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VIBRATION TEST OF A HIGH-RISE MONOLITHIC BUILDING

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ABSTRACT: The relevance of the study is due to the lack of land for Almaty city development. The study purpose is to study the behavior specifics of a 35-story residential building in Almaty city under seismic loads according to calculations during its design. To study the set task, an experimental study of the dynamic load was carried out using a B-3-type vibration machine. Thus, the paper considers the results of dynamic tests of a 35-story building with a frame-wall construction. Dynamic tests were carried out using a vibration machine with an inertial effect installed on the building floor. Vibration recording was carried out using a digital instrument-measuring system. In the course of the study, insignificant differences were revealed in the calculated and experimental values of the vibration periods. When determining the design seismic loads on facilities of such type, the values of logarithmic vibration decrements are recommended to be taken within 0.12-0.18 (ξ=2-3%). Among the conclusions, the need to amend regulatory documents in construction, as well as the following observation of the high-rise were identified.

Keywords: Concrete, Reinforcement, Full-scale tests, Tests methods, Dynamic characteristics of a building

1. INTRODUCTION

Due to the significant cost of land plots in Almaty city and the lack of free territories, there is a tendency to increase the number of stories of residential buildings under construction. Buildings of frame-wall structural systems due to their technical and economic advantages, great potential in the area of architectural expressiveness of the exterior and wide possibilities in terms of organizing "flexible" layouts of premises, have become widespread in the practice of earthquake engineering in Almaty city. An analysis of the consequences of strong earthquakes and previous tests shows that frame-wall structural systems differ from framed systems in many advantages.

Since the beginning of the 2000s of 21st century, intensive high-rise construction of residential buildings has begun. Currently, the population of the city is 2.2 million people, with the prospect of growing to 5 million people in 2030. According to Yerzhanov et al., the first high-rise building in the city was the 25-story hotel "Kazakhstan", which was tested using a vibration machine with an inertial effect and on which the station of the engineering seismometric service is located [1]. For 40 years, the behavior of the building under seismic impacts of various intensities has been monitored. A number of studies on the seismic resistance of multi-storeyed residential buildings, including the analysis of regulatory documents, theoretical and experimental studies, are presented in the work of Nemchinov [2].

Qian analyses new design methods for high-rise buildings [3]. Jing et al. study steel modular constructions.[4]. Safarzadehbased on the Abaqus software (Simulia's Abaqus 6.19) performed a series of three-dimensional calculations to study the effect of the number of floors of high-rise buildings (20, 25 and 30 floors) on seismic characteristics [5]. The issue of reducing seismic loads on high-rise buildings is considered in the work of Bedon and. Amadio [6]. Special mechanical connections are suggested at the junction between the main building constructions and the glassed facade. Facade glazing works as a system to reduce seismic loads and the effect of reducing seismic loads was shown [7].

The purpose of this work was to study the specifics of the behavior of a 35-story residential building in Almaty city of a frame-wall structural system under seismic loads and to verify the correctness of the design assumptions adopted in its design. Such a task is set in Kazakhstan for the first time. The tasks of the experimental studies of the 35-story building included: identification of the conformity degree of the actual values of the dynamic parameters of the building (periods and modes of vibration) with the calculated indicators; assessment of the dissipative properties of a high-rise building; the study of the building behavior under dynamic effects; assessment of the ability of floor slabs to distribute horizontal seismic loads between vertical elements.

2. RESEARCH SIGNIFICANCE

The paper's significance lies in the fact that it presents the results of experimental dynamic tests conducted on a high-rise building to determine its dynamic characteristics, assess its dissipative properties, and study its behavior under dynamic effects. The paper suggested recommendations for determining the design seismic loads on facilities of such type. The research results can be used to improve the design and construction of high-rise monolithic buildings in seismic-prone areas.

3. MATERIALS AND METHODS

A facility, which is a 35-story building under construction in Almaty, was chosen for experimental studies. The building was constructed on the site, which is characterized by a high level of seismicity, which is expressed in 9 points. As for soils, according to classifications by seismic properties, this facility belongs to the first category. Conditions that complicate the seismological or engineering-geological conditions of the construction site have not been identified.

The building has a Y-shape in plan and is separated from the adjoining facilities by antiseismic joints. The planned height of the building from the foundation base to the top of the building (excluding the spire) is 134.12 m. The studied facility forms a frame-wall system. The basement and 29 above-ground floors of the building are made of reinforced concrete constructions, and 6 floors of the domical part are made of steel constructions.

The thickness of the main reinforced concrete walls is from 600 to 700 mm. The levels of the lower floors, up to 300 mm in the upper floors. With horizontal impacts, the joint work of reinforced concrete walls is provided by horizontal floor slabs. The building flooring consists of monolithic reinforced concrete foundations, the thickness of which is 20 cm. The design of the edge strength of the concrete foundation plate was taken as B25, walls (except for the basement walls of the lift shafts) and the columns: up to the mark 13.02 m – B45, from the mark 13.02 up to 25.62 – B40, from the mark 25.62 up to 60.25 – B30, above – B25. The walls of the basement, lift shafts and floor slabs are made of B25 concrete.

The design of the 35-story building was carried out in accordance with the requirements of the standards of the Republic of Kazakhstan [8; 9] and the Special technical regulations for the design of a multi-story residential building (construction site in Almaty city). It is important to note that before the site survey was carried out, 3 basement floors and 29 above-ground floors were built.

A general view of the experimental facility and a standard floor plan is shown in Figs. 1 and 2. A general view of the vibration machine on the floor is shown in Fig. 3. A set of power equipment for vibration analysis of a building consisted of 200 kW direct current motor; six two-shaft vibrators with horizontal axes of rotation of unbalance levers; flashing unbalance loads, hung on the vibrator's levers, if necessary; control console that helps to easily set the rotation frequency of the motor shaft.

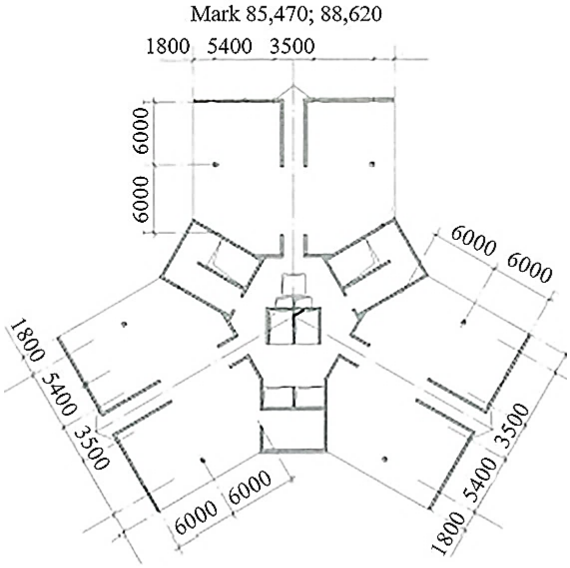

Fig.1 Standard floor plan

Fig.2 The building under construction

The motor and vibrators were rigidly fixed to a horizontal steel frame located at the floor level above the 29th floor of the building. The vibration analysis of the building consisted of three stages, described in Table 1. Each stage consisted of a double smooth pass through the resonances corresponding to different tones of the building vibrations: first, by increasing the rotation frequency of the unbalances (“direct resonance”), and then by decreasing the rotation frequency of the unbalances (“reverse resonance”).

During the implementation of vibration studies, recording vibration waves and processing information, facility optical analysis, as well as its photo and video recording, were performed. Registration of instrumentation data was carried out using a special software and hardware complex developed according to the technical specification of specialists from the Kazakh Research and Design Institute of Construction and Architecture. The hardware component of the complex consists of an analog signal input unit with a device for analog-to-digital conversion, to which a PC-based signal recording and processing unit is connected.

Thirty-four accelerometers were involved in the conducted tests. Sensors attached to building constructions are shown in Fig. 4. Overall, the selection of acceleration sensors will depend on the specific application, budget, and accuracy requirements. It’s essential to choose sensors that are compatible with the building's structural characteristics and capable of measuring the intended vibration or acceleration. To identify the moments of time on the vibration recordings that characterize the onset of resonances, marks were displayed on one of the channels of the analog-digital system from a special pulse sensor installed on the vibration machine. The initial dynamic parameters of the studied building were established based on the study of instrumentation recordings of its microseismic vibrations.

1. RESULTS AND DISCUSSION

4.1 Dynamic Parameters and Features of the Facility Deformation During Testing

Patterns of motion trajectories of the intermediate floor of the building above the 29th floor during testing phase III-3 are displayed in Fig. 5.

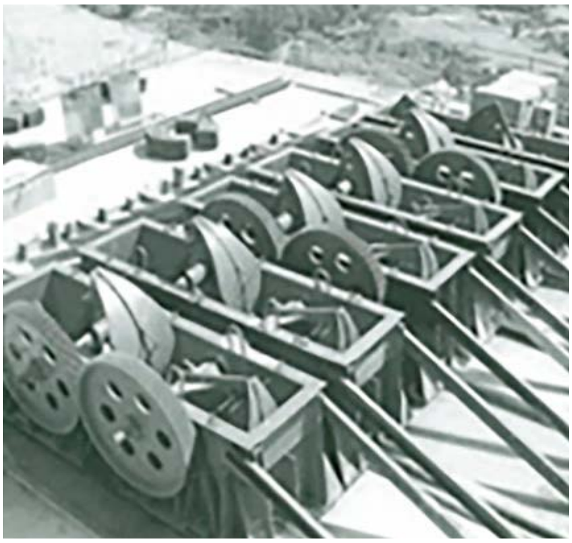

Fig.3 B-3 type vibration machine

Motion trajectories of intermediate floors were built according to the records of sensors 1 and 2 located in the central part of the building. The values of the vibration periods of the building in different modes are disclosed in Table 2. The vibration modes of the vertical axis of the building and the coefficient values of the vibration at different levels of the building are shown in Fig. 6.

The maximum accelerations and relocations of the building in the Y-axis direction, recorded by sensor 1 in the center of the floor above the 29th floor, are disclosed in Table 3. The maximum accelerations and relocations recorded by sensor 3 at the edge region of the floor above the 29th floor were significantly bigger than those recorded at the center of the floor. The values of logarithmic vibration decrements δ and attenuation coefficient ξ, calculated on the basis of the instrumental records analysis of building vibrations at maximum vibration impacts (Table 4) should be considered as quite overestimated compared to the actual values.

Table 1 Test stage

Test stage number		Interlocked vibrators number	Unbalance weights number on each vibrator
I	I-1	1	0
	I-2	1	0
II	II-2	6	0
	II-2	6	0
III	III-1	6	60
	III-2	6	60
	III-3	6	60

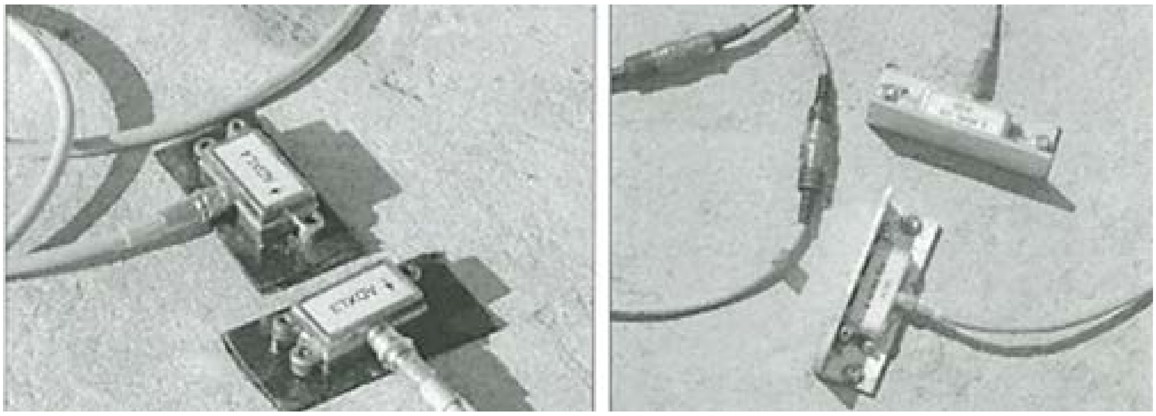

Fig.4 Acceleration sensors – accelerometers

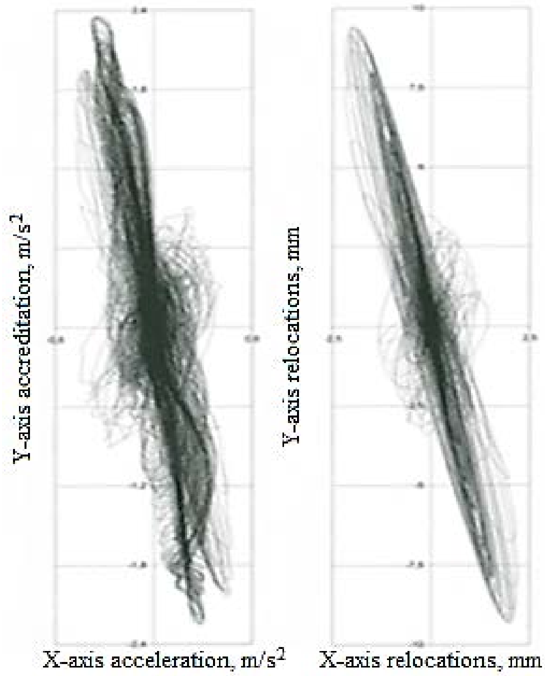

Fig.5 Motion trajectories of the intermediate floor above the 29th floor during testing phase III-3

Table 2 Vibration period test stages η

Number of the vibration mode	Vibration periods (sec) of the building at the test stages			
	I	II	III-I	III-3
1	1.31	1.33	1.40	1.48
2	0.38	0.40	0.42	0.43
3	-	0.20	-	0.22

The horizontal deformations of the intermediate floors of the building due to their compliance did not exceed 3% from the relocations of these floors. The building relocations in the floor level above the 29th floor, caused by the shift compliance of the base were: during vibrations in the first mode – not more than 1%; during vibrations in the second mode – 2-3%; during vibrations in the third mode – 7-8%. The building relocations in the floor level above the 29th floor were: during vibrations according to the first mode not more than 4-5%; during vibrations according to the second mode – 6-7%; during vibrations according to the third mode – 20-25%. The total compliance contribution of the base to the relocations of the top of the building did not exceed: during vibrations according to the first mode – not more than 5-6%; during vibration according to the second mode – not more than 8-10%; during vibration according to the third mode – not more than 27-32%.

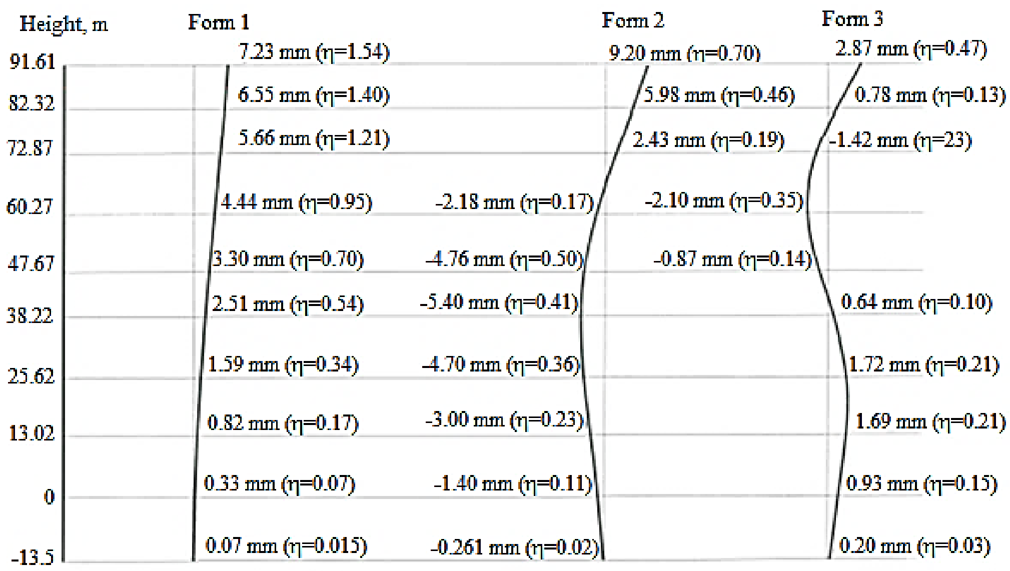

Fig.6 Vibration modes of the vertical axis of the building

Table 3 The values of relocations and acceleration according to the vibration modes in the centre of the floor above the 29th floor

Number of the vibration mode	Dislocation (mm)	Accelerations (in fractions of g)
1	7.2	0.016
2	9.2	0.199
3	2.9	0.240

Table 4 Values of logarithmic decrements and attenuation coefficient

Number of the vibration mode	Logarithmic vibration decrements δ	Coefficient ξ (in % of critical)
1	0.08	1.2
2	0.16	2.6
3	0.22	3.5

The results of a visual analysis of the load-bearing and non-bearing constructions of the building after the vibration impact showed that there were no damages in the bearing constructions of the experimental facility after all stages of vibration impacts and that in some non-bearing constructions (partitions) and in places where they adjoin to adjacent constructions, the cracking formation with a slight opening was visually noted.

According to the [10], the damage level to the load-bearing elements of the facility should be described by the value “0” – no visual damage. Damage to non-load-bearing constructions was close to degree “1” – thin cracks in some non-bearing walls and foundations and their adjunction with load-bearing elements [11]. Assessing the damage degree to load-bearing and non-bearing constructions, it should be taken into account that in the process of vibration effects, the building underwent 7 stages of testing, during which it performed about a thousand cycles of vibrations in higher forms with accelerations up to 0.2-0.3 g. and more.

Non-bearing constructions were subjected to alternating horizontal loads about a thousand times, amounting to at least 20-30% of their own weight. Under real seismic impacts, the number of vibration cycles, in the most unfavorable case, will be no more than 100-150. The state of the building after vibration tests is fully consistent with the state provided for by the scientific and methodological foundations of the [12].

4.2 Analysis of instrumentation data obtained during vibration tests

The studied data of shaking cycles coincide with the initial work stages and, in the denominator, the final stage of the study. From the data on comparison of the vibration period of the experimental facility (Table 5), the following can be stated: experimental values of the vibration periods of the building for three vibration modes differed insignificantly from the calculated values; resonance periods of building vibrations depended on the level of loads operated on it. The values of resonance vibration periods at the final stages of testing exceeded the values of the initial periods by 10...13%. The change in the resonance periods of the building vibrations according to the increase in the intensity of external vibration effects can be explained by the non-linear operation of non-bearing constructions and the foundation; the manifestation degree of the non-linearity of the building and foundation operation, as it follows from the experimental data, was insignificant.

The acceleration values in the center of the floor over the 29th floor were considered (Table 6). The calculated acceleration values were determined for the experimental facility based on its actual vibration periods. It follows from Table 6 that the maximum horizontal inertial forces that operated on the experimental facility during testing: during facility vibrations according to the first mode, they amounted to around 90% of the calculated seismic loads with the intensity of 8 points; during facility vibrations according to the second mode, they amounted to around 80% of the calculated seismic loads with the intensity of 5 points; during facility vibrations according to the third mode, they amounted to around 80% of the calculated seismic loads with the intensity of 9 points. According to the acceleration experimental values, it is possible to determine the root mean square value of acceleration by 3 vibration modes:

$$\boldsymbol{g}\sqrt{(\mathbf{0.016^2}+\mathbf{0.199^2}+\mathbf{0.240^2})}=\mathbf{0.312}\boldsymbol{g} \qquad (1)$$

Assuming that the acceleration effect at the top of the building equals 2, then the root means square value of the acceleration at the base is 0.156 g. According to the seismic intensity scale, the amplitude of the seismic impact will correspond to 7-8 points. The tested facility belongs to long-period systems with a quite low ability to vibrations energy dissipation. The values of the logarithmic vibration decrements characterizing the dissipative properties of the tested structural system turned out to be significantly lower than the values typical for 5-story buildings of similar structural systems [13].

The vibration of high-rise buildings is influenced by various factors, including the design layout, number of floors, total height, and structural system [14]: rectangular, symmetrical and balanced shapes are less prone to vibration than irregular or asymmetric structures since they create wind loads in different parts of the building. Buildings with a large number of floors tend to be more rigid, which reduces the likelihood of vibration. Frame structures tend to be more rigid and less prone to vibration than shear walls or frame wall structures. Hybrid systems that combine frame and wall structures can also provide increased rigidity and reduced vibration.

4. DISCUSSION

T.H. Nguyen [15] studied the issue of vibration testing and characterized the general features and provisions on which the process of vibration diagnostics of buildings is based. The author studied its types, active and passive, realized through the implementation of an active vibration load. The researcher proved that vibration effectiveness does not depend on its type. The features connected with the method for choosing a particular approach are due to the specifics of the studied facility. In the case where the test concerns a highly monolithic building, the use of an active vibration will be a priority.

In turn, M. Salamanova, D. Medjidov and A. Uspanova [16] studied the relevance of using vibration testing to test high-rise monolithic constructions. At the moment the quantity and quality of tools and mechanisms intended for vibration diagnostics are very high. In addition, the researchers note that the development of devices for the implementation of vibration tests is not dynamic. This indicates an urgent need to develop methods and constructions based on which it would be possible to effectively form vibrations, as well as fix changes, in particular in the building state.

Table 5 Vibration periods for the first three modes

Building vibration modes	Values of vibration periods of the building (s)	
	Experimental	Design
The 1st one in Y direction	1.31/1.48	1.38
The 2nd one in Y direction	0.381/0.43	0.38
The 3d one in Y direction	0.201/0.22	0.195

Table 6 Calculated and experimental accelerations

Number of building vibration modes	Acceleration values (in fractions of g) of the centre of the building covering, corresponding to its natural modes	
	Calculated values	Experimental values
1	0.281	0.016
2	0.394	0.199
3	0.264	0.240

Attention should be paid to the conclusions of K. Alimov, Z. Buzrukov and M.Turgunpulatov [17]. The researchers proved that the transfer function that occurs between a point on the base of a construction and a point on its top depends to a greater extent on such indicators as stiffness, as well as the mass of the studied building's element. J.Y. Yang, Z. Chen, T.-L. Li and R. Liu [18] revealed the benefits of using vibration diagnostics for testing high-rise monolithic constructions. Consequently, the researchers were able to establish that this approach allows qualitatively establishing the technical condition of monolithic constructions, especially large ones.

Attention should be paid to the position of M. Arifuddin, M. Aslamiah, M. Misbah and D. Dewantara [19], who emphasizes that the most effective way to implement vibration testing is integrated. This is explained by the fact that at its expense it is possible to systematically apply such tools as computer models and technologies that contribute to the organization and implementation of the study of dynamic elements of construction, on the basis of which residential and commercial high-rise buildings are built. Important in the course of the testing process is the determination of dissipative parameters to establish the initial and final states of the studied facilities. A similar position is adhered to by M. Honic, I. Kovacic, P. Aschenbrenner and A. Ragossnig [20], proving that the formation of a facility test passport is an important and necessary component of this process.

The conducted discussion indicates that vibration tests are currently relevant among specialists [21-24]. Most authors pay attention to the possibility of improving the process of study of high-rise monolithic constructions; this approach is the most effective among others [25-27]. The results of the discussion largely coincide with the authors' ideas and conclusions because they relate to the theoretical foundations of the vibration testing process and also reveal their content.

5. CONCLUSIONS

Based on the study results, the following conclusions were made. The periods for three modes of natural vibration (first stage), determined by calculation T_1=1.38 sec., T_2=0.38 sec. and T_3=0.195 sec., are close to the obtained experimental values, which are T_1 exp.=1.31 sec., T_2 exp.=1.381 sec. and T_3 exp.=0.201 sec., respectively. The revealed differences in the calculated and experimental values of the vibration periods are insignificant. However, the experimental data are obtained without a payload. Therefore, the actual experimental and theoretical vibration periods will differ by approximately 20%. The compliance of the intermediate floor had little effect on the deformation nature of the building. Horizontal deformations of the intermediate floor of the building due to their compliance amounted to no more than 3% of these floor relocations. The total compliance contribution of the base (for shift and rotation) to the relocation of the top of the building amounted to not more than 27-32% for vibrations according to the third mode.

The tested 35-story building belongs to long-period systems with a quite low ability to vibrations energy dissipation. The values of the logarithmic vibration decrements characterizing the dissipative properties of the tested structural system turned out to be significantly lower than the decrement values typical for 5-story buildings of similar structural systems. After vibration tests, no damage or cracks were noted in the load-bearing constructions of the building. In some partitions, cracks with a slight opening were noted, which, usually, are formed at the junction of non-bearing constructions to load-bearing ones. However, to understand whether the results of this study are suitable for building layouts with other structural systems and seismic zones, more research is needed.

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