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Method of testing building models and their engineering systems for seismic impact

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Abstract. Methods of experimental modeling of seismic impact on buildings and their models under force im-pacts, including the stability of building envelope systems, characters and basic parameters that correspond to loads occurring during real earthquakes are considered. The main methods of seismic impact on buildings and structures were analyzed using seismic platforms of software control, directed powerful underground explosion and vibration machines. The advantage of the vibration method is proved, which allows relatively fast and easy and low-cost testing of both full-scale buildings and structures, as well as their models. Experimental installation and method of testing of buildings and their models for seismic impact, excited with the help of simultaneously acting several vibration machines, are presented. Oscillograms of superposition of the first II-III vibration modes were obtained when testing a model of the frame of a 9-storey building. In order to assess the degree of accuracy of the proposed method of simulating seismic impact from an accelerogram of one earthquake, floor movements of a building model were determined theoretically and experimentally. The comparison of the results of theoretical and experimental studies showed that the discrepancy between them is on average 10-15%.

1 Introduction

Solving seismic resistance problems of buildings and structures is associated with various factors of complex physical nature and requires a large number of studies.

Studies of the behavior of buildings under seismic impacts, full-scale and model tests should be carried out under power impacts, the nature and main parameters of which correspond to the loads that occur during real earthquakes. Modeling of seismic forces is carried out using seismic platforms, seismic-explosive impact or vibratory machines [1-7].

Seismic platforms are used to determine the dynamic characteristics of structures, to study the load-bearing capacity of both the structure as a whole and its individual elements under flat and spatial vibrations of any nature.

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Seismic platforms with program and software-free control are distinguished depending on the methods of oscillatory motion control. Due to the simplicity of the design and relative ease of manufacture, seismic platforms of software-free control have become more widely used. These platforms allow to excite stationary harmonic oscillations with a given frequency and amplitude, non-stationary oscillations with a smooth change in frequency and amplitude, as well as free attenuating oscillations. With all the positive qualities, the main disadvantage of seismic platforms of software-free control is the inability to create a complex dynamic load of the seismic type and reproduce seismic impact.

Seismic platforms of software control are used to reproduce earthquake seismic program. The advantage of these platforms in terms of simulating seismic load is undeniable, since they allow to simulate soil oscillations with a high degree of accuracy, simultaneously in both horizontal and vertical directions, in a particular earthquake.

However, due to the high cost, limited use has by found.

Here, it should be noted that the main, general drawback of seismic platforms of both software and software-free control is that they are practically unsuitable for testing full-scale buildings and structures. The disadvantages of seismic platforms also include significant inertia.

For testing of full-scale buildings and structures, seismic explosion impact is used in some cases, which is relatively close to seismic in nature, but its parameters are difficult to adjust in modeling.

In case of instantaneous explosion, impact of blast wave on structure differs significantly from real seismic effect by nature of spectra of shifts, velocities, accelerations and shorter duration of soil oscillation. As a result, an instantaneous explosion has a more severe effect on the structure than a real earthquake, which can qualitatively change the picture of its actual work.

Experimental studies of the earthquake resistance of buildings and structures in nature and on models are now increasingly carried out by the vibration method. The vibrator is installed on the building or is located on the ground next to the building and forced harmonic vibrations are excited in the latter. Gradually changing the frequency of the disturbing force, the building is introduced into the resonant mode for various forms of vibrations and the dynamic characteristics and stress-strain state of the buildings are determined.

The resonant mode of oscillation allows, at relatively small capacities of vibration machines, to excite significant forces in tested buildings or structures.

Vibration machines excite horizontal, vertical or inclined pulsating forces, which vary according to harmonic law.

At preset frequency of oscillation value of disturbing force can be controlled by stepwise change of kinematic moment with the help of detachable sets of eccentric weights.

The advantage of the vibration method is the ability to perform tests of both full-scale buildings and structures, as well as their models, relatively quickly and simply, with low costs. Vibrating machines excite easily adjustable forced vibrations with the implementation of a large level of stress.

The main purpose of the vibration tests carried out, as a rule, was to determine the frequencies and shapes of natural vibrations, the values of attenuation during longitudinal and transverse vibrations of buildings, as well as during their torsion. The use of powerful vibration machines made it possible to study the vibrations of buildings at significant stress levels and evaluate the seismic resistance of the structure on the basis of comparing the destructive value of inertial forces with calculated values.

Furthermore, although the components of the seismic process are close to the respective components of the vibration process, the inertial load generated by the vibration machines differs from the seismic load.

The main difference between the vibration effect on the structure and the seismic one is its one-part and harmonious. A number of researchers' analysis of seismic forces shows that seismic effects are characterized by the superimposition of several harmonics with different frequencies and amplitudes. Therefore, the use of one vibration machine can give reliable results when testing such structures in which oscillations in one form are excited during an earthquake. Thus, the vibration test method, along with advantages over other seismic simulation methods, does not allow to study the behavior of the tested object in a complex stressed-deformed state that occurs during an earthquake.

Based on the above analysis of the main methods of reproducing seismic effects on buildings and structures using software control seismic platforms, directional powerful underground explosion or vibration machines, it can be noted that the latter method is the simplest and most acceptable. However, in order to create a complex dynamic load that most closely corresponds to real seismic impacts, it is necessary to obtain more reliable equivalents for the transition from seismic load to vibration load.

2 Materials and methods

Reliable reproduction of seismic impact on buildings and structures is one of the main unresolved problems of seismic construction [8-14]. In the work [15] the method of experimental reproduction of seismic impact on buildings and structures by earthquake accelerogram by means of several simultaneously acting vibration machines installed on buildings and exciting resonant oscillations by separate forms of natural oscillations is considered.

To study the possibility of practical application of the proposed seismic impact modeling method, a special experimental installation was designed and manufactured (Fig. 1.). It allows you to excite complex seismic-type oscillatory movements in building models in the form of overlapping several forms of natural oscillations.

Experiments were carried out on a model of a 9-story steel frame, which is six times smaller than the conditional original. The model is made with a plan size of 1000×750 mm. The height of each floor is $500\ mm$.

The model frame (Fig.1.) consists of two load-bearing single-span frames interconnected by longitudinal girders of rectangular tubular section with dimensions $60 \times 40 \times 4$. The frame columns, continuous throughout the height of the building, are made of the same rectangular tubular profiles. Frame girders have an I-section composed of two channels No. 6,5. Connection of girders with columns is performed by welding, which eliminates possible changes in dynamic characteristics of the frame during experimental studies. In order to excite oscillations in two mutually perpendicular directions on the floors of the ninth, sixth and third floors of the model (at the places of maximum displacements in this form), six directional vibration machines were installed.

Three vibration machines (B1-Y, B2-Y, B3-Y) excited oscillations in the transverse voltage Y, the other three (B1-X, B2-X, B3-X) - in the longitudinal direction X of the building (Fig. 1.). Each of the vibrators excited resonant oscillations in a certain shape.

Engine racks simultaneously served as supports for transferring the static load model through the cable platform (Fig. 1).

This system also allowed to excite in the tested models free oscillations along the main axes X-X and Y-Y by instantaneously dropping the platform with the load.

Each of the vibration machines has a separate control remote controller, which allows you to smoothly change the rotation speed of the vibrator and, if necessary, fix any mode of its operation. For diagram of electric drive of vibration machines motors refer to Fig. 2.

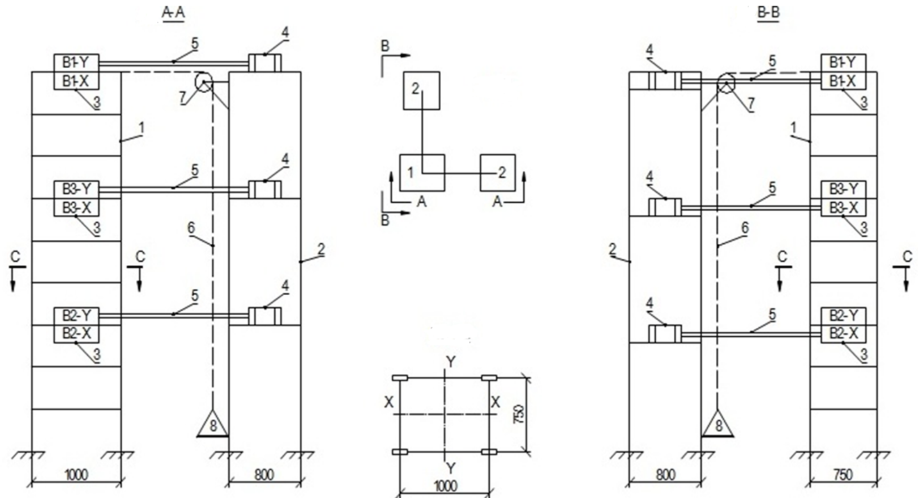

Fig. 1. Structural diagram of the installation. 1 - model, 2 - shelves for engines, 3 - vibration machines, 4 - engine, 5 - flexible shaft, 6 - rope, 7 - block, 8 - platform for loads.

The models were tested according to the following procedure. Prior to dynamic testing, building frame models were subjected to static testing to determine their stiffness characteristics. These tests were reduced to determining the offsets of the 9th floor along the main axes X-X and Y-Y under the influence of a horizontal force applied to the model floor through a cable platform.

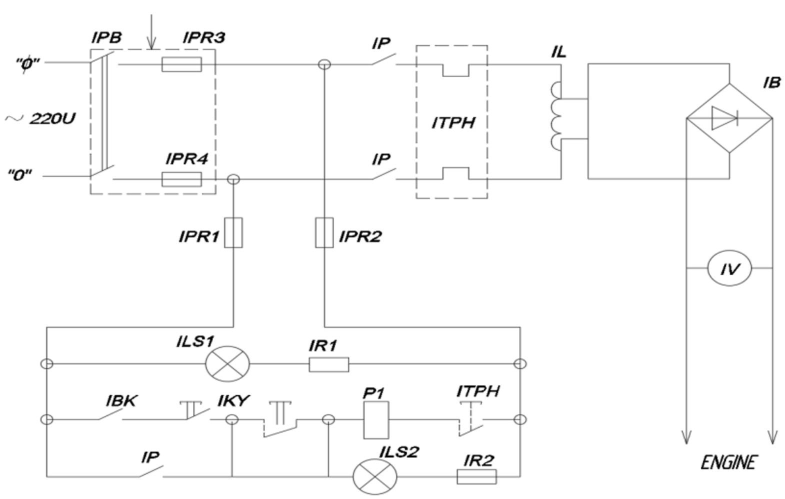

Fig. 2. Diagram of electric drive of vibration machines.

IPB- packet switch; IP - magnetic starter; ITPH- thermal relay; IBK - final switch; IB - rectifier of diodes; IV-voltmeter; IKY- control buttons; ILS- signal lamp; IPR1 and 2 - safety mechanism, IR1 and 2 - additional resistances.

Dynamic tests included free and forced vibrations of models along the main axes X-X and Y-Y. Free oscillations were excited by pulling the models with a cable and instantaneously breaking the platform with a load. Forced vibrations of the models were excited by vibration machines. A smooth change in the number of revolutions of the engines of the building model was introduced into the resonant mode of operation according to individual forms of natural oscillations, the parameters of which were recorded by the control remote controllers of the vibration unit. Then, by simultaneously switching on the vibration machines, the models were informed of complex oscillatory movements in the form of superimposing several forms of natural oscillations - I-II, II-III, I-II-II, etc. Free and forced oscillations were recorded at the floor levels of the model using seismometers on an oscilloscope.

3 Discussion of results

The force excited by the vibration machine was determined by the formula:

$$F = m \cdot r \cdot \theta^2 \cdot \sin \theta t$$

where m is the total mass of eccentrics;
r - eccentricity radius;
θ is a circular frequency equal to $2\pi \frac{n}{60}$;
n is the number of revolutions of eccentrics per minute.

The changes of excitation force of vibration machine at preset speed of channels rotation were performed by change of mass of detachable eccentrics. For experimental reproduction of seismic impact on buildings and structures mass of eccentrics of vibration machines is determined by accelerogram of simulated earthquake [15]. During model tests, it is also necessary to model the accelerogram used [16]. In order to study the practical possibility of modeling the seismic impact, a series of experimental studies was conducted on the above model of a 9-storey building.

As an example, see Fig. 3 and 4 are the waveforms of the superposition of the I-II and I-II-III forms of the natural oscillations of the model.

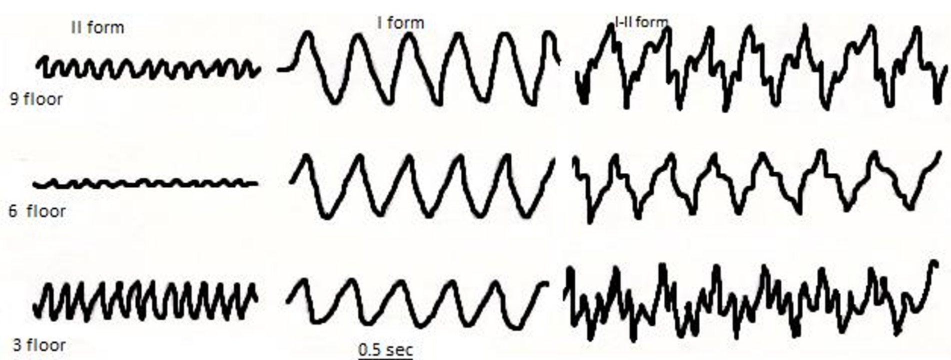

Fig. 3. Oscillograms of application of I-II waveforms of model M-I in the direction of X-XX axis.

During the study of reactions from the oscillation of high-rise buildings when superimposing higher forms of oscillations, it has a certain practical value in terms of improving their calculation for seismic effects. The work on the subject, such as, for example, [8,15], is theoretical. Here are the results of an experimental study of high-rise buildings when superimposing higher forms of oscillation.

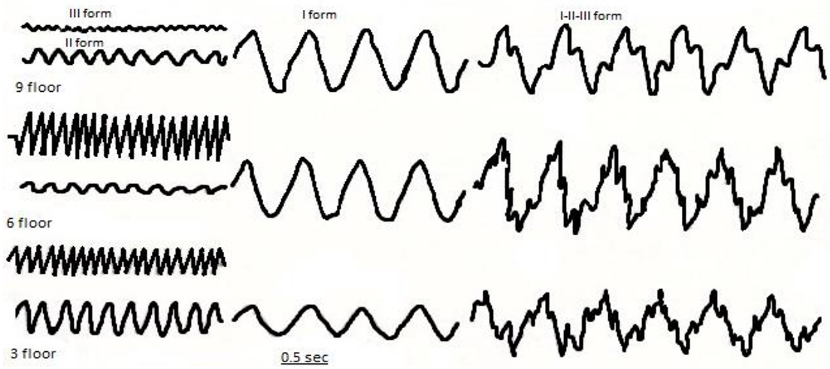

Fig. 4. Oscillograms of application of I-II-III waveforms of model M-I in the direction of Y-Y axis.

Numerous studies have shown that for ordinary buildings and structures, the seismic forces S_{kf} can be determined by taking into account only the first three modes of vibration. Therefore, in the experimental reproduction of an earthquake, it is also advisable to restrict ourselves to the first three modes of vibration, installing three vibrating machines in the building, each of which reproduces earthquakes in a given form of vibration.

In order to facilitate the process of introducing into a resonance state for a given vibration mode, it is advisable to install vibrating machines at the levels of those floors in which the free vibration modes have maximum values. For example, for a 9-storey building with constant stiffness and mass of floors, such floors will be: for the first form - the ninth floor; for the second - the third floor and for the third form - the sixth floor. All three vibrators can also be installed at the level of one, in particular the last floor.

Since the times of occurrence of the maximum values of seismic forces S_{kf}, for each mode of vibration both during a real earthquake and during the simultaneous operation of three vibrators do not coincide, it is necessary to establish the degree of deviation between the maximum values of seismic forces, taking into account the three modes of formula (1) and when they are superimposed with the simultaneous operation of three vibrators [15].

The values of seismic (inertial) forces $S_k(t)$ are:

$$S_k(t) = m_k\left(y''_k + y''_0\right) = m_k \sum_{r=1}^{n} \eta_{kf}\, \tau(T_r, \delta_r, t);$$

$$\tau(T_r, \delta_r, t) = \frac{2\pi}{T_r}\int_0^t y''_0(\xi) e^{-\frac{\delta r \pi}{T_r}(t-\varepsilon)} \sin\frac{2\pi}{T_r}(t-\xi)d\xi \qquad (1)$$

where m_k is the mass of the concentrated load; T_r − period of r-th form of free oscillations;

$y''_0(t)$ − acceleration of base oscillation;

δ_r − damping coefficient of the r-th form of free oscillations;

η_{kf} − coefficient of vibration modes:

$$\eta_{kf} = \frac{C_{kf}\sum_{t=1}^{n} m_i C_{ir}}{\sum_{t=1}^{n} m_i C_{ir}^2} \qquad (2)$$

where C_{kf} is the amplitude of free vibrations.

For this purpose, the following numerical experiment was performed. According to the accelerograms of various earthquakes for various buildings (5-, 10- and 13-storey, reinforced concrete), the maximum values of seismic and shear forces were determined using the exact formula (1) and the following formula:

$$S_k(t) = m_k \sum_{r=1}^{3} \eta_{kr}\, \tau^{max}(T_r, \alpha_r) \sin\frac{2\pi}{T_r} t \qquad (3)$$

that is actually tantamount to installing three vibrators on a building, operating in a resonant mode in all three modes of vibration simultaneously. The influence of the phase shift λ_j of the vibrators, as well as the sequence of their switching on, as shown in [17], with real ratios T_1, T_2, T_3, are negligible, so they are not taken into account in formula (3).

Accelerograms of two earthquakes recorded at one station and one earthquake recorded at two stations were used as a seismic effect [18, 19].

Table 1. Cross force ratios at ground floor level for different earthquakes by formulas (1) and (2).

Registration station	Earthquake date	Component	$y''_0(t)$, in fractions g	For 5-storey building $T_1 = 0.45$ $T_2 = 0.15$ $T_3 = 0.09$	For 10-storey building $T_1 = 0.90$ $T_2 = 0.3$ $T_3 = 0.18$	For 13-storey building $T_1 = 1.10$ $T_2 = 0.37$ $T_3 = 0.20$
Ferndale, USA	7. 10. 1951	44 W	0. 123	0. 89	1. 16	1. 15
-„- -„-	7. 10. 1951	46 E	1. 119	0. 93	1. 29	1. 04
-„- -„-	21. 12. 1954	44 W	0. 166	0. 95	0. 95	0. 98
-„- -„-	21. 12. 1954	46 E	0. 209	0. 83	0. 98	0. 95
ULCINJ-2, Yugoslavia	15. 04. 1979	N—S	0. 181	0. 87	1. 22	1. 02
-„- -„-	15. 04. 1979	N—E	0. 227	0. 94	0. 98	0. 98
HERCEC NOVI, -„-	15. 04. 1979	N—S	0. 221	0. 95	1. 06	1. 27
-„- -„-	15. 04. 1979	N—E	0. 251	0. 97	1. 21	1. 04

From the results obtained (table) it can be seen that the stress-strain state of the structure under real seismic action, taking into account three modes of vibration and according to the proposed method of its experimental reproduction using three vibrators, are quite close. The average deviation is 10-15%.

4 Conclusion

Obtained floor oscillograms of application of the first II-III forms of oscillations attests of the 9-storey building frame model indicate the possibility of application proposed method of simulation of seismic impact on buildings and structures.

- developed a technique for testing of full-scale buildings and their models for the seismic effects;
- the practical possibility of exciting buildings of complex dynamic load of seismic type with the help of a system of vibration machines, both in one and two mutually perpendicular main directions of the structure, is proved;
- a method for determining the dynamic characteristics of buildings and structures in two mutually perpendicular directions is proposed;
- the way for experimentally reproducing the seismic impact on buildings and structures by simulating their stress-strain state was developed. It was occuring during earthquakes with the help of several simultaneously operating vibration machines installed on the building and exciting resonant vibrations by separate forms of natural vibrations.

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