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Original Research Article

DYNAMIC BEHAVIOR OF A HIGH-RISE BUILDING UNDER SEISMIC LOADS FOR DIFFERENT BEARING FRAME TYPES

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Abstract

Paper presents the results of dynamic behavior analysis of a high-rise building under seismic loads as part of the “base-foundation-building” system. Analysis covers different types of reinforced concrete construction with girder frame and non-girder frame. Using modal analysis, paper presents differences in mode shapes and frequencies caused by the presence or absence of girders. Paper also demonstrates variations in the stress-strain state for the vertical bearing structures under the seismic load for different frame types.

Keywords: bearing frame, girder frame, dynamic response, seismic load, modal analysis, numerical methods, soil base, foundation, high-rise building

1. INTRODUCTION

Recent years, the activity of many earthquakes has been recorded around the world, many of which have led to terrible consequences. Among them are earthquakes in Ecuador, Italy, Japan and other countries.

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Ukraine has also experienced elevated seismic activity during recent years. Coupled with an ever-growing tempo of high-rise construction and increased construction density, this has created a demand for new and modern approaches to earthquake-resistant construction design.

As part of this, it is important to analyze the overall interaction of elements within the "base-foundation-building" system as a whole, which is a very complicated and complex problem.

In accordance with the requirements of norms of building design in Ukraine [1], the intensity of seismic influences in seismic regions is assigned on the basis of general seismic region maps while taking into account the importance of the building and the soil conditions of the construction site. Also, depending on the type of building, there are requirements for choosing the method of calculating seismic influences. The norms of building design in Ukraine [1] specify requirements for volume-planning and construction solutions depending on the seismicity of the construction site, such as the type of bearing framework and allowable number of storeys. Instructions are given for choosing a reinforced concrete building frame with or without girders.

Because of the complexity of full calculations, an evaluation of the dynamic response of high buildings to seismic loads is carried out using simplified methods and models of environment deformation, which can cause qualitative and quantitative errors [3]. On the other hand, applying more complex calculations, such as considering the real characteristics of soil base, requires significant computing resources. Thus, to increase the reliability and safety of construction in seismically dangerous areas, we face the problem of exploring and applying novel approaches to engineering calculation methods that would take into account the most important processes of deformation of different environments.

The norms of building design in Ukraine [1] outline requirements for volume-planning and construction decisions depending on the seismicity of the construction site, including the type of bearing frame and number of storeys in the building. However, the construction of reinforced concrete frames with girders requires significantly larger amount of material resources compared to non-girder frames with a flat slab panel. That is why the issue of choosing the type of bearing frame during construction in seismically dangerous areas is also relevant and requires specific exploration.

This work investigates this problem by performing modal analysis of the element displacements and analyzing lower modes of the spectrum.

The goal of this analysis is an evaluation of the dynamic response of the building under seismic load, for both girder and non-girder load-bearing frame types.

2. NUMERICAL SIMULATION OF THE HIGH-RISE BUILDING

2.1. The object of study. Finite element model

The object of study is a 21-storey residential and office building in Kyiv. It has three sections, separated from each other by the strain seams. The building relies on a monolithic reinforced concrete frame with additional hardness kernels. The foundation is pile-based, combined with a reinforced concrete raft slab. One distinct feature of this building is an irregular step of the vertical frame elements and a presence of monolithic walls around the perimeter of the building on the ground floor (Fig.1).

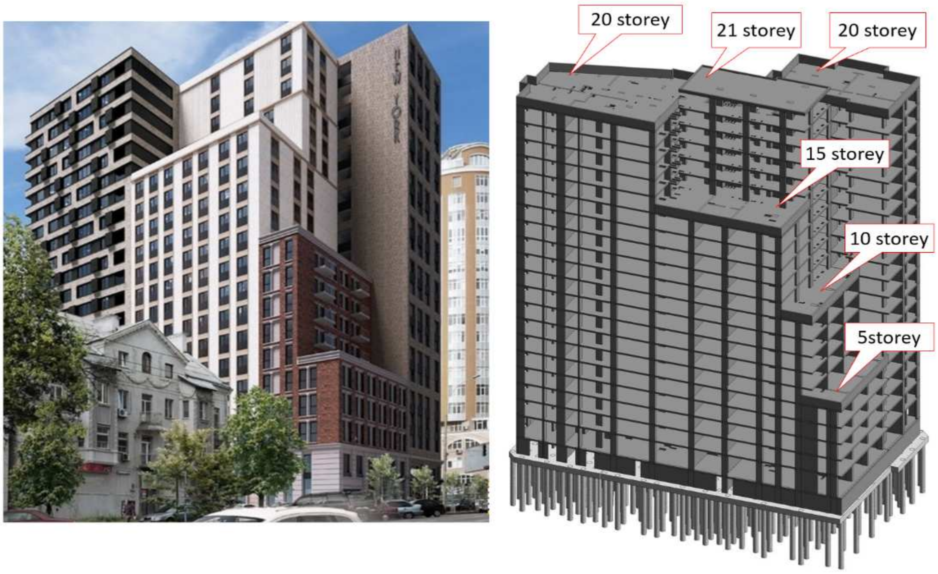

Fig. 1. The object of study: a) general view of complex, b) bearing frame of the building

Such construction design exhibits an irregular distribution of spatial stiffness and mass, which has a significant influence on the character of the oscillations. The soil base consists mainly of clay soils. From the surface up to 4 meters there are bulk soils. Further down, there are layers of loamy sand and loam (7 m thick), which are grounded by semi-solid marl clays. At a depth of 35 m there are small dense sands.

The developed finite-element model, shown in Fig.2, has 2 586 450 variables. The soil base is represented as a 3D volumetric mass according to the data from engineering -geological surveys (Fig.2).

To reduce the wave reflection effect from boundary conditions of the simulated area, dimensions of the soil mass around the building were taken with respect to the condition of providing more than ten times wave absorption [3]. The depth of the soil mass was based on the recommendations [2] of no less than triple maximum linear size of the foundation in the construction plan. The building construction, including foundations, were modeled by shell- and beam- finite elements.

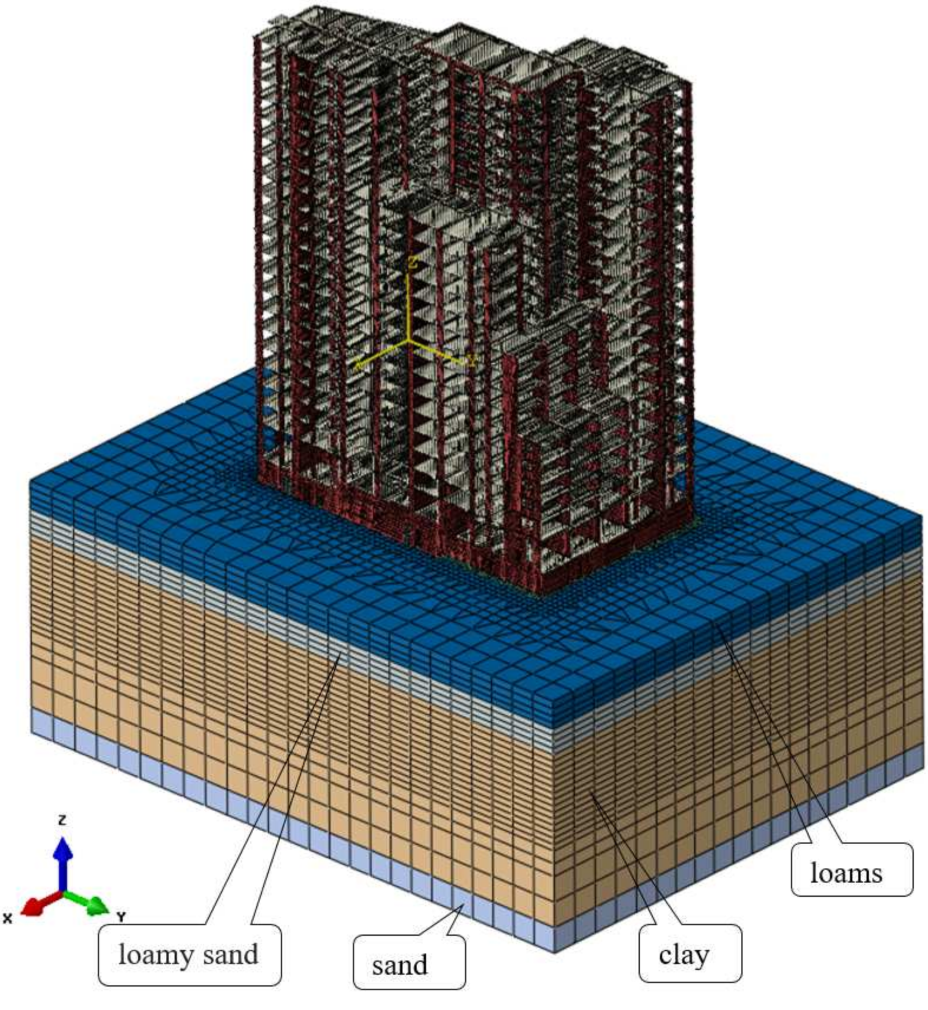

Fig. 2. Finite-element model of the “base-foundation-building” system

With the aim of identifying changes in the dynamic response of the building depending on the type of bearing frame, numerical simulations of two different types of reinforced concrete frame (with or without girders - Fig.3) were performed, with the seismic load including the interaction of neighboring sections. Calculations were made by numerical modeling of mutual interactions of a "base-foundation-building" system using the finite element method in a viscoelastic setting, carried out using the Simulia Abaqus software suite.

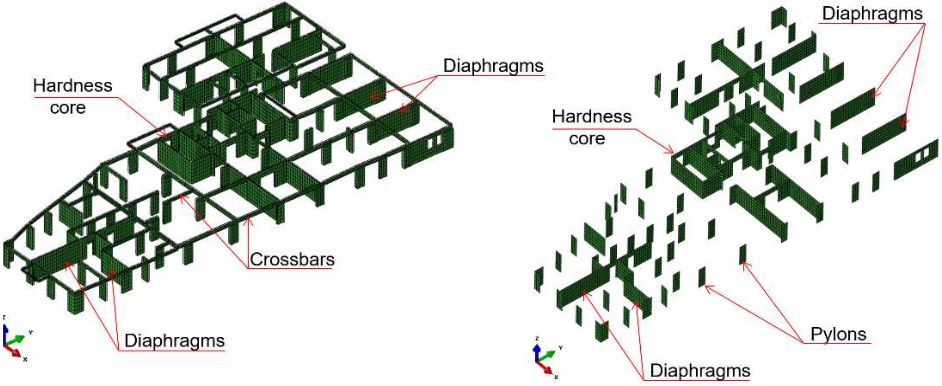

Fig. 3. Types of reinforced concrete frame: a) girder , b) non-girder

Three component accelerograms from the standard set [1] were used as the dynamic load. These were scaled to 6-point seismic intensity, with a duration of 168 seconds. Accelerograms were chosen so that their prevailing periods where similar to the period of natural vibrations of the building by first form.

2.2. Mathematical model

During an earthquake, as a result of a moving base with acceleration $\ddot{X}_0(t)$, according to the D'Alamber Principle the inertial forces $-m\ddot{X}_0(t)$ appear, which bring the building out of equilibrium and force vibrations. The general equation [4] for discrete systems taking into account attenuation according to the Voigt-Kelvin hypothesis describes such movements U as:

$$[M]\frac{d^2\{U\}}{dt^2}+[C]\frac{d\{U\}}{dt}+[K]\{U\}=\{Q(t)\} \tag{2.1}$$

where $[M]$, $[C]$, and $[K]$ are, respectively, the matrices of mass, damping and stiffness.

From a mathematical point of view we need to apply either the spectral element method and perform direct integration in time in order to solve the problem above. In this analysis, we applied the method of normal coordinates where the moving vector was represented by amplitudes A^i of the partial spectrum of eigenforms X_i:

$$\{U\}=\sum_{i=1}^{N}A^i\{X_i\} \tag{2.2}$$

where N is the number of eigenforms of vibrations.

It is known that for most problems, higher order modes give a smaller contribution to performed work, so their influence on the solution is insignificant. Thus, while modeling dynamic problems, it is not necessary to take into account all found modes [5]. Only the lower part of spectrum, in which the most modal masses accumulate, has practical importance. The number of used modes can be decided based on the accumulation of modal masses [1], taking into account the given frequency range [5], or other criteria.

Initially, modal analysis of the system is performed to find mode shapes and corresponding frequencies. Then, assuming initial conditions $X(0) = X_0$ for each of the selected spectral components, direct integration is performed over the entire seismic load time period. For example, this can be done using Duhamel's integral [2]:

$$x(t) = -\frac{1}{\omega_D}\int_0^t X_0(\tau)e^{\zeta\omega(t-\tau)}\sin[\omega_D(t-\tau)]\,d\tau \tag{2.3}$$

This procedure allows us to replace a complex (using explicit or implicit scheme) integration of a differential equation system describing system motion with a much simpler integration of the independent equations [2] and to significantly improve productivity while carrying out engineering calculations by using ordinary personal computers. In this case, additional restrictions are imposed on taking into account the system damping characteristics.

Accounting of the damping processes is done using the Rayleigh model, in which the damping matrix $[C]$ is represented as a linear combination of stiffness matrices $[K]$ and mass $[M]$:

$$[C] = \alpha[M] + \beta[K] \tag{2.4}$$

Recommended norms [1] suggest the use of a logarithmic vibration decrement δ=0.3 in order to estimate damping. To use this recommendation with the Rayleigh model, the parameter of general viscosity ξ can be represented through the oscillation decrement δ:

$$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{2.5}$$

and taking that general viscosity ξ:

$$\xi = \xi_M + \xi_K \tag{2.6}$$

where ξ_M, ξ_K correspond to viscosity for mass and rigidity components, resulting in:

$$\alpha = 2\omega_0\xi_M; \quad \beta = \frac{2\xi_K}{\omega_0} \tag{2.7}$$

where ω_0 – angular frequency (first natural frequency of building).

3. FORMULAE

Accounting for the additional stiffness in a girder frame led to some changes in the dynamic properties of the building. The change of the frame weight was insignificant (up to 4%).

Performed analysis has shown that in the case of a frame with girders there was an increase in the first natural frequency of the structure (up to 16%). Displacement values were significantly larger in the corner sections of the building for both the first and second mode shape. Of particular interest is the fact that girder frame was characterized by translational oscillations, while non-girder frame by bending-twisting oscillations. Starting with the third mode, there are oscillations of all three sections for the girder frame. However, for the non-girder frame the third mode shape still mostly shows bending-twisting oscillations at the corner sections of the building with the middle section having significant oscillations only starting from the fourth mode.

Applying extra rigidity using girders allows small increase of natural frequencies which in practice may allow to control resonance frequencies. Furthermore, additional spatial rigidity significantly reduces the twisting and bending components for low frequencies - which will result in better dynamic stability of the building in general. However, it should be noted that the effectiveness of impact on the dynamic response of the building is highly dependent on both the prevailing frequencies of the seismic loads and the characteristics (including rigidity) of the soil base.

The analysis of tensions in the bearing elements of the frame showed that the change of frame type influences the distribution of forces. Under the action of the seismic load, at the 4th floor level, there are normal tensions in the pylons in the girder version of the frame. These tensions, located along the perimeter of the building, are 20-45% more than in non-girder case (Fig.4).

It is necessary to note that pylons located on the perimeter have more uniform tensions in the girder version of the frame. The non-girder frame has pylons in which there are considerable concentrations of tensions, which facilitates the creation of irreversible deformations.

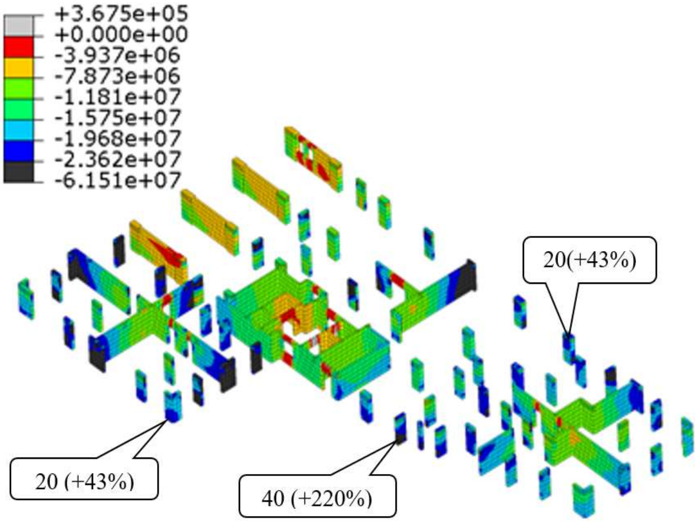

Fig. 4. Range of vertical normal tensions (maximum tension) in frame elements at the 4th floor level for a girder version of frame, in Pa (notes in MPa).

Analysis for the given seismic load has shown that there were no significant differences in oscillation amplitude for the girder and non-girder frame types. Deviation of the top of the building from a steady state was approximately 10 to 18 cm with maximum horizontal amplitudes occasionally reaching 30 cm for both frame types.

4. CONCLUSIONS

Based on the conducted analysis, it is shown that adding additional rigidity in form of girders allows us to shift the spectrum of modal frequencies and to influence the distribution of oscillation forces and, at the same time, to reduce twisting components for the lower range of modal frequencies. It also allows for a more uniform distribution of tension in vertical bearing elements of the frame along the building's perimeter.

It is shown that the degree of influence of the girders on building's dynamic response significantly depends on specific dynamic properties of the building, properties of the soil base (including rigidity) and prevailing frequencies of the seismic load. Including girders may lead to increased tension in some bearing elements of the frame.

A criterion that would restrict the supported number of building floors in the case of a non-girder frame requires additional research and will highly depend on the specifics of the particular construction project.

It is also shown that the use of the method of normal coordinates allows precise estimation of the stress-strain state evolution for elements of the "base - foundation - building" system under the seismic load. This method is recommended for engineering tasks that could be solved with the help of personal computer systems.

REFERENCES

1. *DBNB.1.1-12:2014 Construction in seismic regions of Ukraine*, Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, Kyiv 2014 (in Ukrainian).
2. Birbraer A.N. *Analysis of structures for earthquake resistance* (in Russian). Nauka Publishing House, Sankt-Petersburg 1998.
3. *SP 23-105-2004. Evaluation of vibration in the design, construction and operation of metro facilities.* State Committee of the Russian Federation for Construction and Housing and Communal Complex (Gosstroy of Russia) Moscow, 2004 (in Russian)
4. Perelmyter A.V. *Design models of structures and the possibility of their analysis*, VPP “Kompas”, Kyiv 2001 (in Russian)
5. Sakharov, V.O, *Application of spectral super elements in the tasks of the dynamics of the system "foundation - foundation - building"*: Bulletin of Pridneprovsk State Academy of Civil Engineering and Architecture, **1**, PDABA - Dnepr 2015, 37-46 (in Ukrainian)
6. Boyko, I., Sakharov, O., Sakharov, V. (2013): *Behavior of the multistory building under seismic loads with the account of the viscoplasticity of the soil base*, Proceedings International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013, 1443-1446.

DYNAMICZNE ZACHOWANIE SIĘ BUDYNKU WYSOKIEGO POD OBCIĄŻENIEM SEJSMICZNYM DLA RÓŻNYCH TYPÓW SZKELETU BUDYNKU

Streszczenie

W artykule zostały przedstawione wyniki analizy dynamicznej zachowania się wielokondygnacyjnego budynku wysokiego pod obciążeniem sejsmicznym jako układu "podłoże gruntowe – fundament – budynek". Analiza obejmuje różne rodzaje konstrukcji szkieletowych z betonu zbrojonego o ramie nośnej z belkami wzmocnienia i bez nich. Wykorzystując analizę modalną, w artykule podane różnice we własnych formach i częstotliwościach dla różnych rodzajów szkieletu budynku. W prace również zostały wykazane zmiany w rozkładzie naprężeń w pionowych konstrukcjach nośnych budynku pod obciążeniem sejsmicznym w zależności od rodzaju szkieletu budynku.

Słowa kluczowe: rama nośna budynku, konstrukcja szkieletowa z belkami, odpowiedź dynamiczna, obciążenie sejsmiczne, analiza modalna, metody numeryczne, podłoże gruntowe, fundament, budynek wysoki

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