

## IMPACT OF REDUCED RIGIDITY OF DAMAGED STRUCTURES ON THE MAIN DYNAMIC CHARACTERISTICS OF REINFORCED CONCRETE RESIDENTIAL BUILDING

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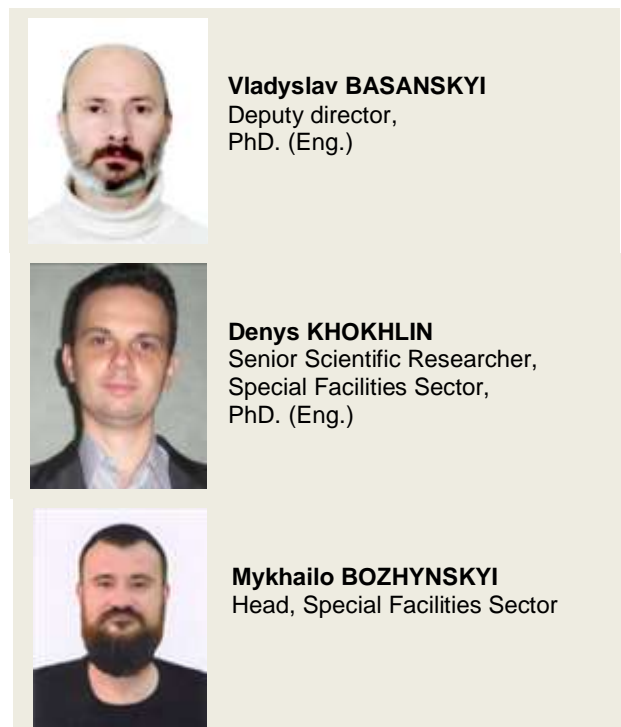
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**Abstract.** The article considers the specifics of reduced rigidity impact of damaged structures on the main dynamic characteristics of the structural system using the example of a reinforced concrete residential building for the further development of recommendations for planning dynamic monitoring of the technical condition of similar buildings.

A dynamic calculation was performed for a building with a cohesive monolithic reinforced concrete frame with 10 above-ground floors and standard architectural, planning, and structural solutions for earthquake-resistant buildings. Considering that the impact of damage to individual structures (including individual sections of walls) on the dynamic characteristics of the building as a whole is, as a rule, insignificant, to assess the impact of damage at different levels (floors) of the structural system, their distribution was assumed for all wall structures (diaphragms) within one floor. It has been found that the greatest effectiveness of dynamic monitoring using the "free vibration" method for residential and public buildings can be achieved when determining significant areas of damage to load-bearing structures that significantly affect the overall rigidity of the structural system at the lower height levels of the system (base and foundation, lower floors of the building).

At the same time, provided that the equipment has sufficient accuracy and resolution in terms of the energy and amplitude of free vibrations of the structure, the parameters of the second mode of vibrations should be determined, which can



provide a significantly larger amount of data on the spread and intensity of damage along the height of the building. From an applied point of view, the following main areas of wide use of dynamic monitoring by the "free vibration" method for residential and public buildings have been identified: for structures under dynamic loads that cause damage and deformation of load-bearing structures; detection of significant weakening of large sections of the "base-foundation" system;

assessment of the impact of significant uneven deformations of the foundation on load-bearing structures; in general (regardless of the characteristics of loads and influences), to identify significant areas of structural damage that significantly affect the overall rigidity of the structural system at the level of the lower floors.

**Keywords:** residential or public building; natural vibrations; damage; building condition assessment; dynamic characteristics; building investigation; monitoring.

## PROBLEM STATEMENT

A key factor in the widespread implementation of monitoring measures for large-scale construction projects (primarily CC-2) could be the reduced complexity and cost of such monitoring. One type of monitoring that meets this criterion is dynamic monitoring using the “free vibration” (or microseismic vibration) method, which differs from others primarily in that it measures background or microseismic vibrations of the building and the adjacent ground surface [1]. This method utilizes the direct relationship between the dynamic characteristics of the structure and the rigidity characteristics of the elements of the “foundation–structural system” and, accordingly, its generalized (integral) technical condition. Important advantages of this method typically include the relatively low labor intensity of the work, the absence of a need for extensive access to the structure’s components, and the convenience for monitoring the condition of the “structural system–foundation” system and its individual components.

Therefore, it is essential to develop and widely implement methods for monitoring the technical condition of buildings and structures classified as CC-2, including methods such as dynamic monitoring using the “free vibration” method.

## ANALYSIS OF PREVIOUS RESEARCH

The application and rationale of the “free vibration” (microseismic) method are occasionally discussed in the literature [1–10,

etc.], primarily in the context of dynamic testing of critical buildings and structures to assess their condition and the quality of construction work, to determine the dynamic response of individual structures or sections of structures, including for the purpose of assessing compliance with health safety requirements, as well as in seismically hazardous areas.

The current status of the practical application of such measurements for the diagnosis of building structures in Ukraine can be tracked through references in building codes and standards. The thorough application of dynamic tests for assessing technical condition can be found in certain specialized regulatory documents, for example, in the fields of earthquake-resistant [11] and transportation [9,12] construction. At the same time, the most general documents regulating the inspection and diagnosis of technical condition either do not mention the possibility of applying dynamic characteristic measurements at all [13] or address this issue only superficially [14]. General requirements for vibration monitoring are presented in [10]. These requirements need to be clarified and detailed according to the type of construction objects and their specific characteristics, as has already been done, for example, for transportation structures [9]. At the same time, when planning measurements within the framework of dynamic monitoring (and understanding the limits of its effectiveness), one should take into account the degree of influence of possible damage and weakening of various components of the “foundation–structural system” on the building’s vibration parameters in their various modes. Therefore, it is relevant to study the characteristics of changes in a building’s dynamic properties depending on the development of damage and other weakening of various components of the “foundation–structural system” in order to determine the limits of the effectiveness of their measurement for assessing and monitoring the technical condition of mass-produced buildings in modern Ukraine (in particular, such as residential and public buildings), developing

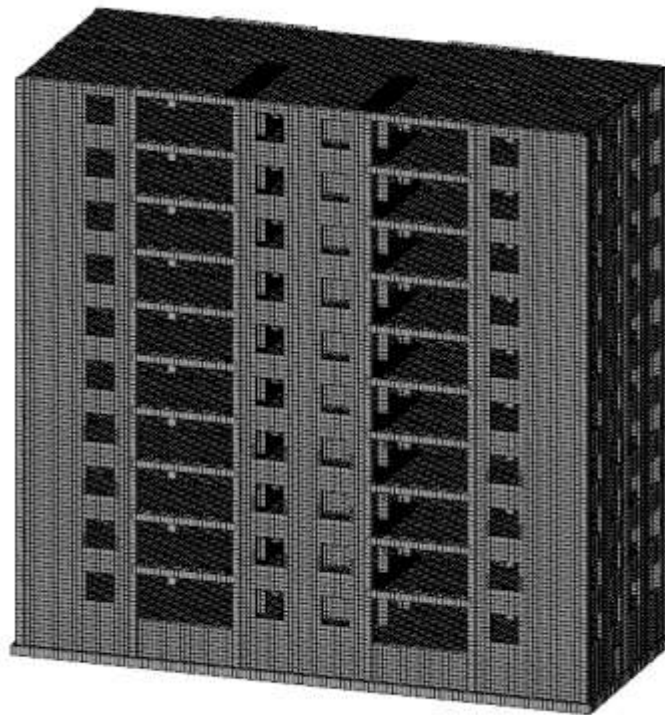
relevant recommendations, and incorporating them into existing codes and standards.

The aim of this study is to identify the specific effects of reduced rigidity in damaged structures on the primary dynamic characteristics of a structural system, using a reinforced concrete residential building as an example, with a view to developing recommendations for planning the dynamic monitoring of the technical condition of such buildings.

### MAIN RESEARCH

For the computational experiment, a building with a continuous monolithic reinforced concrete frame (with 10 above-ground floors) was selected, featuring standard architectural, layout, and structural solutions

(for earthquake-resistant buildings [11]); the exterior of the model is shown in Fig. 1. Useful time-dependent loads were adopted for residential buildings in accordance with [15]. To analyze the main dynamic characteristics, horizontal seismic loads were applied in accordance with [11] along and across the building at a minimum intensity of 6 points. The foundation is accounted for using dynamic bedding coefficients (uniform compression)  $C_{z,dyn}$ , determined according to the proposals in [16]. The following value of the average dynamic bedding coefficient is assigned (assuming the foundation consists of sandy loam and loam): 44'000 kN/m<sup>3</sup>. In addition, the non-uniform distribution of foundation rigidity near the edges of the building footprint was accounted.



**Fig. 1** General view of the FE model of reinforced concrete building for the calculation experiment in 3D view.

**Рис. 1** Загальний вигляд СЕ моделі залізобетонної будівлі для розрахункового експерименту у 3D-вигляді.

Table 1 presents the main results of the dynamic analysis of the building. To further evaluate the dynamic characteristics of the


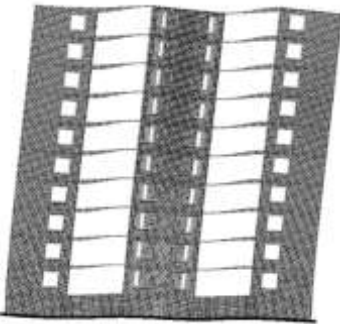
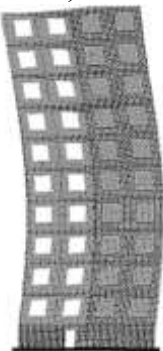
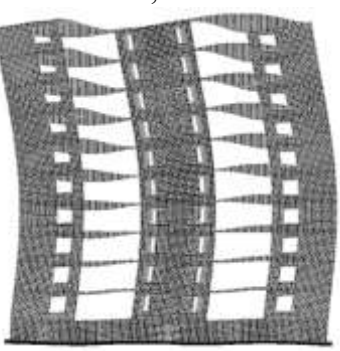
structural system obtained from the simulation, empirical relationships for the main periods of vibration collected in [11,17,18] were used. The

following building parameters were used for this purpose: building height –  $H = 30.15$  m or  $h_n = 98.9$  ft; dimension along the direction of vibration –  $D = 30$  m (along the building) or  $D$

$= 12$  m (across the building). The results of the calculations are presented in Table 2.

**Table 1.** Periods and modes of natural vibrations according to dynamic analysis.

**Табл. 1.** Періоди та форми власних коливань згідно динамічного розрахунку.

	Direction of vibration across the building	Direction of vibration along the building
<b>Mode 1</b>	$T = 0,623$ sec 	$T = 0,515$ sec 
<b>Mode 2*</b>	$T = 0,113$ sec 	$T = 0,109$ sec 

\*Note: The scale of the movements has been increased compared to mode 1.

**Table 2.** Periods of the first mode of natural vibrations in seconds, according to empirical relationships.

**Табл. 2.** Періоди першої форми власних коливань в сек. згідно емпіричних залежностей.

Direction of vibration across the building	Direction of vibration along the building
$T=0,020(h_n)^{3/4}=0,020(98,9)^{3/4}= 0,627$ sec	$T=0,020(h_n)^{3/4}=0,020(98,9)^{3/4}= 0,627$ sec
$T = 0,09 \frac{H}{\sqrt{D}} = 0,09 \frac{30,15}{\sqrt{12}} = 0,783$ sec	$T = 0,09 \frac{H}{\sqrt{D}} = 0,09 \frac{30,15}{\sqrt{30}} = 0,495$ sec
$T=0,066(H)^{3/4}=0,066(30,15)^{3/4}= 0,758$ sec	$T=0,066(H)^{3/4}=0,066(30,15)^{3/4}= 0,758$ sec
<b>Average value</b>	
0,723 sec	0,627 sec

The corresponding natural periods for the first mode, determined during the model

calculation, were 0.623 sec across the building and 0.515 sec along its length, which are,

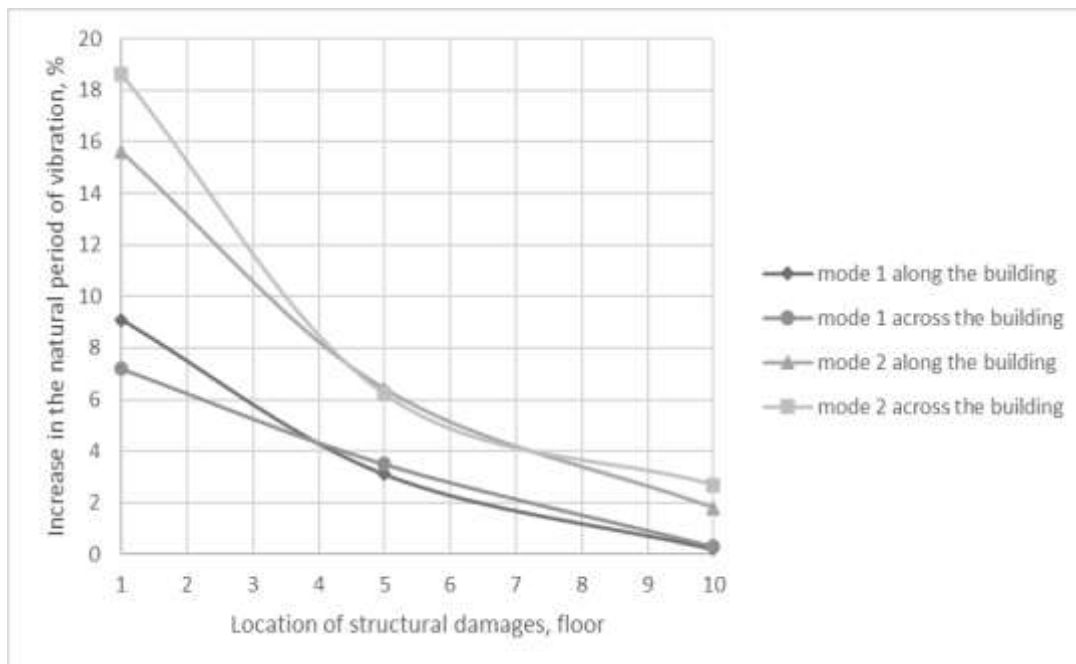
respectively, 13.8% and 17.9% (averaging a satisfactory 15.9% overall) shorter than the average empirical values. The lower values can be explained, first and foremost, by the developed system of wall structures (diaphragms), which increase the overall rigidity of the system.

The consideration of damage to primary load-bearing structures, which, due to their inherent rigidity, determine the dynamic characteristics of the building in the horizontal directions of vibration, is implemented based on Table 6.8 of DBN [11]. According to this table, for reinforced concrete frames with vertical diaphragms or stiffening cores, the limit relative deflection within a floor increases from 0.004 to 0.025 as the level of horizontal seismic load increases from a weak earthquake (assuming no damage) to the maximum (the highest level of damage at which the overall stability of the structural system is maintained). This corresponds to a reduction in the overall rigidity of the structures by approximately a factor of 6. For damage modeling, it is assumed that the damage level is slightly lower and that

the rigidity of wall structures and diaphragms is reduced to 0.2 of the initial rigidity.

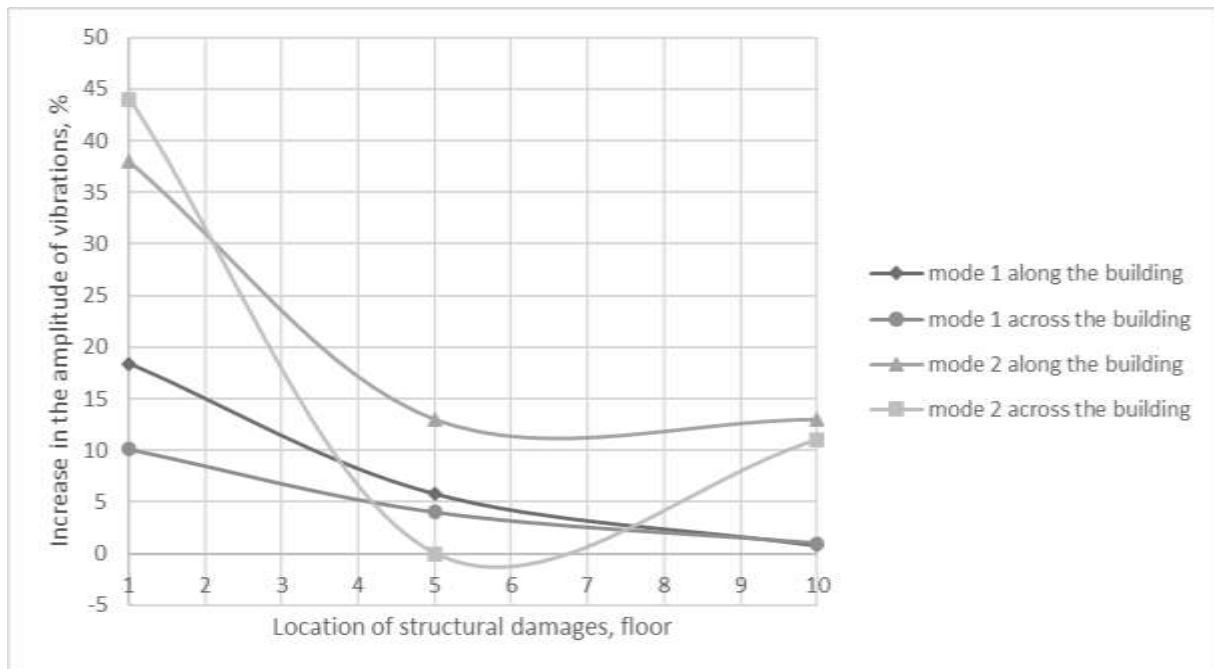
Given that the impact of damage to individual structural elements (including specific sections of walls) on the dynamic characteristics of the building as a whole is expected to be negligible, to assess the impact of damage at different levels (floors) of the structural system, its spreading was assumed for all wall structures (diaphragms) within a single floor. Overall, damage was modeled for the 1st, 5th, and 10th floors.

The reduction in the rigidity of the load-bearing structures predictably led to an increase in the periods and amplitudes of vibrations (and, consequently, to a decrease in vibration frequencies). Graphs showing the decrease in vibration frequency as a function of the level (floor) of damage spreading are shown in Fig. 2. Graphs showing the increase in vibration amplitudes (in terms of displacements) as a function of the level (floor) of damage spreading are shown in Figs. 3 and 4.



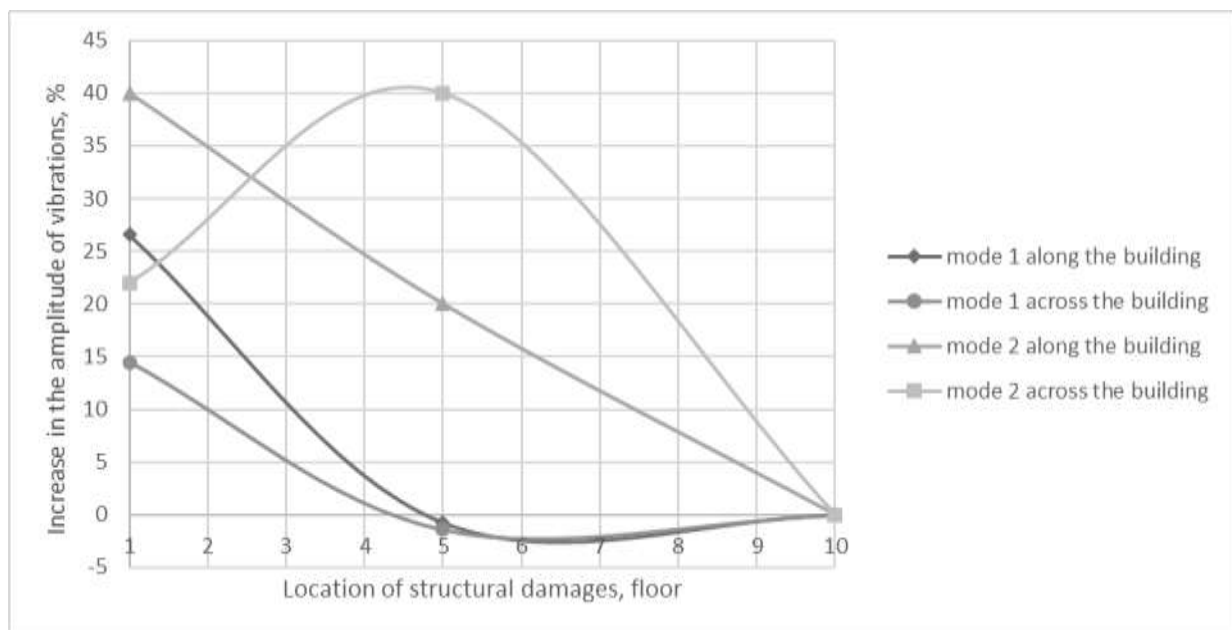
**Fig. 2** Increase in the natural period of building vibration depending on the location of structural damage.

**Рис. 2** Збільшення періоду власних коливань будівлі залежно від розташування ділянки пошкоджень конструкцій.



**Fig. 3** Increase in the amplitude of vibrations at the roof level depending on the location of structural damage.

**Рис. 3** Збільшення амплітуди коливань на рівні покриття залежно від розташування ділянки пошкоджень конструкцій.



**Fig. 4** Increase in vibration amplitude at the 4th-floor level depending on the location of structural damage.

**Рис. 4** Збільшення амплітуди коливань на рівні перекриття 4-го поверху залежно від розташування ділянки пошкоджень конструкцій.

The results presented in Fig. 2 show that (here and below, this applies to buildings with similar structural system parameters) the periods (frequencies) of vibrations for the second mode are approximately twice as sensitive to the effects of damage at all levels of the above-ground floors. At the same time, even assuming the spreading of damage across all vertical structures at the floor level, a measurement accuracy exceeding 10% (according to DSTU [10]) was observed only for damage at the 1st–3rd floor levels for the second mode of vibration. Assuming a measurement accuracy of 5%, the corresponding damage spreading can be detected for the 1st and 2nd floors using the 1st mode of vibration and for the 1st–5th floors using the 2nd mode of vibration.

The results presented in Fig. 3 show that when measuring the amplitude (displacements) of vibrations at the floor level with a measurement accuracy of 10%, the spreading of damage in vertical load-bearing structures (across the entire floor plane) can be detected using the 1st mode only for the 1st–2nd(3rd) floors of vibration (and the 1st–3rd(4th) floors with 5% accuracy). Measuring vibration amplitudes using mode 2 along the building (greater system rigidity than in the across direction) allows for the detection of corresponding damage for all floors, and in the across direction – for the 1st–3rd(4th) floors (with 5% accuracy – also for the top 2 floors).

The results presented in Fig. 4 show that when measuring the amplitude (displacements) of vibrations on the 4th floor with a measurement accuracy of 10%, the extent of damage to vertical load-bearing structures (across the entire floor plane) can be detected using the 1st mode similarly for the 1st–2nd(3rd) floors of vibrations (and the 1st–3rd(4th) floors with 5% accuracy). Measuring vibration amplitudes using the second mode along the building allows for the detection of corresponding damage for the 1st–7th(8th) floors, and across the building – for the 1st–8th(9th) floors.

It should also be noted that the values of the oscillation amplitudes for the second mode in the system under study (and similar systems)

are approximately 30–50 times smaller than the corresponding values (at the same height level) for the first mode. Consequently, this requires equipment with high resolution (primarily for determining frequency) and high accuracy (for determining amplitudes) for measuring absolute values of velocities or accelerations, as well as a low level of background vibration noise. This can be partially compensated for by using an additional vibration generator (of higher energy) near the building.

A summary and analysis of the data obtained lead to the conclusion that the greatest effectiveness of dynamic monitoring using the “free vibration” method for residential and public buildings (with architectural and structural solutions similar to the building under consideration) can be achieved by identifying significant areas of damage and weakening in load-bearing structures that significantly affect the overall rigidity of the structural system at the lower levels of the system (basement and foundation, lower floors of the building). At the same time, provided that the equipment has sufficient accuracy and resolution with respect to the energy and amplitude of the structure’s free vibrations, the parameters of the second mode of vibration should be determined, which can provide a significantly greater amount of data regarding the spreading and intensity of damage along the height of the building.

## CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

As a result of the analysis is performed in this work, the following conclusions can be drawn:

- To determine the general characteristics of how reduced rigidity in damaged structures affects the primary dynamic characteristics of the structural system of a reinforced concrete residential building, a dynamic analysis was performed on a building with a braced monolithic reinforced concrete frame comprising 10 above-ground floors and standard architectural, planning, and structural (for earthquake-resistant buildings);

- given that the impact of damage to individual structural elements (including specific sections of walls) on the dynamic characteristics of the building as a whole is generally insignificant, to assess the impact of damage at different levels (floors) of the structural system, its spreading was assumed for all wall structures (diaphragms) within a single floor;
- the greatest effectiveness of dynamic monitoring using the “free vibration” method for residential and public buildings can be achieved by identifying significant areas of damage and weakening in load-bearing structures that significantly affect the overall rigidity of the structural system, particularly at the lower levels of the system (basement and foundation, lower floors of the building). At the same time, provided that the equipment has sufficient accuracy and resolution with respect to the energy and amplitude of the structure’s free vibrations, the parameters of the second mode of vibration should be determined, as this can provide a significantly greater amount of data regarding the distribution and intensity of damage along the height of the building;
- from an applied perspective, the following main areas of wide use of dynamic monitoring using the “free vibration” method for residential and public buildings can be identified: for structures subjected to dynamic loads that cause damage and deformation of load-bearing structures; detection of significant weakening of large sections of the “base-foundation” system; assessment of the impact of significant uneven deformations of the base on load-bearing structures; in general (regardless of the specific nature of loads and influences), to identify significant areas of structural damage growth that substantially affect the overall rigidity of the structural system at the lower floor levels.

Further research could focus on investigating how reducing the rigidity of damaged structures affects the dynamic

behavior of buildings with different structural and architectural-planning characteristics – such as brick buildings with fewer stories – as well as conducting field measurements of the dynamic behavior of damaged buildings to compare with the results of analysis based on their corresponding models.

#### ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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## ВПЛИВ ЗНИЖЕННЯ ЖОРСТКОСТІ ПОШКОДЖЕНИХ КОНСТРУКЦІЙ НА ОСНОВНІ ДИНАМІЧНІ ХАРАКТЕРИСТИКИ ЗАЛІЗОБЕТОННОЇ ЖИТЛОВОЇ БУДІВЛІ

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**Анотація.** В статті розглянуті особливості впливу зниження жорсткості пошкоджених конструкцій на основні динамічні характеристики конструктивної системи на прикладі залізобетонної житлової будівлі для подальшої розробки рекомендацій з планування динамічного моніторингу технічного стану відповідних будівель.

Виконаний динамічний розрахунок будівлі зі зв'язковим монолітним залізобетонним каркасом з 10 надземними поверхами та стандартними архітектурно-планувальними та конструктивними для сейсмостійких будівель рішеннями. Враховуючи, що вплив пошкоджень окремих конструкцій (в т.ч. окремих ділянок стін) на динамічні характеристики будівлі в цілому є, як правило, незначним, для оцінки впливу ушкоджень на різних рівнях (поверхах) конструктивної системи їх розповсюдження приймалося для всіх стінових конструкцій (діафрагм) в межах одного поверху.

Виявлено, що найбільша ефективність динамічного моніторингу методом «вільних коливань» для житлових і громадських будівель

може бути досягнута при визначенні значних ділянок розвитку пошкоджень несучих конструкцій, що суттєво впливають на загальну жорсткість конструктивної системи, на нижніх висотних рівнях системи (основа та фундамент, нижні поверхи будівлі). При цьому, за умови достатньої точності та розподільної здатності обладнання відносно енергії та амплітуди вільних коливань споруди, слід визначати параметри 2-ї форми коливань, яка може надати суттєво більший обсяг даних щодо розповсюдження та інтенсивності пошкоджень по висоті будівлі. З прикладної точки зору виділено наступні основні напрями широкого використання динамічного моніторингу методом «вільних коливань» для житлових і громадських будівель: для споруд, що піддаються динамічним навантаженням, які викликають пошкодження та деформації несучих конструкцій; виявлення суттєвих ослаблень великих ділянок системи «основа-фундамент»; оцінки впливу на несучі конструкції значних нерівномірних деформацій основи; в загальному випадку (незалежно від особливостей навантажень і впливів), для виявлення значних ділянок розвитку пошкоджень конструкцій, що суттєво впливають на загальну жорсткість конструктивної системи, на рівні нижніх поверхів.

**Ключові слова:** житлова або громадська будівля; власні коливання; пошкодження; оцінка технічного стану будівлі; динамічні характеристики; обстеження будівель; моніторинг.

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