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CONCRETE STRUCTURES UNDER QUASISTATIC LOADING

Igor Shardakov, Irina Glot, Aleksey Shestakov, Roman Tsvetkov, Valeriy Yepin
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EXPERIMENTAL STUDY OF DEFORMATION PROCESSES IN LARGE-SCALE CONCRETE STRUCTURES UNDER QUASISTATIC LOADING

IGOR SHARDAKOV, IRINA GLOT, ALEKSEY SHESTAKOV,
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Physical experiments with large-scale models of engineering structures provide invaluable information for understanding the deformation processes in objects of complex configuration and allow researchers to reproduce the interactions between the structural elements on different scales. The article presents test stand designed and assembled at the Institute of Continuum Media Mechanics (Perm, Russia). Using this stand, studies of deformation processes in a large-scale model concrete structure were carried out. The deformation response of structural elements to the locally applied quasistatic and impulse loads was studied. The patterns of the spatial-temporal distribution of deformation parameters over the structural elements were obtained. The tests conducted in the elastic deformation mode allowed to obtain the vibration portrait of the structure, which provided basic information for the future experiments aimed at studying inelastic deformation of the structure until its ultimate failure.

1. Introduction

The assessment of the stress-strain state of large engineering constructions and complex structures is of great importance. This issue arises at the stages of construction and operation of buildings, as well as at the stage of evaluation of risks associated with the occurrence of emergency situations. Estimating the stress-strain state in complex and large-sized buildings and engineering structures is based on a combination of experimental and theoretical approaches. The theoretical approaches involve the creating of a mathematical model of the examined structure and determination of principal regularities of its behavior using for this purpose the classic analytical and numerical simulation methods in the framework of elastic and non-elastic models. Today, the numerical implementation of these models is possible due to the application of a number of well-developed universal software systems for finite element analysis, such as ANSYS, ABAQUS, NASTRAN, COMSOL, LIRA-CAD. As a rule, such software packages offer a wide scope of options for describing the composition of the object and taking into account the interactions between structural elements. They involve various models to simulate the physical and mechanical properties of materials used in the structure. However, the development of a mathematical model of the structure composed of many elements of different size necessitates the simplification of its properties and the neglect of structural details beginning from a certain scale. Such a model is not always appropriate for displaying the whole variety of processes, which occur on different scales and can provoke the structure failure. In addition, the problem of furnishing such mathematical models with material parameters is not as simple as might appear at the first sight. Information about the physical and mechanical properties of materials obtained from the standard tests, which usually realize simple

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stress-strain state, is often insufficient for describing the state of a real structure. Therefore, an important stage in numerical simulation is a reliable verification of the mathematical model by means of comparing its predictions with the results of experiments simulating the deformation processes in real structures to the maximum possible accuracy.

Experimental approaches to the assessment of the stress-strain state of large structures are based on the monitoring of the behavior of real structures under real operating conditions, or examining the behavior of model structures subjected to loads reproducing to a certain extent the action of real loads. A review of experimental methods for studying large structures is given in [16; 22].

Traditionally, mechanical tests of complex large-sized structures conducted at the stages of their construction and operation with the aim to determine the actual bearing capacity, rigidity and crack resistance of structures, as well as to estimate the possibility of their future operation. Often, such tests are carried out to study the ways to strengthen the structure and assess the possibility of extending its life. Such tests are generally performed under conditions of elastic deformation, which does not allow the occurrence of irreversible strain states of the object [17; 14]. Some experiments are known on loading real structures to their complete destruction [31; 23]. However, for such studies, special conditions are required associated with the search for the test structure, the organization of the necessary loading system, the technology for recording experimental data in the field, etc.

Modeling of the deformation behavior of large structures in laboratory conditions makes it possible to study the impact of a wide variety of experimental loads. During the experiments the changes in the stress-strain state of model structure are under control and it is possible to register many different parameters of the structure. Modern test stands provide ample opportunities for conducting experiments, which can simulate not only elastic, but also inelastic deformation of examined object, the initiation and evolution of damages, and ultimate failure of the structure [19; 27].

Conducting large-sized structure tests is a complex and expensive procedure, which requires large material costs, special equipment and highly qualified specialists. However, in the past few years interest in such tests has quickened due to the fact that large-scale modeling allows realistic representation of physic-mechanical properties of structure materials and ensemble interactions of all dissimilar and different-scale elements of the structure. This is especially important due to the widespread use of new materials and technologies in engineering and construction. Large-scale experiments provide valuable information for interpreting the mechanical behavior of structures made of heterogeneous materials. They provide required data for the verification of mathematical models of deformation processes in complex structures. Furthermore, keen interest in such tests is generated by a rapid development of experimental devices for recording, gathering and processing of information, which allow one to study the behavior of the investigated objects with a desired accuracy. An analysis of resent publications indicates that large-scale modeling is actively progressing field of research.

Specialized stands for conducting large-scale structure experiments are unique structures in themselves. The experimental laboratories of this kind are generally organized on the principle of universality to allow studying structures made of various materials and reproducing a wide range of operating loads. Large test centers usually hold several types of strong floors and reaction walls, vibration platforms and shake tables with different degrees of freedom, and also contain a variety of devices for performing both the primary and secondary structure tests. The size and shape of these testing units are specified depending on the purpose of a test laboratory. Such laboratories often comprise the structural units of large industrial

corporations [30; 6; 9]. Therefore, as a rule, such research centers limit their interests to a certain class of objects and a certain range of impacts.

In the construction industry, the most-in demand area of experimental research is related to seismic impacts on buildings and engineering structures. Now, there are a number of world-class research centers with unique facilities, which simulate seismic impacts on the structure [26; 20; 11; 5; 25]. The studies conducted at these centers are mainly concerned with observation of the movement of structural elements under conditions of high amplitude dynamic loads, the analysis of the crack formation and propagation, and recording of scenarios of damage accumulation and failure [29; 8]. The focus of research is both on the behavior of load bearing structures and on the objects inside buildings, as well as the study of the ways to protect structures from seismic loads. Among the subjects of research are the structures of steel [21], concrete [18; 34] wood, large-scale fragments of low-rise and high-rise buildings [4; 15], fragments of bridges [12; 2], power transmission line supports and other engineering structures. The information obtained is used to solve the problems of seismic resistance of existing and newly constructed structures.

Information about the experimental studies of large-scale buildings and engineering structures under the action of static or slowly changing external loads is found less frequently in scientific publications. Such processes occur in structures under the action of operational loads, as well as due to changes in the state of foundations caused by karst effects, freezing of soils, and various technogenic processes in the surrounding soil massif. Laboratory tests of full-size reinforced concrete fragments under static and quasi-static loads are described in [7; 13]. Bench tests simulating the interaction of large-scale models of engineering structures with subgrade soil are reviewed in [1; 24; 33; 32]. The focus of those works is on the observed scenarios of damage evolution, detection of the most vulnerable structural elements and ascertaining whether the deformation state of the structure complies with building codes.

However, such issues as the early diagnosis of structural damage, the search for damage precursor, and the assessment of workability of structures with a certain level of accumulated damage should be investigated further. Information obtained during these studies is essential for the development of effective automated deformation monitoring systems. A desire to solve these problems has motivated researchers of the Institute of Continuous Media Mechanics of the Russian Academy of Sciences (Perm, Russia) to construct a large-scale test stand intended for studying the deformation processes in complex building and engineering structures.

Unlike most of the known experimental facilities of this kind, our stand was designed and created as a tool for exploratory research. It has great variability in the formulation of research tasks, the choice of research methods and registration tools. Our goal is to obtain fundamental knowledge about regularities of deformation processes, search for precursors of fracture, development of the methods for recording the early signs of failure in structures of various configurations and from different materials. Based on these tasks, it is very important to plan and correctly design the configuration of the power elements of the stand, providing the possibility of varying the external loads by type and value. An important point is the design of measuring and recording systems. It should be easily reconfigurable in accordance with the objectives of the study and the type of test structure. This paper provides information about the design of the stand, its equipment and capabilities.

Currently, a large cycle of experiments has developed and started at our stand. It aims to examine the behavior of a reinforced concrete structure under static and dynamic loading. We are going to study the spatial-temporal distribution of the deformation response of load-bearing elements to the onset of

critical processes, as well as to find and register damage precursors. In the experiment, such processes as contact interaction of structural parts, binding of structural elements due to steel reinforcement, real material composition, etc., are reproduced. These experiments provide the grounds for the development of automated deformation monitoring systems, which make it possible to control the current state of the observed structure and predict the development of critical processes in it. This paper presents the first results of the experiments simulating the deformation response of structural elements to the local quasi-static and impulse loads.

2. An experimental stand for mechanical testing of large-scale structures

The experimental stand of the Institute of Continuous Media Mechanics is a universal test site designed for mechanical testing of large-scale structures of various kinds. It is fitted with advanced equipment capable of applying various types of dynamic and static loads, and monitoring the observation of deformation processes in a wide range of execution times. The stand's equipment allows a variety of experiments, simulating the differential settlement of building foundation and impact of local static, vibrational and pulsed loads on various parts of model structure. The stand allows the observation of the structure through all stages of the deformation process including the elastic-to-inelastic transition. It allows researchers to observe the nucleation and evolution of damages, the failure of individual parts of the structure and, finally, the complete destruction of the specimen.

The main load-bearing elements of the stand are four load frames, combined by the horizontal and vertical connecting elements. The usable volume inside the frames is $8 \times 12 \times 8$ m (Figure 1). The load frames are based on a concrete foundation of 3 m depth. The design force, which can be realized within each loading frame, is 1000 kN. The stand is equipped with a beam crane, as well as supplementary devices and units, which provide assembling and loading of the model structure, registration, collection and processing of experimental data.

Differential settlement of building foundation is simulated using a specially designed jack system. It provides displacements of the base of each column using hydraulic jacks with the ability of fine adjustment. The jack control system ensures kinematic and force impacts on the structure in automatic mode according to the specified time dependencies. This makes it possible to realize different column settlement scenarios. The stand provides a vast variety of tools for realization of quasi-static loads.

The deformation response of the model structure to external loads is recorded using several recording systems. The stand is equipped with various types of sensors, which can register deformation processes with characteristic times ranging from 10 microseconds to several years. The lower boundary of this range corresponds to the acoustic emission signals. The registration of these signals is carried out with the aid of the original system developed by the team of co-authors. It provides the online, 8-channel registration of acoustic vibrograms with the accuracy comparable to the accuracy of the world-known brands of devices. The developed system has the advantages of easy increase of the number of channels and sensors, low cost, easy integration with well-known software products for processing primary data of acoustic vibrograms. Deformation processes with characteristic times of 0.1 ms are recorded using the system of 30 single-component vibration sensors (accelerometers). The physical and program-based integration of the sensors allows its synchronization and controlling the registration modes of the initial vibrograms. Dynamic deformation processes with characteristic times from 2 ms to 2.5 s are recorded
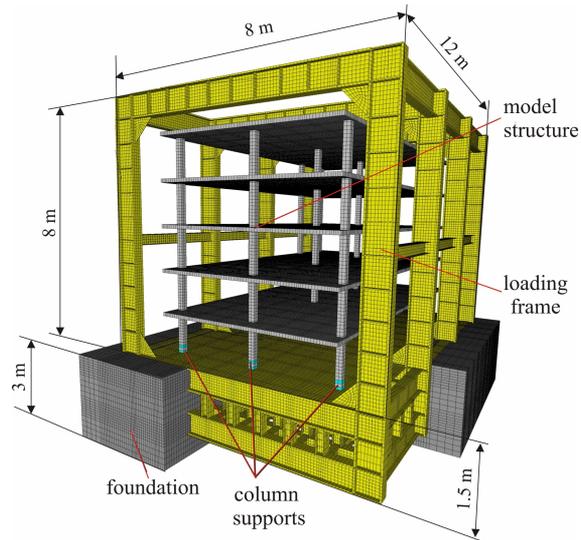
Figure 1. Test stand with installed model concrete structure: photo and schematic diagram.

by six 3-component seismic sensors.

The deformation response of the structural elements to a given local quasistatic load is measured by a system of 57 strain gauges and fiber-optic sensors integrated with the recording equipment. Registration of vertical displacements of the column bases is carried out by the system of hydraulic leveling sensors and the system of automatic data recording with web cameras [3].

In order to evaluate in practice the operability and functionality of the stand and the accompanying systems, an experiment was developed to study the deformation behavior of a model concrete structure subjected to quasi-static load. The experimental sample is a fragment of a precast-monolithic building on a scale of 1:2, including 24 standard cells combined into a 4-story structure (Figure 1). The dimensions
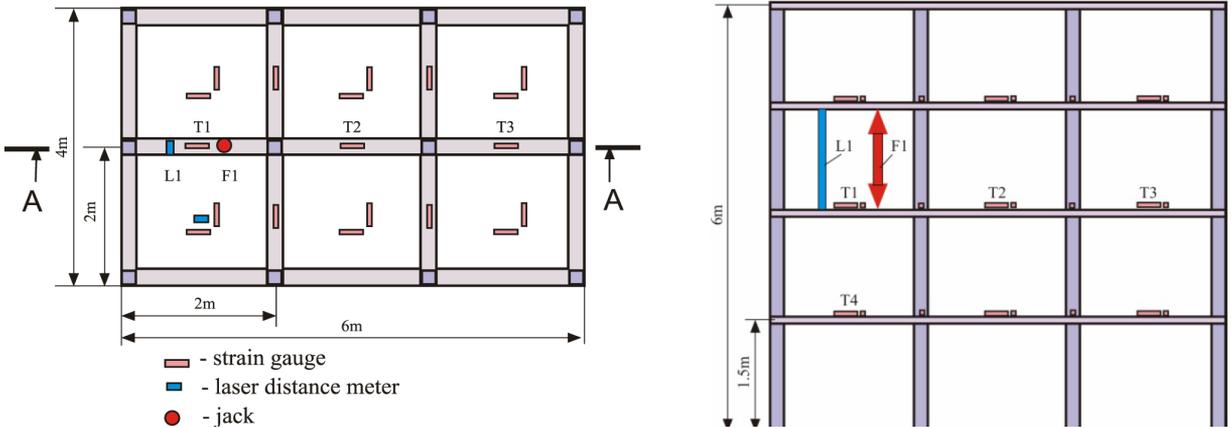
Figure 2. Scheme of load application and sensor location: second floor plan of model structure (left) and vertical section A-A (right).

of the sample are as follows: length 6 m, width 4 m, height 6 m. The model structure was designed based on the results of numerical simulation of the deformation processes in it, from an elastic state to inelastic one. These processes are accompanied by the occurrence and accumulation of cracks, formation of zones of damaged material in some parts of the structure and, finally, a complete loss of bearing capacity [28]. Analysis of the results of modeling made it possible to determine the dimensions and structural features of the model object, evaluate the mode and level of external loads. The deformation parameters, showing the greatest promise from the viewpoint of possibilities of recording subcritical and critical states, were identified, and the parameter ranges and accuracy of their recording were evaluated.

Creating an experimental sample took about 4 months. This included the development of a mathematical model, a numerical simulation of possible scenarios of elastic and inelastic deformation of the structure, and finally the sample manufacturing.

Now, the model structure is installed on the experimental stand. It is equipped with the following facilities.

- 12 hydraulic jacks are used to apply localized self-balanced force.
- 57 strain gauges are used to record deformations (gauges are distributed over the structure according to Figure 2).
- laser displacement sensors are used to record the relative displacements at the force application points (Figure 2).
- 24 one-component piezo-accelerometers are used to register the vibration response (gauges are distributed over the structure according to Figure 3, sensors are indicated by circles).
- A hammer equipped with an accelerometer is used to register a localized impulse force.

The deformation state of the structure during the experiment is controlled by an automated monitoring system. All measurement data are synchronized and collected in the monitoring database and go through primary mathematical processing. So, we obtain the opportunity of the online observation the deformation processes in the model structure during all stages of the experiment.
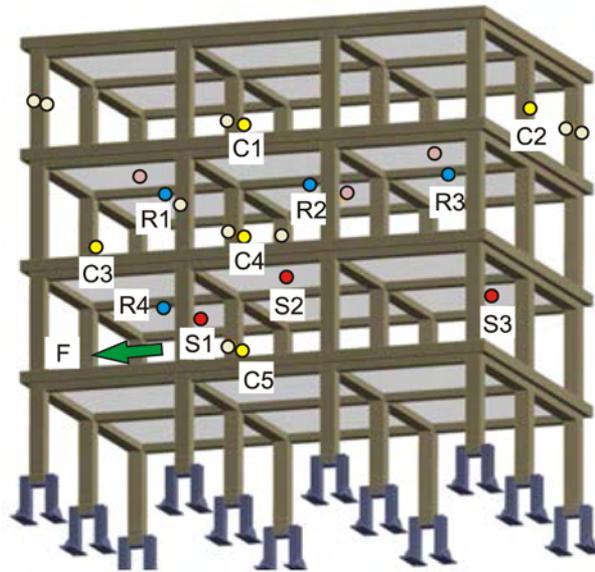
Figure 3. Scheme of accelerometer location.

3. Basic vibration portrait of the model structure

To study the dynamic processes in the model structure, it is necessary to know its vibration characteristics at the initial state. For this, we proposed to create a basic vibrational portrait of the structure. To obtain such information, a series of experiments was carried out. The experimental conditions were specified in such a way as to keep the structure in the elastic state. This was realized due to a reduced-impact mode in which the applied load could not cause inelastic deformation of its elements.

The vibration portrait is a set of information about the spatially distributed vibrational response of the structure to a series of test impulse impacts applied in its various parts. Having this information, we can compare it with the picture of the spatially distributed deformation response of the structure to certain external impact. Such comparison makes it possible to evaluate the change in the vibrational characteristics of the structure caused by a change in its deformation state, including the occurrence and accumulation of damage. Thus, it becomes possible to assess the magnitude and location of damage.

Obtaining the vibrational portrait of the structure is a complex procedure. The structure, which was under its own weight, was subjected to testing impulse force, which was applied sequentially at each basic element of the structure. Impact was produced by a hammer of 470 grams equipped with accelerometer. The force was applied to the surface of each vertical column in two perpendicular directions in the horizontal plane and to the floor slabs along the normal to their upper surface. The vibration response was recorded by a system of 24 accelerometers located on the columns, crossbars and floor slabs. The distribution of sensors by model structure is shown in Figure 3 (sensors are shown by circles). In total, 120 impulse forces were realized at different locations, and for each impulse a set of 24 vibrograms was obtained. Thus, we got 120 sets of 24 vibrograms which characterize spatial vibrational responses of the structure to 120 test impacts.
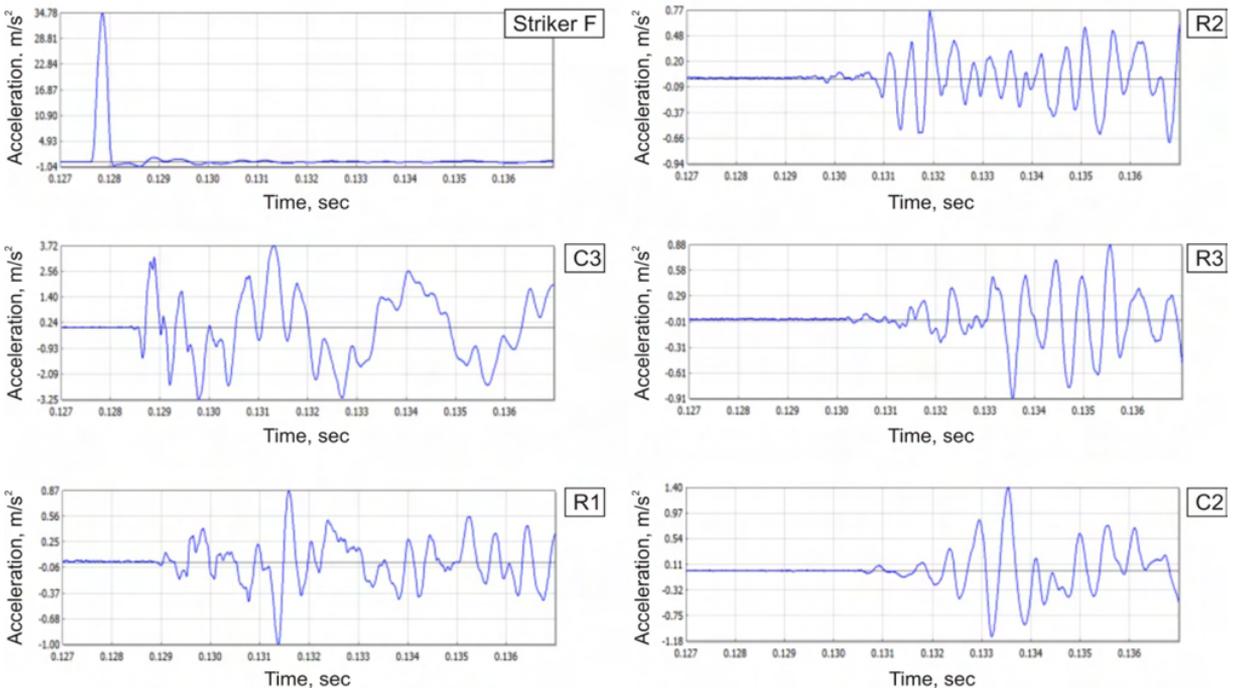
Figure 4. Acceleration vibrograms recorded on the striker and several sensors.

For each acceleration vibrogram, the corresponding Fourier and wavelet images were obtained. The total set of vibrograms and the results of their processing represent the basic electronic vibration portrait of the model structure. Composing the vibration portrait is a rather long procedure. In our case, it took about 1 month. But such number of measurements are necessary in order to describe the initial vibrational properties with sufficient accuracy. In addition, to generate statistically reliable data, it is advisable to perform this procedure repeatedly.

Figure 3 gives a schema of one test of this series. The point of application of test impulse force and its direction are shown by the arrow. Figure 4 presents vibrograms of accelerations in the direction normal to the surface of sensor attachment. The figure shows the data recorded by the striker sensor and sensors attached to 2 columns (C2, C3) and 3 crossbars (R1, R2, R3). Designation and arrangement of sensors correspond to Figure 3. Matching vibrograms clearly demonstrate the time of the wave front passage through each sensor and the delay of the wave front as the distance from the impact point increases.

The experimentally recorded pattern of the wave front propagation is in qualitative agreement with the results obtained by the numerical simulation [10]. Figure 5 displays the propagation of the displacement wave front caused by a localized impulse force applied at one ground floor column (result of simulation). The figure demonstrates the positions of the displacement wave front, which correspond to three successive instants of time, elapsed from the moment of impact: 0.36 ms, 1.1 ms and 2.4 ms. The histogram on Figure 5 compares the arrival times of the deformation wave front at some points of the structure obtained by the numerical simulation and during the experiment. These data were recorded by sensors
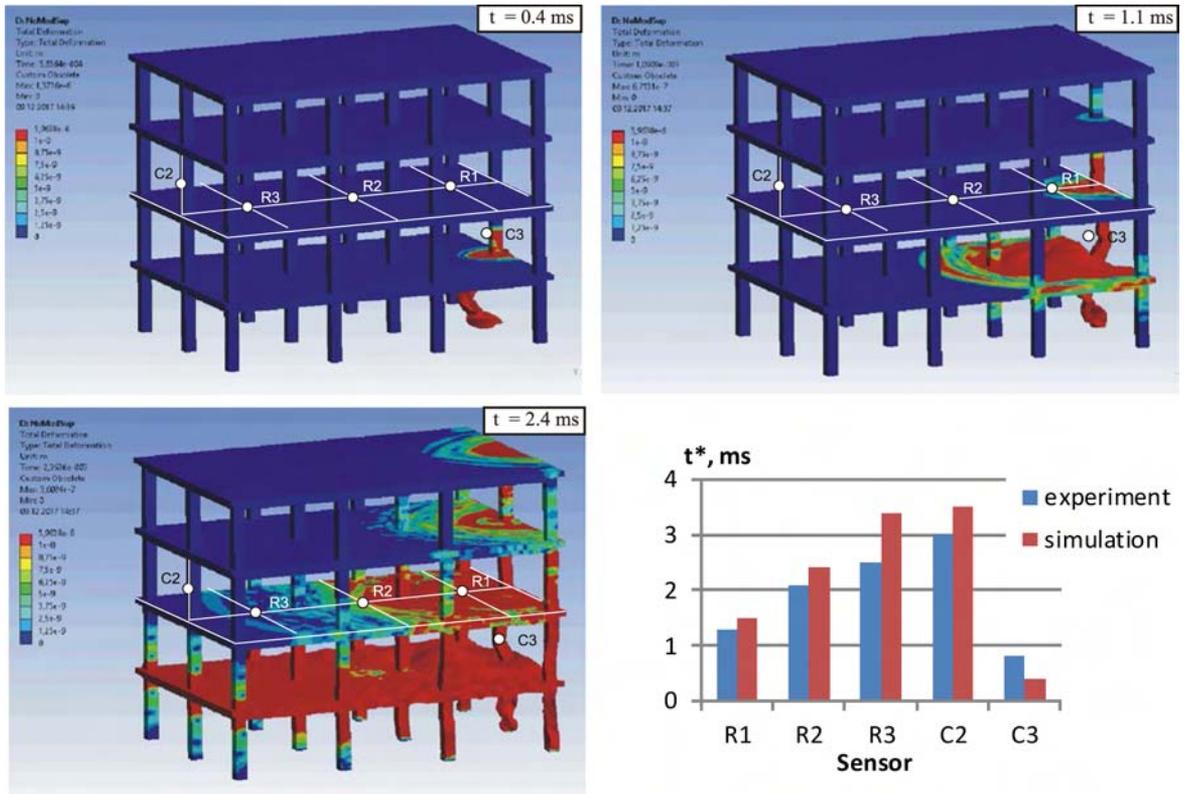
Figure 5. The displacement wave front in structural elements at three time instants and arrival time of the deformation wave at different points of structure.

located on three crossbars (R1, R2, R3) and two columns (C2, C3). The calculated and experimental data demonstrate a fairly good agreement.

Figure 6 shows several wavelet images of accelerations recorded by sensors located at different points of the structure. Designation of the sensors and their positions are indicated in Figure 3. The patterns clearly demonstrate the "lifetime" of free vibrations at different frequencies. The most long-lived vibrations have the frequency of ∼200 Hz. The vibration amplitudes for columns, crossbars and floor slabs differ significantly.

4. Quasistatic loading of the model structure

Thus, having complete information about the initial state of the model structure, we began to study its deformation response to static load. Here we demonstrate the results obtained by loading the structure in a low-impact mode in which deformations remain elastic.

First of all, the spatial deformation response of the structure to the applied localized self-balancing bursting force was studied. Static load F1 was applied by means of a jack, installed between two floor slabs (Figure 2). The loading was carried out stepwise, with increasing the load at each step and reset to zero before the next step. Figure 7 shows change in force F1 and corresponding changes in vertical
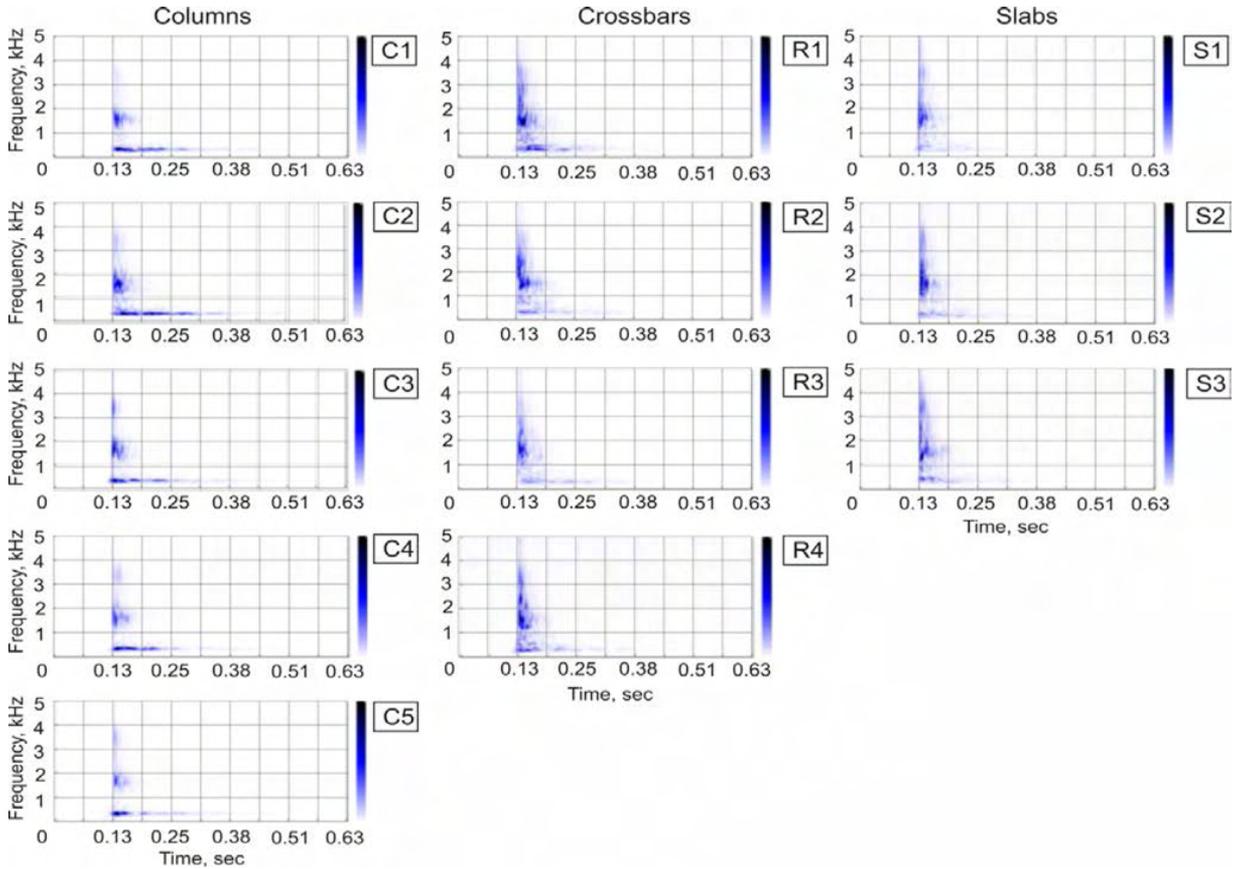
Figure 6. Wavelet images of acceleration vibrograms at different points of model structure.

displacement L1 in the vicinity of the loading point as well as deformation response of individual elements at the points T1–T4. Strain gauge notation corresponds to that given in Figure 2. Similar data were obtained for all points of the structure, equipped with strain gauges.

The above measurements were made for several quasi-static load arrangements. For all variants of loading we obtained the patterns of spatial distribution of deformations as well as the plots of deformation and displacement as a function of the applied force. An analysis of these graphs in Figure 7 shows that if the applied force is less than 20 kN, all structural elements remain elastic. As soon as the applied load exceeded 20 kN (this corresponds to the 5th loading step), the strain value in unloading state becomes non-zero. This fact indicates the beginning of inelastic processes in the structure. Comparing the graphs obtained from the sensors located at different distances from the jack, we can see that the strain decreases rapidly when the distance from the loading point increases. So, at a distance of 5 meters from the jack the strain level decreases by 30 times.

To study the dynamic properties of a structure subjected to static loading, we acted as follows. After each loading step, structural vibrations were excited at some points of the structure, and the acceleration vibrograms were obtained and compared with the vibrograms recorded prior to loading (vibrograms
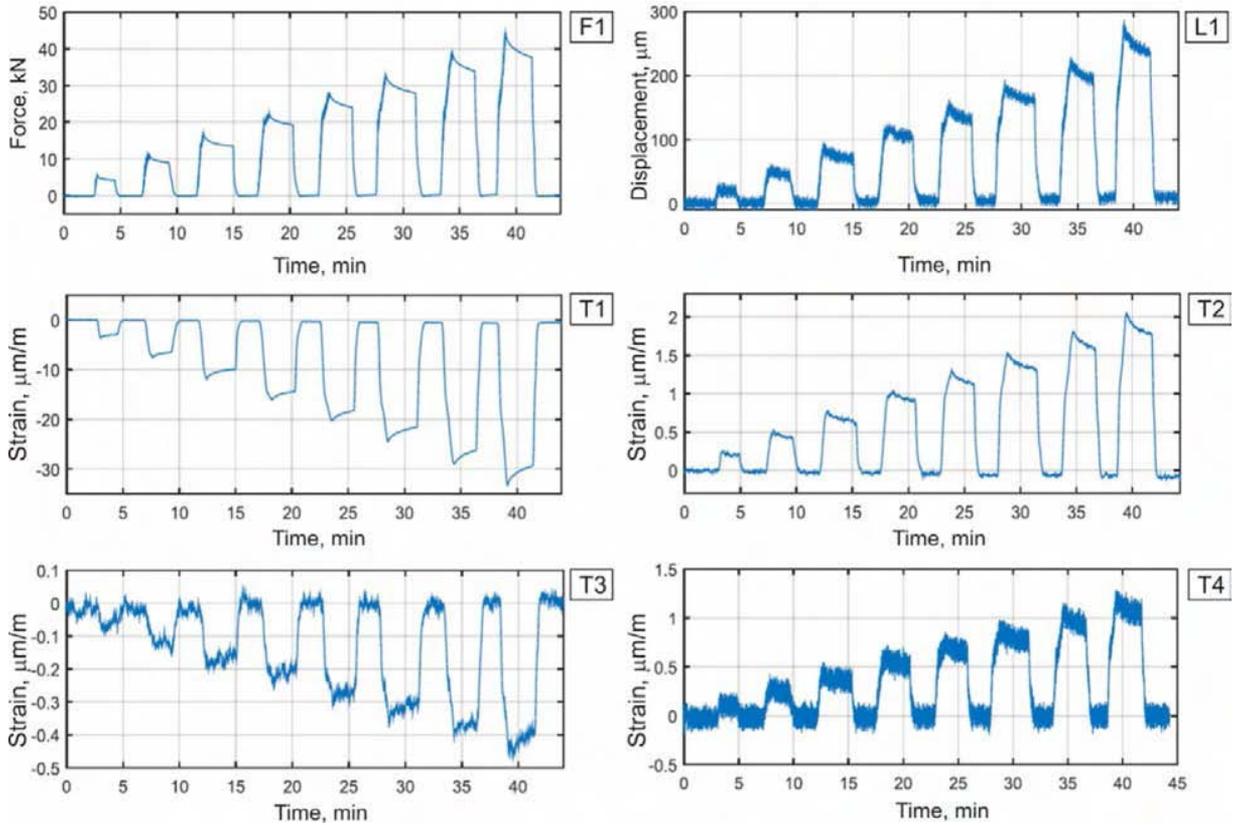
Figure 7. Changes in the applied force F1 and corresponding changes in the displacement L1 and strain at points T1-T4 of model structure.

from the basic vibration portrait). Figure 8 shows a diagram of half the sample with sensors and the vibrograms recorded by C4 sensor located on the column close to the jack. The position of the jack is shown by the red arrow, the position and direction of the pulse force is indicated by the green arrow. The vibrogram is normalized to the acceleration amplitude of the striker. The lower graph is a detailed image of the marked fragment of the upper graph. A comparison of the vibrograms taken from the basic vibration portrait and obtained after the third loading step shows that the difference is insignificant. Thus, we can conclude that the quasi-static loading in the low-impact mode does not significantly affect the dynamic deformation response of the structure to the external impulse loads. This fact is consistent with the current opinion that the "initial" stress state doesn't affect the dynamic behavior of a deformable system.

5. Conclusions

A review of information on modern test stands, which are used to study the deformation processes in large-scale building and engineering structures, showed that this line of research is in great demand and is actively progressing. On the one hand, this is connected with the tendency to create increasingly
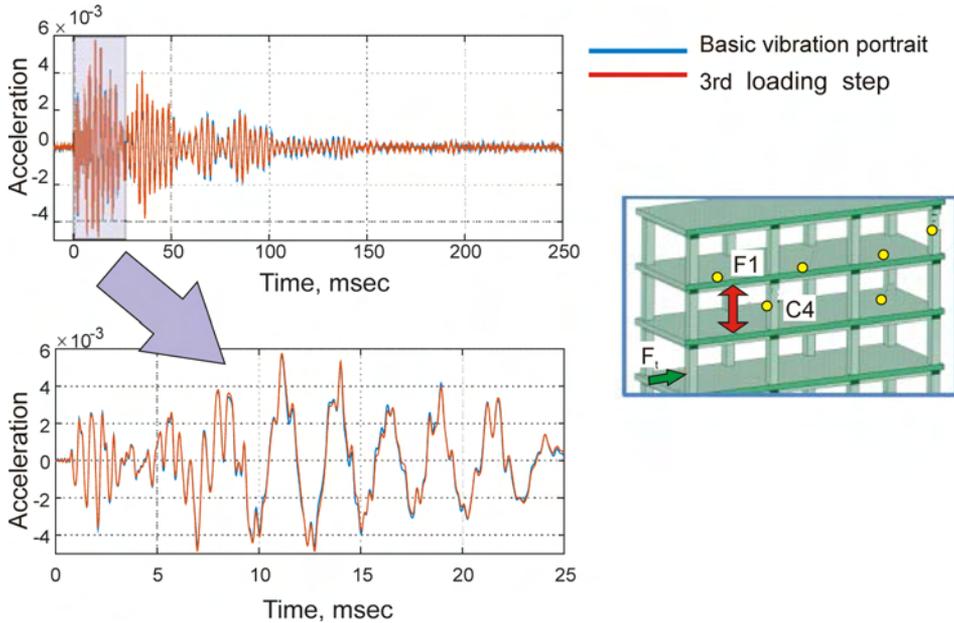
Figure 8. Vibrograms recorded by accelerometer C4 prior the loading and after the third loading step.

complex unique structures using new engineering materials and technologies. On the other hand, there is considerable progress in the development of experimental data recording systems, as well as the systems for processing large amounts of information. These circumstances significantly increase the informative value of experimental studies and gives impetus to the development of methods for the assessment of the stress-strain state of structures and prediction of their performance capacity.

The experimental stand created by the team of authors is aimed at studying the deformation processes in large-scale model structures, searching for precursors of failure, as well as elaborating criteria for establishing the pre-critical state of the structure. The research stand is designed and created as a tool for exploratory research. Our goal is to obtain fundamental knowledge about the patterns of the emergence of damage precursors, to develop the instruments for observations of early signs of destruction in structures of various configurations and from various materials. The stand is a multifunctional experimental site that allows you to explore the features of static and dynamic deformation processes in a variety of building and engineering structures.

Presented series of experiments demonstrates the capabilities of the experimental setup, which allows one to study deformation processes in large-scale objects with a multi-element structure, and dissimilar deformation interaction. The obtained results are as follows:

– A basic vibrational portrait of the model structure has been created, which provided basic information for the future experiments aimed at studying inelastic deformation of a structure until its ultimate failure.

– The deformation response of structural elements to the local self-balanced load specified in the loading-unloading mode has been studied. The spatial distribution of linear deformations over structural elements has been obtained under external loads applied at different points. It was shown that in the range of applied forces up to 20 kN, the structural elements experience elastic deformation.

– The dynamic response of structural elements to a locally applied impulse load has been studied. The patterns of the spatial-temporal distribution of deformation parameters over the structural elements have been obtained. The study has shown that the propagation of the deformation wave through the structural elements is of complex character. With regard to the characteristic times of propagation of the deformation wave over the structural elements, the obtained experimental data are found to be in good agreement with the results of numerical simulation.

The presented experiments allow us to accumulate unique data on the strength, reliability and durability of concrete structures under static and dynamic loads. These data are needed to understand the mechanisms of damage formation in concrete structures, to find precursors of failure, as well as to develop criteria allowing registration of the onset of the critical state.

Acknowledgements

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IGOR SHARDAKOV: shardakov@icmm.ru
intelligent monitoring laboratory, Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science,
1, Akademic Korolev street, Perm, 614013, Russia

IRINA GLOT: glot@icmm.ru
intelligent monitoring laboratory, Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science,
1, Akademic Korolev street, Perm, 614013, Russia

ALEKSEY SHESTAKOV: shap@icmm.ru
intelligent monitoring laboratory, Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science,
1, Akademic Korolev street, Perm, 614013, Russia

ROMAN TSVETKOV: flower@icmm.ru
intelligent monitoring laboratory, Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science,
1, Akademic Korolev street, Perm, 614013, Russia

VALERIY YEPIN: epin.v@icmm.ru
intelligent monitoring laboratory, Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science,
1, Akademic Korolev street, Perm, 614013, Russia

GEORGIY GUSEV: gusev.g@icmm.ru
intelligent monitoring laboratory, Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science,
1, Akademic Korolev street, Perm, 614013, Russia

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