Predicting the service life of buildings and facilities to minimize the risk of losses in the conditions of natural and technogenic emergency situations

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Abstract. This article discusses the solution to the task of predicting the consequences of catastrophic earthquakes for operational buildings and facilities. We suggest using such basic parameters for verifying the calculation models as natural frequencies, oscillation forms and decrements of objects under earthquake loads. At the same time we substantiate the possibility to use micro-oscillations for that purpose, even though buildings and facilities are cushioned systems. We present the methods and means to conduct tests to estimate the dynamic parameters of buildings, as well as an example of such a test and the process of verification of the calculation model in the example of a panel multi-storey building. We set an example of evaluation of the consequences of an accident with a building in St. Petersburg, which was partially destroyed as a result of non-uniform setting of soils in the base. We drew the conclusion that using dynamic parameters makes it possible to solve various tasks for current predicting the remaining service life of damaged objects.

1. Introduction
In the modern world, the risk of natural disasters and catastrophes has greatly increased. In this situation, we have to be able to predict the possible consequences of the earthquake in advance. In this context, the “possible consequences” mean the reaction of the building to seismic loads. On the one hand, we can note a significant progress in the calculation methods to predict the possible seismic load, for example, using synthetic accelerograms. On the other hand, we can model the reaction of the building itself with high accuracy. However, without detailed inspection of the building, it is practically impossible to take all its particular features into account, due to the possible presence of concealed defects and damage, non-observance of project characteristics etc. that do not manifest themselves under operating loads but can cause destruction under seismic impact. That is why the task of quick assessment of the technical state of the building is actual to answer the question about the consequences of emergencies [1–7].

2. Materials and Methods
At the current moment, the most widely used method to estimate the dynamic parameters of buildings is called the “Method of free oscillation” (MFO) [8–12].

In the MFO, the following operations are used:
• exciting and recording free or forced micro-oscillations;
• calculating their Fourier specters;

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• analyzing the Fourier specters to find the resonance peaks corresponding with different waveforms of free oscillations;
• using the Fourier reverse transformation, obtain the impulse realizations of the detected resonance peaks for each waveform of free oscillations;
• identification and graphical representation of different oscillations waveforms.

Using the MFO made it possible to develop a universal mechanism to elaborate the dynamic parameters of calculation models for buildings using different software packages (Scad, Abacus, Ansys, Lira).

3. Results

As an example, let us discuss a high-rise panel building in Moscow district: how can we compile a reliable calculation model for predicting the results of any external influence, including the seismic one (in this case, the application of the method of free vibrations is limited to specific building geometry, i.e. buildings with load-bearing brick walls, not with flexible geometry). The measuring system consisted of sensors installed in the vertical cross-section at different levels in the building (from the basement to the roof) and connected with the recording equipment. Oscillations were excited in the upper and the middle part of the building by applying multiple strikes, with pauses during the attenuation period of natural oscillations of the building (Figure 1).

![Figure 1. Scheme of load application, sensors arrangement and form of oscillations](image)

The test results were graphically represented as the oscillations of the building in the longitudinal and the transverse directions. The obtained dynamic parameters were used to adjust already constructed FE model of the building in the FEA program Ansys with an ultimate goal to use this model for predicting the responses of the building in future strong earthquakes (see Figures 2, 3 and 4). The mass, damping, and stiffness matrices of a building are obtained by spectral approach – decomposition motion into natural oscillation forms, based on the Duhamel integral. The vertical axis denotes the height of the building in meters, and the horizontal one shows the relative movement recorded with the sensors (points in the diagram) installed across the height of the building, for different forms of oscillations:

- Bending by the height; transverse direction (first tone) – 1.25 Hz;
- Bending by the height; transverse direction (second tone) – 5.96 Hz;
- Bending by the height; transverse direction (third tone) – 14.89 Hz;
- Bending by the height; longitudinal direction (first tone) – 1.92 Hz;
- Bending by the height; longitudinal direction (second tone) – 6.98 Hz;
- Bending by the height; longitudinal direction (third tone) – 18.99 Hz;
- Bending by the front (first tone) – 1.94 Hz;
- Bending by the front (second tone) – 7.812 Hz.

For convenience, the maximum deflection of the sensor during oscillations for each form was assigned a value of one. The readings of other sensors are expressed as a fraction of the maximum deflection.
How can dynamic parameters be obtained with such a weak impact? The responses are summarized using extremely sensitive sensors (100 mV/m/sec²). This significantly raises the dynamic range of measurements (the excess of the useful signal over interference). Obviously, the second and the third oscillation forms are compiled with the use of the possibilities of the principle of superposition of oscillations and are quite a rare result for a residential building (higher forms of oscillations are very difficult to record due to their small amplitude). The obtained forms help elaborate the character of building deformation and investigate it without consideration of conditions of its “sticking” in the ground, which largely determine oscillations frequency of the first form.

Further on, the parameters of the calculation model were elaborated in the following manner. During the first stage, a modal analysis was carried out and the lowest frequencies were estimated as well as their corresponding forms of natural oscillations. These values were analyzed and compared with similar data obtained from tests. In our opinion, the refusal to take into account changes in the geometry (coordinates of nodes) can cause a significant reduction in the quality of the calculation. But in the current practice of computational justification, it is considered quite acceptable not to allow for the change in the geometry of the computational model at different stages of the existence (installation) of the structure. On condition that the geometric dimensions, weight and structural features of the building were modelled correctly, the changes were applied to the parameters describing the generalized stiffness of the structure materials. As a result of a series of corrections to the values of generalized material stiffness, we were able to achieve satisfactory correspondence between the calculated and the experimental values of natural oscillations frequencies. The actual measured values of natural oscillations frequencies recorded during dynamic tests well correspond between themselves (Table 1).
Table 1. Comparative data on oscillations frequencies of the examined building

| Oscillation forms acc. to the calculation model | Oscillation frequencies recorded during tests, Hz | Oscillation frequencies acc. to the calculation model adapted by dynamic characteristics, Hz | Difference of the calculated oscillation frequencies |
|------------------------------------------------|-----------------------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------|
| 1                                              | 1.25                                          | 1.291                                                                         | -3.1 %                                            |
| 2                                              | 1.92                                          | 1.944                                                                         | -1.2 %                                            |
| 3                                              | 1.94                                          | 2.045                                                                         | -5.1 %                                            |
| 4                                              | 5.96                                          | 5.604                                                                         | -5.9 %                                            |
| 5                                              | 6.98                                          | 6.832                                                                         | -5.1 %                                            |
| 6                                              | 7.812                                         | 7.456                                                                         | -4.5 %                                            |
| 7                                              | -                                             | 11.716                                                                        | -                                                |
| 8                                              | -                                             | 12.587                                                                        | -                                                |
| 9                                              | 14.89                                         | -                                                                              | -                                                |
| 10                                             | 18.99                                         | -                                                                              | -                                                |

Thus, we can state that we were able to create an adequate calculation model that can be used for reliable predicting the results of emergency influences, including seismic impacts.

On the other hand, specialists of emergency services often have to assess the remaining service life of partially damaged or destroyed buildings in order to make decisions on restoring or reinforcing the damaged structures. An example of such investigations is the accident in Dvinskaya street (St. Petersburg, 4 July, 2002), when the Southern 17-m long part of the 9-level building suddenly collapsed. Four lives were lost. Immediately after the accident, the natural oscillations of the building in the following frequencies were detected:
1.8 Hz – bending oscillation in the transverse direction (vertical cross-section);
2.18 Hz – swaying on the foundation in the transverse direction;
2.25 Hz – bending oscillations in the longitudinal direction (vertical cross-section);
5.4 Hz – bending oscillations, second form, transverse direction (horizontal cross-section).

Analysis of the obtained dynamic parameters showed that the building had a typical frequency of natural oscillations for such objects by the first tone [5], which is the evidence of sufficient spatial stiffness of the entire structure. Relative movement of the foundation during oscillations was more than 10%, i.e., the foundation has high mobility. As the main features, it was noted that there is low stiffness of connections between sections at frequencies from 6 Hz (this frequency is usually 15 Hz and more for buildings with deformed links) and a large input (up to 55 %) into the bending form of oscillations of the building swaying on the foundation (this value is usually within 15%).

4. Discussion

The most important finding the authors made in this study is that the dynamic responses of a building when subjected to the impact of a mass of 30 to 50 kg over aduration equal to half of the period of the first vibration mode is sufficient to evaluate the frequencies and mode shapes of the free vibrations of the building. At the present time, there are two methodical approaches to carry out measurements in the active and passive modes of exciting oscillations in the object. During the “passive” recording, the response is recorded of the inspected structures to the background micro-seismic impact. During the “active” recording, the response is recorded to the deliberate impact onto the structure. If such impact is applied to the strength nod in the upper part of the structure (with a weight of up to 50 kg), and the duration of the application is about 0.5 period of oscillation of the building by its first form, then the amplitude of the recorded response is good enough to evaluate the frequencies and waveforms of free oscillations [4-5]. At the same time, there are more methods to increase the dynamic range of the recording equipment as well as achieve the maximum amplitude of oscillations with the required form. They are: exciting and recording oscillations under a pointed impulse load applied at different locations of the structure; adding up (with consideration of the load vector) the oscillations recorded during the impact of the load at different locations of the structure (imitating simultaneous application of loads at several locations). The damping/stiffness matrices of a building may change significantly if the building is damaged. It is true that the NDT techniques can only estimate the damping/stiffness of
a building at its present state (which may have slight to no damage at the moment when the NDT test is performed). However, if destructive changes occur, we will see this by changing the natural frequency of oscillation and take them into account in the design model as, for example, reducing the stiffness of the damaged element. We agree without pushover curves of the individual columns and/or the entire building (i.e., the nonlinear responses of the building at various ductility levels), the current mass/damping/stiffness matrices of a building could not be used to predict the responses of the building after it is severely damaged in strong earthquakes. It is important to accent the values of frequencies and the corresponding vibration mode shapes being those parameters that "feel" any "features" of both the model and the real object. They are compared to establish the reliability (correctness) of the assembled model [13–14].

With a strict approach to the theoretical substantiation of correctness of division between the actual oscillations of buildings into harmonics, it is known that, in the general case, the attenuating systems cannot be completely divided, because it is impossible to completely negate the multiplication of coefficients of dampening different forms [15]. Accepting the fact that the nonlinear factor will be too small for standard constructions it will not be erroneous to assume that the damping factor of each mode is linearly dependent on the system frequency. From the physical viewpoint, there are no isolated own forms of oscillations, and they are not in-phase with oscillations with any form of movement of different points. However, if the attenuation is small enough, this feature can be ignored and it can be assumed that a cushioned system has classical own forms of oscillations when all the masses reach their maximum deviations simultaneously. Therefore, if the building oscillation decrement (oscillations attenuation) is small, the proposed method can be reasonably used for diagnostics. Practically, it means that, if there are isolated peaks in the specter of recorded realizations, the attenuation can be ignored. An indirect evidence of the “small” attenuation is the possibility to clearly divide between different forms of oscillations [16–17].

5. Conclusions

1. Using dynamic parameters in calculations not only helps the best model of the facility in each case, but also elaborates its parameters to achieve its authenticity to the strength of load-bearing structures.

2. The authors have made other contributions in simplifying the procedure for constructing the FE model of a building using the data collected from NDT tests. The main theoretical provision allowing reliable assessing of dynamic parameters using the MFO method is the assumption about the linearity of the examined systems. In this case, the method of solving the differential equation systems we should use is the method of decomposition by own forms; with this method, instead of a coherent system of differential equations, we obtain a number n of independent equations, with which, using constant coefficients, we can establish the input of each own form number j into the overall response of the system to the external influence. If we know the frequency and form of oscillations, we can reliably estimate the properties of all the elements in the system.

3. Linearity of the discussed systems makes it possible to use the principle of frequency superposition during measurements; this allows artificial “amplification” of the oscillations of the examined forms for massive and high objects.

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