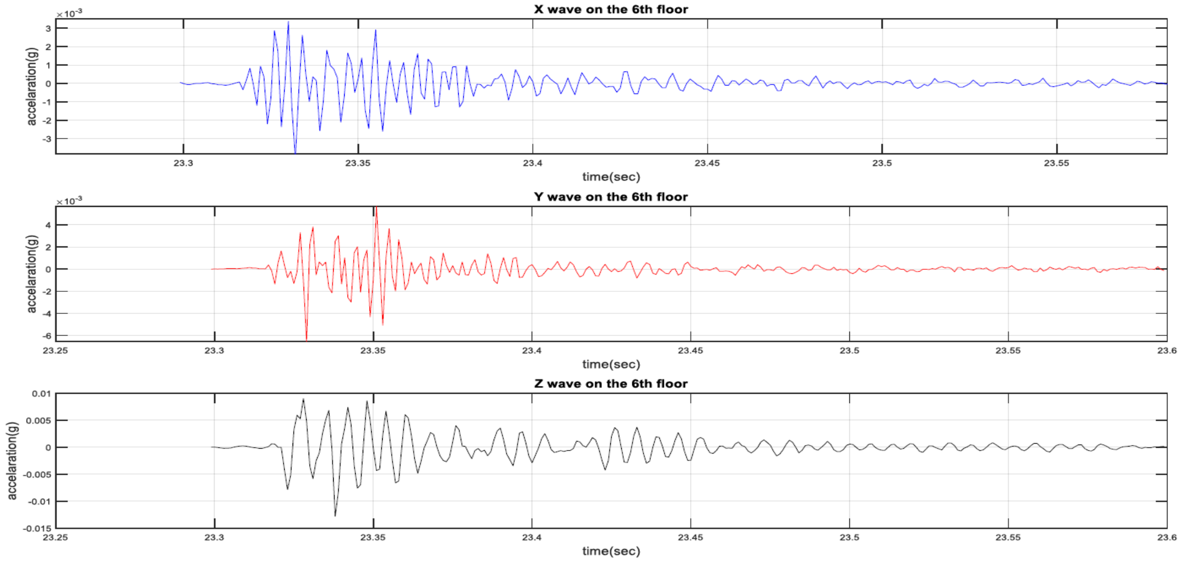

Figure 5: Measured acceleration records at the sixth-floor level, g (m/s²).

Special attention was paid to the following parameters during modelling:

- self-weight of structural elements (including self-weight of the structures, soil pressure on basement walls, and loads from protective structures);
- permanent (dead) loads (dead loads from floor slabs and roof covering elements);
- short-term (live) loads (imposed/floor live loads and snow loads);
- vertical component of the earthquake;
- seismic load along the X-axis;
- seismic load along the Y-axis.

The reliability of numerical seismic assessment also depends on the representation of earthquake excitation and the dynamic interaction of structural components. Computational studies based on recorded earthquake motions have demonstrated the importance of dynamic modelling for evaluating the seismic response of complex engineering systems [11].

As a result of the performed simulation, the deformations of the building structure under seismic loading, as well as the values of linear displacements, were determined numerically. Their compliance with the normative (code-specified) limits was evaluated.

Through graphical results, the zones of maximum stress concentration and the points experiencing the largest displacements were identified (Fig. 6 and 7).

The values of linear displacements of the building structure along the X and Y axes under seismic loading, as determined from the simulation model created in the LIRA software package, are presented in Table 1.

According to Clause 2.12 of KMK 2.01.03-19, the deformations of the structural system shall not exceed the prescribed code limits [12].

Table 1: Maximum tip displacements and allowable values.

H (building height, mm)	Coordinate axis	δ, mm	[δ]=H/N, mm
23870	X (T_x - 0.35 s, f_x - 2.89 Hz)	27.0	119.35
	Y (T_y - 0.35 s, f_y - 2.89 Hz)	61.2	

As a result of the numerical modal analysis, the fundamental natural frequency adopted for comparison was approximately 2.89 Hz. This value was consistent with the experimentally identified frequencies of 2.89 Hz along the X-axis and 2.95 Hz along the Y-axis. The relative (inter-storey) displacement at the roof level was found to be 27.0 mm along the X-axis and 61.2 mm along the Y-axis.

The obtained results satisfy the deformation requirement specified in Clause 2.12 of KMK 2.01.03-19 [12]. The calculated displacements do not exceed the allowable code limits presented in Table 1.

$$\delta \leq [\delta]. \qquad (1)$$

Here, δ - relative displacement at the roof level determined by the numerical method; [δ] - allowable relative displacement at the roof level.

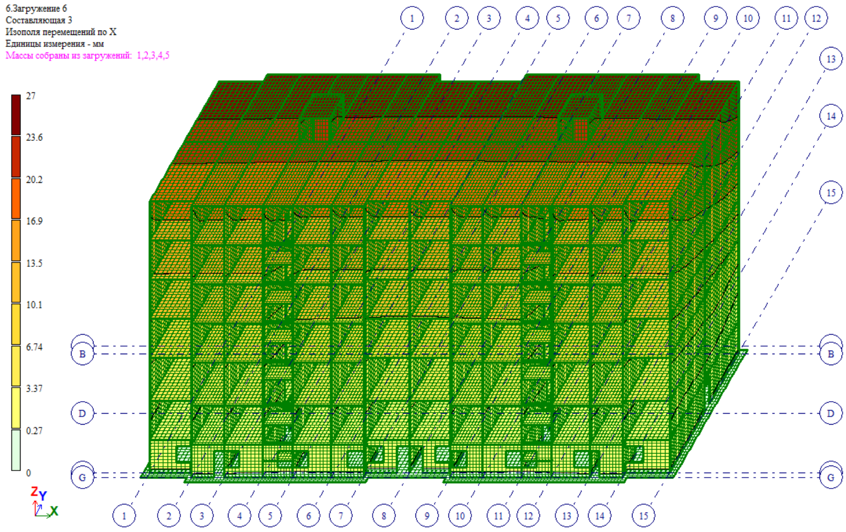

Figure 6: Maximum displacement of the building along the X-axis under seismic loading.

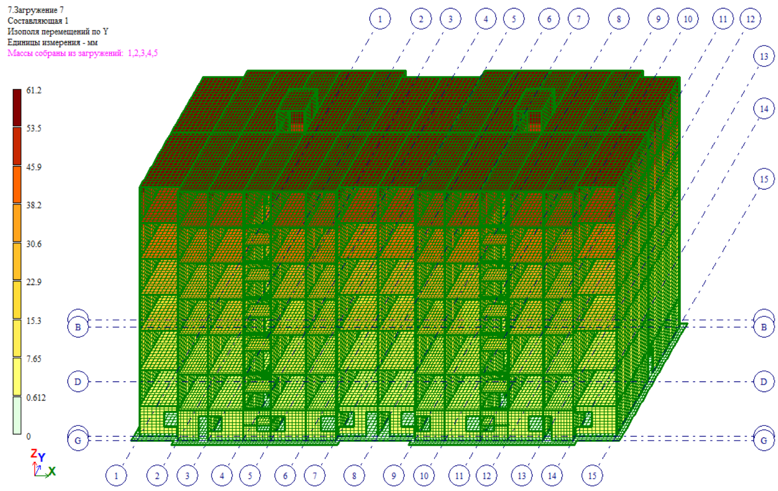

Figure 7: Maximum displacement of the building along the Y-axis under seismic loading.

The data obtained from the instrumental investigations carried out based on the ambient vibration measurement method were also analyzed.

Based on the processing and analysis of the ambient vibration measurement results, the periods and frequencies of the fundamental natural vibrations of the residential building in the transverse and longitudinal directions were determined from the recorded instrumental data. These values are presented in Table 2 below:

Table 2: Fundamental Natural Periods and Frequencies along the Principal Axes.

Along the X-axis		Along the Y-axis	
T_x, s	f_x, Hz	T_y, s	f_y, Hz
0.34	2.89	0.33	2.95

It can be observed that the dynamic characteristics of the building in the transverse and longitudinal directions exhibit nearly identical values.

In the ambient vibration regime, the dynamic stiffness is consistently governed by an initial elastic modulus that is higher than the calculated (design) value, which directly influences the dynamic properties of the structure.

Furthermore, during the modeling of the building in computational schemes, it is extremely difficult to fully account for the actual composite (coupled) behavior of the structural elements and the real properties of the construction materials; in most cases, only average (nominal) parameters are adopted.

To compare the results obtained from the two different methods applied to determine the dynamic characteristics of the residential building (natural frequencies in Hz and corresponding periods in seconds), and to quantify the average relative difference between them, additional calculations were performed using mathematical models. The results are presented in Table 3 below.

Table 3: Average relative difference between FEM and instrumental measurements.

№	Parameter	Along the X-axis	Along the Y-axis	Average relative difference (%)
1	ΔT (s)	0.01	0.02	2.76
2	Δf (Hz)	0.00	0.06	
3	δT (%)	2.94	6.06	
4	δf (%)	0.00	2.03	

This study demonstrates that the results obtained from the two methods — the ambient vibration measurement method and the numerical method based on the Finite Element Method (FEM) — are closely aligned in predicting the dynamic characteristics of the residential building (multi-storey frame building).

While FEM simulation provides comprehensive and detailed modeling capabilities, ambient vibration measurements serve as a crucial tool for verifying and validating the results through real empirical data.

The combined application of both methods, namely ambient vibration testing and FEM-based numerical analysis, enhances the reliability of seismic vulnerability assessment by combining empirical dynamic observations with detailed computational modelling.

3 CONCLUSIONS

In this study, the seismic vulnerability of a multi-storey residential building located in Tashkent city, within a 9-point seismic intensity zone, was evaluated using a combination of instrumental ambient vibration measurements and numerical modeling based on the Finite Element Method (FEM).

The computational results obtained in the LIRA-SAPR 2022 software package demonstrated that the deformations and displacements of the building structural elements under seismic loading fully comply with the requirements of the current normative document KMK 2.01.03-19. This confirms that the structure possesses sufficient operational reliability and serviceability.

A comparison of the natural frequencies and periods determined from ambient vibration measurements with the corresponding FEM results revealed close agreement, with relative differences ranging from 0 to 6.06%.

This close correspondence highlights the effectiveness of the ambient vibration monitoring method as a reliable empirical tool for assessing the real dynamic state of buildings and structures. Furthermore, the integrated (hybrid) application of ambient vibration measurements together with numerical FEM modeling significantly increases the reliability and confidence level of seismic vulnerability assessments.

REFERENCES

[1] Decree of the President of the Republic of Uzbekistan No. PF-184, “On measures to further improve state control and management in ensuring the seismic resistance and seismic safety of buildings and structures,” Oct. 20, 2025.

[2] Law of the Republic of Uzbekistan No. 713, “On ensuring seismic safety of the population and territory of the Republic of Uzbekistan,” Art. 14, “Inspection and monitoring of seismic resistance of buildings and structures.”

[3] Interstate Scientific and Technical Commission for Standardization, Technical Regulation and Conformity Assessment in Construction, Buildings and Structures. Rules for Inspection and Monitoring of Technical Condition, GOST 31937-2024, 2024.

[4] Y.-J. Cha, W. Choi, and O. Büyüköztürk, “Deep learning-based crack damage detection using convolutional neural networks,” Comput.-Aided Civ. Infrastruct. Eng., vol. 32, pp. 361-378, 2017.

[5] T. Khotamov, S. R. Kholbekov, and S. U. Rashidov, “Digital simulation model for assessing the level of earthquake damage of buildings,” Miasto Przyszłości Kielce, vol. 54, 2024.

[6] State Committee for Construction Standards, System for Ensuring the Accuracy of Geometrical Parameters in Construction. Process Tolerances, GOST 21779-82 (ST SEV 2681-80), 1982.

[7] Y. Nakamura, “A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface,” Q. Rep. Railway Tech. Res. Inst. (RTRI), vol. 30, no. 1, pp. 25-33, 1989.

[8] Mamatov, X. Sotvoldiyev, M. Talipov, S. Shaumarov, K. Gafarbayli, and D. Bekmirzaev, “Metrological calibration and uncertainty evaluation of MEMS accelerometers for structural health monitoring in seismic regions,” Vibroengineering Procedia, vol. 62, pp. 140-144, Jun. 2026, [Online]. Available: https://doi.org/10.21595/vp.2026.26360.

[9] F. Lamonaca, C. Scuro, P. F. Sciammarella, D. L. Carnì, and R. Olivito, “Internet of things for structural health monitoring,” in Proc. IEEE Int. Workshop Metrology Ind. 4.0 IoT, Apr. 2018, pp. 73-78.

[10] Harsono, F. M. Mahadiva, Tavio, M. M. Talipov, and H. Hermawan, “Pushover analysis of simple house structures in seismic zones,” AIP Conf. Proc., vol. 3374, no. 1, art. no. 050035, Mar. 2026, [Online]. Available: https://doi.org/10.1063/5.0319164.

[11] I. Mirzaev, D. Bekmirzaev, E. Kosimov, E. An, N. Nishonov, and M. Talipov, “Seismodynamics of segmented underground pipeline systems based on real earthquake records,” AIP Conf. Proc., vol. 3447, no. 1, art. no. 060001, May 2026, [Online]. Available: https://doi.org/10.1063/12.0044018.

[12] Ministry of Construction of the Republic of Uzbekistan, Construction in Seismic Areas, Construction Norms and Rules KMK 2.01.03-19, Tashkent, Uzbekistan, 2019.