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Dynamic characteristics of a reinforced concrete frame under vibration load conditions

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Abstract. The object of the research is the reinforced concrete frame of an industrial building. A review of publications on methods of dynamic calculation of reinforced concrete structures is presented. Computational studies were carried out using the finite element method. The initial data for the calculation are the physical characteristics of the material of concrete, steel and base, the geometric parameters of the reinforced concrete frame obtained as a result of laser scanning. The resulting point cloud was combined with a mathematical model built based on design documentation. Based on a cloud of terrestrial laser scanning points, the computational model was refined. A comparison was made between the actual and design dimensions of columns and nodes. Discrepancies in the geometric dimensions of columns, nodes and connections were determined. The strength and stability of the reinforced concrete frame were not included in the methodology, but were used to determine the geometric dimensions of the structure, which are the initial data for the research. To determine the natural frequencies and vibration modes of the reinforced concrete frame, dynamic calculations of the equipment-frame-based system were performed. The equipment is presented in the form of distributed point masses on the marks of the frame consoles. An analysis of vibrations of the frame, based on which the structure was strengthened, is presented. The dynamic load from equipment operation is specified based on the measurements of vibration values in the longitudinal direction of the frame. The resonance zone during equipment operation was determined. Based on the results of the dynamic calculation, the frame structure was strengthened to prevent resonance phenomena. Test calculations and measurements showed the efficiency of the proposed method. The first translational (in the longitudinal direction) natural frequency increased from 3.609 Hz to 6.4258 Hz.

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1. Introduction

Columns of a reinforced concrete frame of an industrial structure are often used as foundation supports for placing equipment on them. Reinforced concrete columns are the main load-bearing elements of the frame, and the load on the columns is distributed unevenly due to operation-related equipment vibration. A feature of the dynamics of this system is that the reinforced concrete frame is modeled together with the base and equipment, which is installed at the marks of the column consoles. At the same time, the vibration effect from the operation of the equipment causes vibrations of the structure.

The study was carried out based on a numerical model of a reinforced concrete frame together with the foundation and equipment (Fig. 1). The equipment is presented in the form of distributed point masses on the marks of the frame consoles.

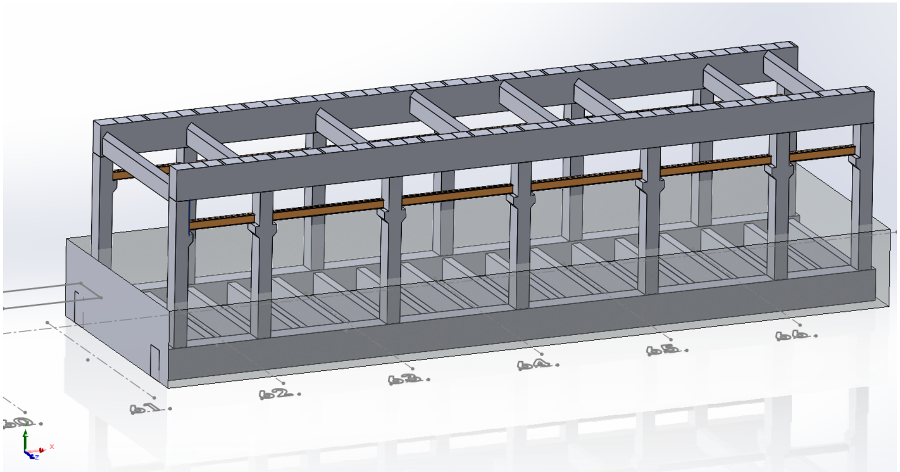

Figure 1. Three-dimensional geometric model of a reinforced concrete frame with a base.

Carrying out a dynamic calculation of a reinforced concrete frame with a base involves analyzing vibration modes and determining the predominant (resonant) frequency during equipment operation. Thus, in article [1], sets of records of accelerograms obtained at certain points of a real reinforced concrete four-story building structure subjected to forced vibrations are presented. The design has vertical indentations from the central axis, which gives it a natural eccentricity in one direction. The tests were carried out to study the torsional moment of a structure subjected to forced vibrations. A mechanical eccentric exciter was used for testing. The exciter was attached to the roof slab in two places, and the resulting force varied in position, magnitude, direction, and frequency. During testing, the only vertical loads applied to the building structure were the self-weight loads of the columns, beams, and slabs. There were no additional vertical dead or dynamic loads. Given the design characteristics and test results, the generated data can be used for several purposes such as building torsion and design verification. The simplicity of the building allows the tests to be accurately reproduced analytically, since there is no interference with non-structural elements or live loads.

In article [2], a new method for reinforcing multilayer (4-layer) vibration insulation of industrial buildings is presented. A new reinforcement method using a shear wall with short supports is also proposed. In addition, an engineering example of a multi-layer industrial building with high vibration is presented. A three-dimensional finite element model of a multi-layer industrial building was created and field vibration tests were carried out. The test results showed that the large vibration of the industrial building was caused by the resonance between the machines and the sandwich industrial building. Finally, the multi-layer industrial building was strengthened with a new reinforcement method, and after reinforcement, a vibration experiment was carried out. The results show that the new reinforcement method has a good effect. The strength and stiffness of the sandwich industrial building were improved, the natural frequency of the industrial building in one direction increased from 2.45 Hz to 5.87 Hz, and in the other direction increased from 2.94 Hz to 7.83 Hz. At the same time, the frequencies of the equipment and the frequencies of the multi-layer industrial building were not in the resonant range, and the vibration characteristics of the multi-layer industrial building were improved. The study can serve as a source of recommendations for reinforcement of a multi-layer industrial building with a similar structural configuration.

In article [3], studies were carried out on the use of forced vibration testing and finite element model verification to assess existing damage in a four-story reinforced concrete structure. The so-called "Four Seasons Building" located in Sherman Oaks, California is examined. It was damaged in the 1994 Northridge earthquake. Using mobile testing equipment, accelerations as well as deformations at selected locations were measured during forced vibration tests using linear and eccentric vibrator devices. This data was used to update the finite element model of the structure. The updated model correlates well with the observed distribution of damage throughout the building and allows us to quantify its magnitude.

In the article [4], a new indicator is proposed for detecting damage in reinforced concrete (RC) beams based on the transient characteristics of nonlinear vibration. Two reinforced concrete beams were studied, one of which was reinforced with external sheets of fiber-reinforced polymer. Both beams were loaded statically and dynamically to relate the dynamic behavior of the beams to the deformations. A model is developed to simulate the general behavior of cracked concrete elements using a softening Duffing generator. Numerical results and test data show that the index increases rapidly with increasing damage and is very sensitive to cracking even under service loads. The indicator is directly related to transient processes along the crack surface and does not require a baseline for practical use. The experimental test results also show that the fundamental natural frequency of the reinforced beam suddenly decreases when cracks occur and then remains almost constant, while the natural frequency of the unstrengthened beam continuously decreases as the beam undergoes concrete cracking and reinforcement yielding.

The article [5] presents the results of studies of vibration of buildings with reinforced concrete frames based on vibration measurements and numerical analysis. Vibrations were measured at roof level for 29 selected buildings ranging in height from one to six storeys. Using Nakamura's technique [6], horizontal and vertical spectral ratio curves were obtained in two orthogonal plotting directions. Period estimates ranged from 44 % to 91 % of the elastic periods suggested by local regulations. Preliminary period-altitude relationships have been proposed using regression analysis of the measured periods. Due to the lack of structural details, the vibration periods of only 15 buildings were estimated using linear modal analysis of 3D computer models, including the influence of masonry concrete infills. Considering the cracking of structural reinforced concrete elements, the vibration period increased by 40–50 % compared to the elastic value. The analytical period values showed large differences with both measured and calculated values.

In article [7], two models were tested on a vibration stand. One of the models is a conventional reinforced concrete megaframe structure, and the other is a multi-functional vibration-absorbing reinforced concrete megaframe structure, in which laminated rubber supports are placed between the main and small frames. During the test, two seismic motions are used (El Centro wave [8] and Taft wave [9]). This paper presents the dynamic characteristics, seismic responses, and failure mechanism of these two models at different peak acceleration levels for each of the earthquake motions. The test results show that the seismic behavior of the multifunctional vibration-absorbing reinforced concrete megaframe structure is significantly better than that of the conventional reinforced concrete megaframe structure.

Article [10] investigated the influence of the time-varying modulus of elasticity of concrete, pouring of structural elements, assembly of a temporary frame fastening system and impacts from operating construction equipment on the dynamic behavior of a reinforced concrete frame structure during construction. Dynamic tests of an eight-story reinforced concrete frame structure at the full-scale stages of construction of the sixth floor were carried out by external vibration. Natural frequencies, corresponding mode shapes and attenuation coefficient were determined by processing the power spectrum of the test signal data in the frequency domain. Changes in frequencies, vibration modes and damping coefficients at different stages of construction are presented. The results show that the natural frequencies and modal damping coefficients reach a maximum during the fresh concrete pouring stage, especially for higher modes. Modal damping coefficients at each stage of construction are less than 5 % of the coefficients during operation.

Many articles and books are devoted to methods for numerical solution of problems of dynamics of structures [11–25]. Among the famous scientists who studied seismic resistance and dynamic characteristics of structures, it is necessary to note the works of Ya.N. Eisenberg, A.N. Birbraera, S.P. Tymoshenko.

The relevance of the research topic is determined by the safety of the frame working together with the equipment. Vibrations from equipment operation often result in resonance phenomena, which can lead to sudden structural failure. This task is especially relevant for frames and equipment during long-term operation.

The objective of the study is to determine the natural frequencies and analyze the vibration modes of a reinforced concrete frame, as well as proposals for increasing the rigidity of the frame, ensuring the absence of resonances during equipment operation.

2. *Materials and methods*

A method for dynamically calculating vibration loads for equipment standing at the marks of frame columns is presented. The strength and stability of the reinforced concrete frame is not included in the methodology but was carried out when determining the geometric dimensions of the structure, which were used as initial data for this work.

To calculate the reinforced concrete frame, a final elemental “frame-base” model was built. The “frame-base” model was divided into three-dimensional 4-node tetrahedron elements connected to each other at nodes. Coordinate system: OX axis – along the frame, OZ axis – across the frame, OY axis vertically upward (Fig. 1).

Computational studies were carried out within the framework of the spatial formulation of the problem using the Finite Element Method (FEM). FEM and its application in structural calculations are presented in works. The construction of the calculation model was carried out based on the geometric and physical parameters of the reinforced concrete frame and foundation. The calculation model of the frame is presented in Fig. 2.

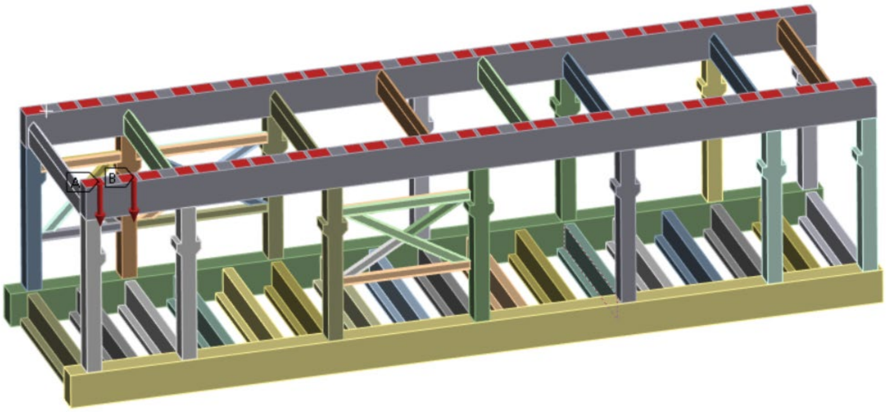

Figure 2. Computational finite element model of the frame.

The initial data for the calculation are the physical characteristics of the concrete, steel and foundation materials obtained because of engineering surveys and frame strength calculations. For dynamic calculations, an accelerogram of vibration impact in the OX direction (along the frame), obtained from the measurement results, was used.

The main stages of the method are as follows

1. Construction of a mathematical dynamic model “frame-base”, including geometric construction, division into finite elements, setting the properties of materials, setting boundary conditions.
2. Model verification based on terrestrial laser scanning.
3. Dynamic calculation of the original structure based on the original accelerogram. Determination of natural frequencies and vibration modes of the frame
4. Strengthening the structure to increase dynamic rigidity.
5. Dynamic calculation of the reinforced frame structure based on the newly measured accelerogram.

3. Results and Discussion

Stage 1

Fig. 2 shows the finite element calculation model of the frame, together with the foundation.

Description of boundary conditions:

- The nodes on the lower edge of the foundation are secured against movement and rotation along all axes.
- The nodes on the vertical faces of the foundation are secured against movement in the direction perpendicular to each face.

Physical characteristics of materials

The frame is made of structural concrete – B22.5.

The characteristics of concrete are accepted:

- Concrete density pb = 2.4t/m^3.
- Calculated resistance of concrete in compression Rb and tension Rbt for limit states of the first group:
- Rb = 11.5 MPa;
- Rbt = 0.9 MPa;
- Transverse concrete deformation coefficient (Poisson's ratio) for slab structures ν = 0.20.

Additional longitudinal I-beams are made of steel C245:

- Steel density ps =7.85t/m^3.
- Rs = 280 MPa = 280,000 kPa.

- Poisson's ratio of steel ν = 0.30.
- Modulus of elasticity of steel in compression and tension Es = 2.1×105 MPa.

Stage 2

At stage 2, the model was verified using terrestrial laser scanning. Based on the results of registration of 12 stations (119,256,031 points), 24 connections were created. The locations of the stations are shown in Fig. 3.

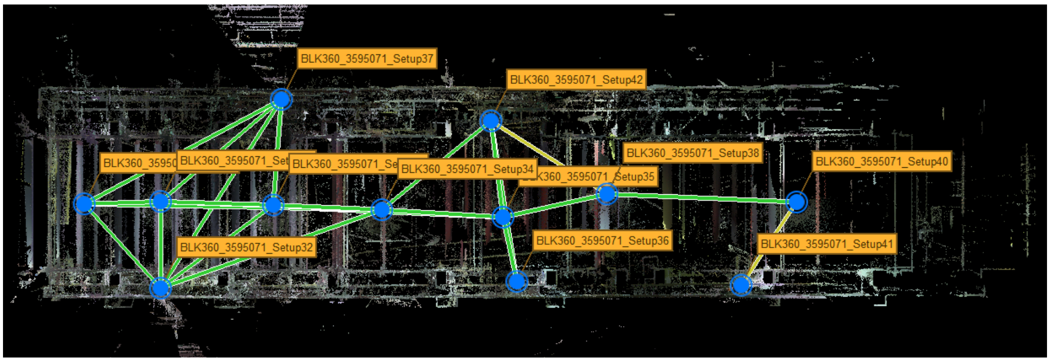

Figure 3. Location of laser scanning stations and links.

The total error was 7 mm (primarily due to the Setup41 station, located in a hard-to-reach place with an overlap of 18 %), and the average overlap was 46 %. Registration is carried out in a local coordinate system. The resulting point cloud was combined with a model built based on design documentation. Based on a cloud of terrestrial laser scanning points, the calculation model was refined. A comparison was made of the design dimensions of the assembly with the values obtained as a result of laser scanning. The actual dimensions of some units are slightly larger than the design ones. The calculation model was built based on the results of actual measurements.

Stage 3

At the third stage, the calculation of the natural frequencies and vibration modes of the structure with the base was carried out.

The calculation obtained the first 15 natural frequencies from 3.609 to 11.237 Hz. The first translational natural waveform with a frequency of 3.609 Hz is shown in Fig. 4.

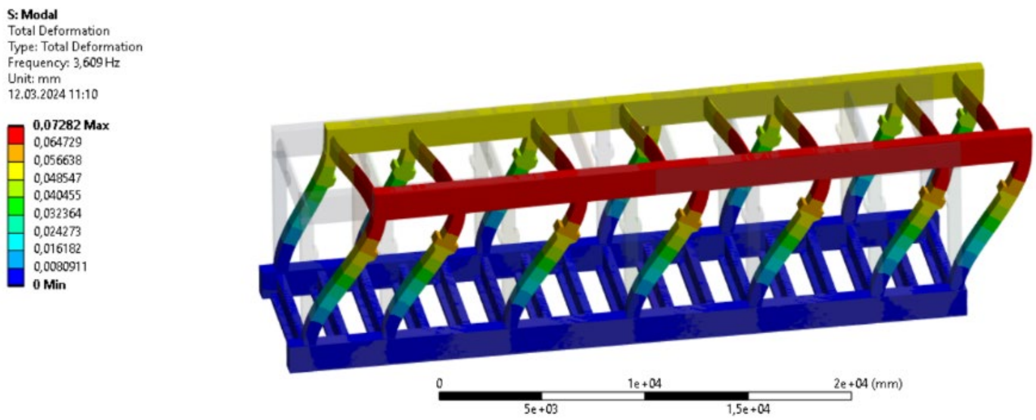

Figure 4. The first translational natural vibration mode of the frame is 3.609 Hz.

The disturbing frequency is 3.18 Hz. The corresponding accelerogram is shown in Fig. 6.

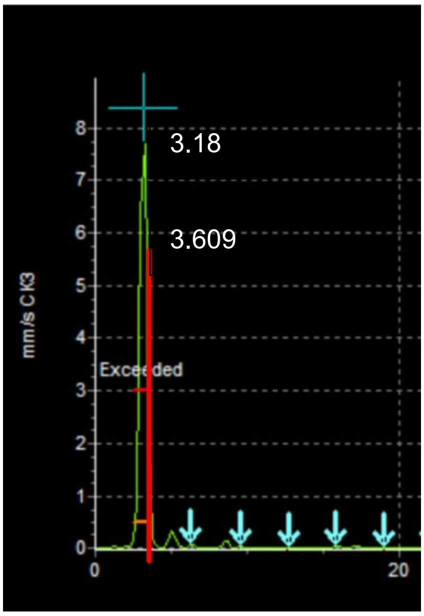

Figure 5. Accelerogram for the original model.
The disturbing frequency is 3.18 Hz along the X axis.

When vibration is applied to equipment with a disturbing peak frequency of 3.18 Hz, the phenomenon of partial resonance occurs when the lower boundary of the disturbance coincides with the first translational frequency of the frame, which is 3.609 Hz. To get out of the state of resonance, the structure was strengthened to increase its rigidity.

Stage 4

As reinforcement, 3 vertical connections between the columns were chosen, 2 on one side and 1 on the other side. Mechanical reinforcement option is shown in Fig. 6.

The strengthening of the structure turned out to be asymmetrical due to the presence of technological elements in the operating frame. Thus, the reinforcement is performed using cross connections in the openings between the columns where there are no technological elements.

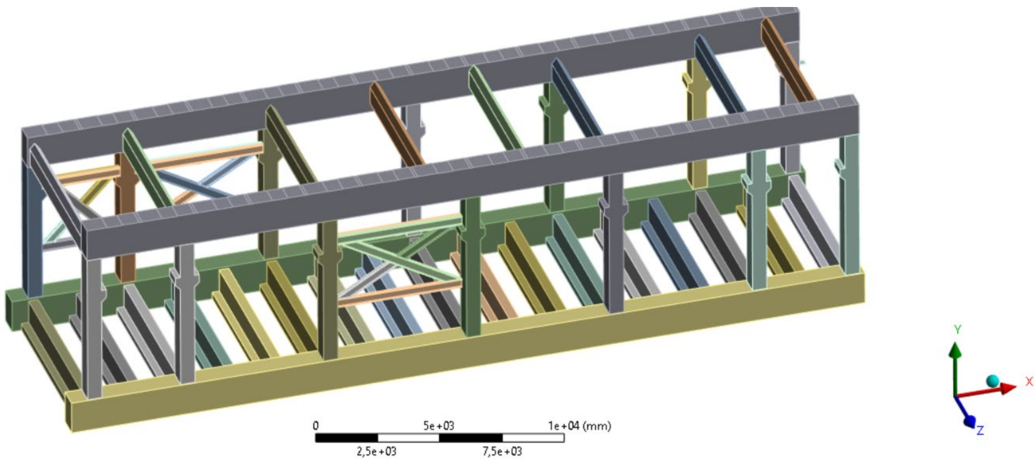

Figure 6. Strengthening structures.

The first translational natural frequency, considering the strengthening of the structure, is 6.4258 Hz, the corresponding vibration shape is presented in Fig. 7.

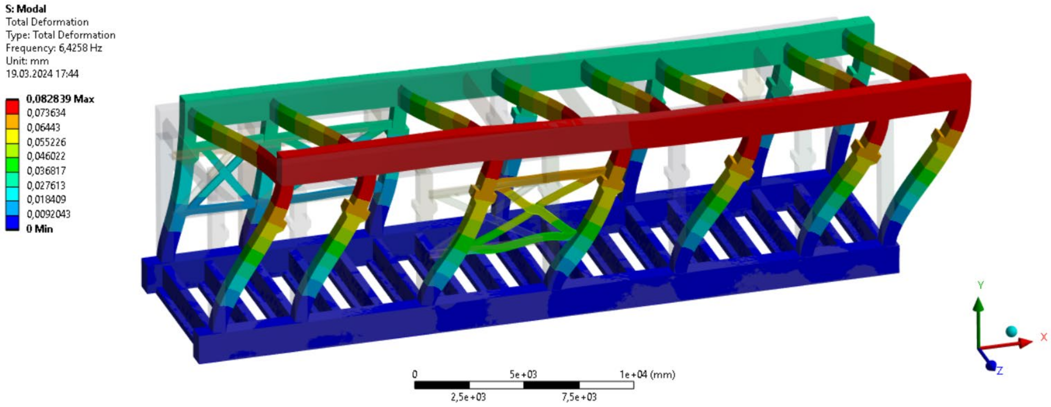

Figure 7. The first translational form of natural vibrations, considering the reinforcement of the frame, frequency 6.4258 Hz.

After strengthening the structure, vibrations from the operation of the equipment were measured. The new accelerogram is presented in Fig. 8.

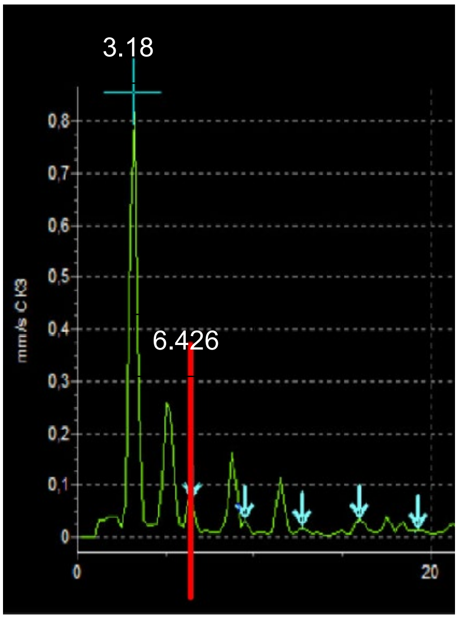

Figure 8. Accelerogram of the reinforced structure. The first translational form of natural vibrations, considering the reinforcement of the frame, frequency 6.462 Hz.

The disturbing resonant frequency is 3.18 Hz. The first natural translational frequency of the frame is 6.4258 Hz. Thus, the resonance phenomena of the reinforced concrete frame, considering the amplification during equipment operation, are completely excluded.

The obtained research results are compared with similar calculations in [2]. When the rigidity of a structure increases in a certain direction, a significant increase in the frequency of translational vibrations occurs, which removes the structure from resonance with the operating equipment.

4. Conclusions

1. As a result of modal analysis, 15 natural frequencies and vibration modes from 3.609 to 11.237 Hz were obtained. In this case, the first translational mode of vibration with a frequency of 3.609 Hz causes the phenomenon of partial resonance with a disturbing peak frequency of 3.18 Hz.
2. Dynamic calculations were performed based on the calculated accelerogram of the translational impact obtained during field measurements of equipment vibrations.
3. The phenomenon of resonance was studied; design solutions were made to strengthen the reinforced concrete frame, leading to exit from the zone of resonance phenomena. The frequency of the disturbing influences did not change and amounted to 3.18 Hz, while the first translational form of oscillation was obtained with a frequency of 6.4258 Hz.

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