Numerical and experimental studies of deflections of conventional and strengthened reinforced concrete bendable elements under short-term dynamic loading

Dmitry Yu. SARKISOV[1], Georgy I. ODNOKOPYLOV[2], Vladimir V. KRYLOV*[,3],
Andriy O. ANNENKOV[4]

*Corresponding author
[1]Department of Reinforced Concrete and Stone Structures,
Tomsk State University of Architecture and Building,
2 Solyanaya Sq., 634003, Tomsk, Russian Federation,
Milandd@yandex.ru
[2]Department of Electric Power Engineering and Electrical Engineering,
Tomsk State University of Architecture and Building,
2 Solyanaya Sq., 634003, Tomsk, Russian Federation,
OGIz@yandex.ru
[3]National Research Moscow State University of Civil Engineering,
26 Yaroslavskoe Shosse, 129337, Moscow, Russian Federation,
albet-group@yandex.ru*
[4]Department of Engineering Geodesy,
Kyiv National University of Construction and Architecture,
31 Povitroflotskyi Ave., 03037, Kyiv, Ukraine,
geodez74@gmail.com

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Abstract: *The relevance of this study is conditioned by the technical complexity of the design solutions for construction projects of ground-based space infrastructure. It is associated with the possibility of special loads in the form of an air shock wave in the event of a launch abort, a fall of a fragment, an emergency shutdown of engines, an air shock wave from the indirect impact of nuclear weapons, seismic loads, accidental cargo falls, terrorist attacks, etc. Such impacts with a high degree of probability lead to damage to building structures and in the future, they need to be reinforced. These building structures must have survivability under special loads and deform without collapsing. Under the dynamic loading, the energy intensity of the bendable structures is important, to determine which it is necessary to know the magnitude of the acting force and deflections. The effective load in a wide class of problems refers to the initial data, and the determination of reliable values of the dynamic deflection of the bendable structure is an actual problem. The purpose of this study is to conduct a numerical and experimental investigation of the deflection of conventional and strengthened reinforced concrete structures under short-term dynamic loading. This study used the following research methods: measurements of deflections and loads by strain measurement, graphical analytic research using Microsoft Excel, numerical calculation in the environment of the Explicit Dynamics module of the Ansys software package. As a result of the study, experimental investigation of conventional and strengthened bendable* *reinforced concrete elements under short-term dynamic loading was carried out, the values of the effective force and deflections were obtained. The same experiment was modelled in the environment of the Explicit Dynamics module of the Ansys software package. A comparison of the deflection parameters was made, based on the results of numerical and physical experiments on the example of a specific design, which showed satisfactory convergence.*

Key Words: *survivability factor, loading, design solutions, experimental studies, construction engineering*

1. INTRODUCTION

In accordance with Article 48.1 of the Urban Planning Code of the Russian Federation, space infrastructure facilities are classified as particularly dangerous and technically complex construction projects, being objects of an increased level of responsibility (class KS-3). The building structure of such facilities can be affected by special short-term dynamic loads, which include an air shock wave during a launch abort, a fall of a fragment, an emergency engine shutdown, an air shock wave from the indirect impact of nuclear weapons, seismic loads, accidental cargo falls, terrorist attacks, etc. When the load-bearing structures of ground-based space infrastructure facilities are destroyed, significant direct damage occurs due to the cost of the object itself, the cost of the technological line, downtime, as well as indirect reputational damage because information about accidents at such facilities attracts increased attention of the global mass media [1], [2], [3], [4], [5]. The relevance of this study is conditioned by the technical complexity of the design solutions for construction projects of ground-based space infrastructure. It is associated with the possibility of special loads in the form of an air shock wave in the event of a launch abort, a fall of a fragment, an emergency shutdown of engines, an air shock wave from the indirect impact of nuclear weapons, seismic loads, accidental cargo falls, terrorist attacks, etc.

The main requirement for such facilities is security [6], [7], which is determined by their ability to withstand the occurrence and distribution of various loads in normal and non-standard situations throughout the entire operation period. Security is expressed by the functional set of basic parameters [8], such as: risks; safety; survivability; stability; rigidity; strength, etc. One of the main parameters that determine the exclusion of the possibility of collapse of load-bearing building structures of the facility is the survivability of the system. When applying the provisions of the theory of survivability [9], it is possible to more accurately assess the residual resource of technical systems, for example, load-bearing structures or the facility as a whole after exposure to short-term excess dynamic loads. To increase survivability, the energy intensity of load-bearing building structures is important, to determine which the values of the acting loads and deflections are necessary. And if the load is an external value and essentially depends on the specific operational situation at the facility, then the deflection is directly related to the rigidity characteristics of the structure and should be calculated during design [10], [11], [12], [13], [14], [15].

Many load-bearing structures in facilities of ground-based space infrastructure are made of reinforced concrete. The complex processes occur in building structures, and especially in reinforced concrete, due to its nonlinear properties under short-term dynamic loads characteristic of the objects of ground-based space infrastructure under consideration [15], [16], [17], [18], [19].

Thus, the calculation of deflections of reinforced concrete structures under such types of impact presents a scientific problem. In addition, there is a possibility of significant damage to structures under such impacts, which requires their further strengthening to ensure the repeated endurance of such loads. The solution of such a problem requires a separate theoretical and experimental approach.

But due to the fact that the preparation and conduct of experimental studies of short-term dynamic loading is a complex task that requires the use of special equipment and significant material expenses, it is necessary to obtain numerical solutions, and experimentally confirm the results of calculations only by reference points of correlation.

The purpose of this study is to conduct a numerical and experimental investigation of the deflection of conventional and strengthened reinforced concrete structures under short-term dynamic loading [20], [21], [22].

2. MATERIALS AND METHODS

In the course of experimental studies, two tests were conducted. First, the bending reinforced concrete element was tested for short-term dynamic loading, then it was strengthened with a reinforced concrete element and re-tested with similar loading parameters.

The design of the prototype had the following characteristics: length – 2.0 m, design span – 1.8 m, cross-section dimensions – 90*180 mm, reinforcement in the form of a space frame with four principal reinforcing bars of class A400 with a diameter of 10 mm, transverse reinforcement wire of class B500 with a diameter of 3 mm (step – 100 mm in the support zone and 150 mm in the span), heavy aggregate concrete of class B25.

After strengthening, the structure had the following parameters: length – 2.0 m, design span – 1.8 m, cross-section dimensions – 240*150 mm (the thickness of the cage – 30 mm), reinforcement of the cage – 4 bars of class A400 with a diameter of 10 mm, cross-reinforcement of the cage-wire of class B500 with a diameter of 3 mm (step – 100 mm along the entire length), heavy aggregate concrete of class B25. The designs of both elements are shown in Figure 1.

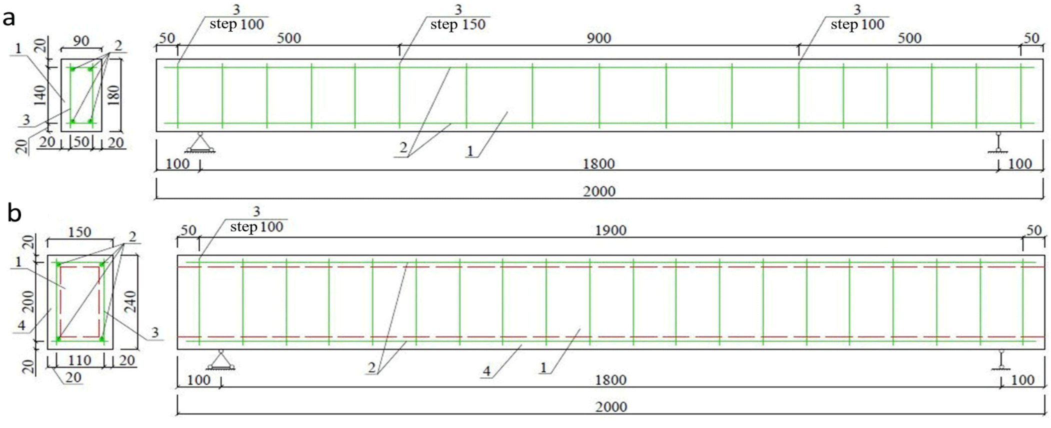

Fig. 1 – Construction: a) conventional bending element; b) cage-reinforced bending element; 1 – concrete B25; 2 – longitudinal reinforcement Ø10 A400; 3 – transverse reinforcement Ø3 B500; 4 – concrete reinforcement B25

The conditions for fixing both elements were the same – hinged supports on both sides, the single-span design. Both tests were carried out on the effect of short-term dynamic loading using a drilling rig.

The load on the sample in both cases was created by a weight of 430 kg falling from a height of 500 mm. The model and implementation of the stand for conducting experimental studies are shown in Figure 2.

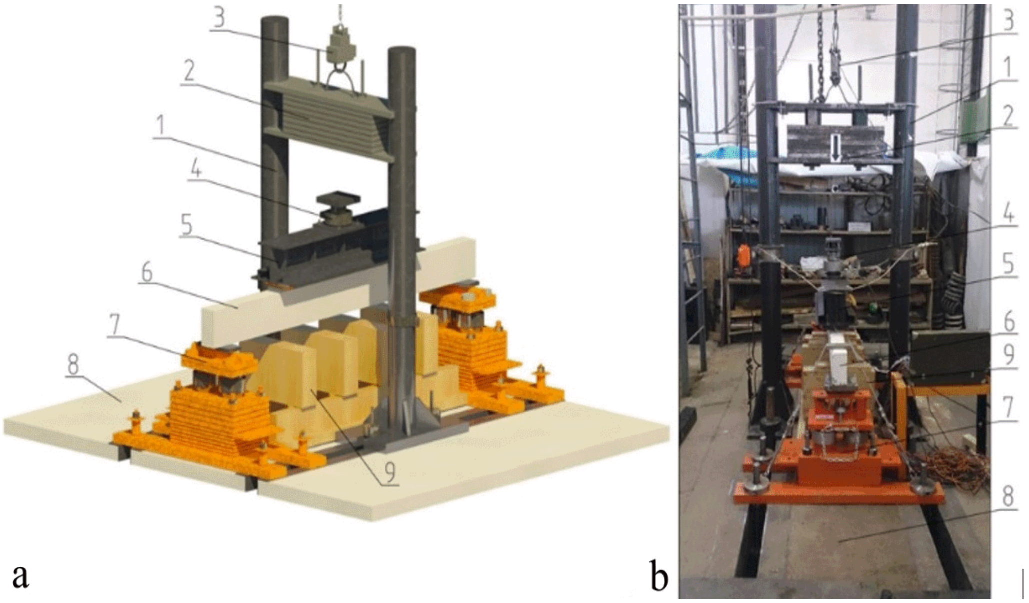

Fig. 2 – General view of the test stand: a) model; b) implementation; 1 – impact drop installation; 2 – cargo weighing 430 kg; 3 – release mechanism; 4 – dynamometer; 5 – distribution transverse; 6 – experimental sample; 7 – support; 8 – power floor; 9 – safety device

During both tests, the effective load in the middle of the span and the deflections of the sample at five points evenly distributed along the length were recorded in the same way over time. To obtain data on the loading, a force-measuring sensor of the strain-resistant type DST4126 (static load up to 200 tons) was used.

The sensor was installed in the middle of the sample span on a metal distribution beam. The traverse served to ensure the transfer of the load to the sample in the quarters of the span. To increase the time of the load on the sensor, a set of rubber gaskets was installed on top.

To obtain the deflection values of the studied element, the WayCon RL150-G-SR deflection indicators were installed. In total, five deflection indicators were installed along the length (one in the centre and four more symmetrically to the sides with a step of 300 mm) [23], [24], [25], [26], [27].

The sensor readings were recorded by certified measuring systems MIC-300m and MIC-036r with a frequency of 1,551 Hz.

All sensors were connected via cables that were protected from interference, which contributed to the accuracy of measurements and synchronisation of the readings of all sensors in time.

The assembled representation of the devices and sensors is shown in Figure 3. The registered source signals from all sensors were converted to the .xls format (Microsoft Excel) and the results were processed.

As a result, graphs of the dependence of the force and deflections on time were constructed.

The deflection graphs in this paper are given for the midpoint along the length of the sample. The graph of the dependence of the effective force on time is shown in Figure 4 [28], [29], [30], [31].

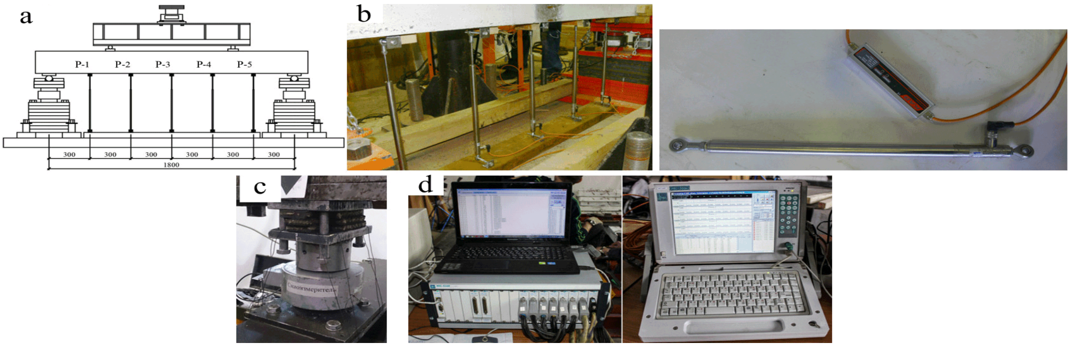

Fig. 3 – Devices used: a) the layout of the deflection indicators; b) the WayCon RL150-G-SR deflection indicators; c) the DST4126 dynamometer; d) the MIC-036r and MIC-300m measuring systems

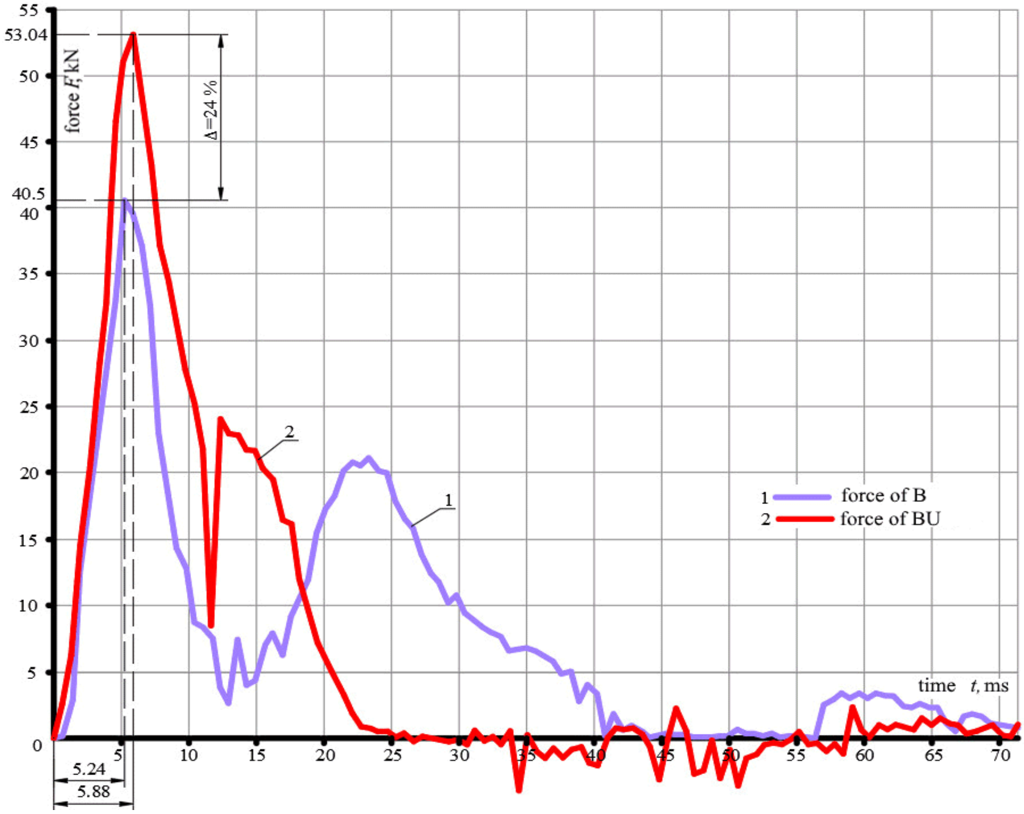

Fig. 4 – Graph of the change in the effective force over time: 1 – for a conventional bendable element; 2 – for a cage-reinforced bendable element

3. RESULTS AND DISCUSSIONS

Experimental studies. The analysis of the graphs showed that the maximum load perceived by the reinforced element compared to the conventional one increased by 24% (40.5 kN and 53.04 kN, respectively); the loading interval for the conventional element was 41 ms, and for the reinforced element – 26 ms (37% deviation).

According to the graphs of the effective force, it can be seen that the behaviour of the strengthened element is more rigid in comparison with the conventional one.

The analysis of the deflection graphs of both elements in the places of force application from time (Figure 5) showed: the maximum deflection value for a conventional element is 37.31 mm, and for a strengthened element – 12.29 mm (deviation of 67%); the time to reach the maximum deflection for a conventional element is 23.85 ms, and for a reinforced element – 7.73 ms (deviation of 67%); on the graph for a conventional element, the peak has fewer edges and stretched in time, and for a reinforced element it is edgier.

As a consequence of the above, it can be concluded that a conventional element is more energy-intensive compared to a cage reinforced, the process of its deformation takes longer, the deflection value is higher and less load is required to achieve it.

Thus, a conventional element is less prone to brittle destruction than a reinforced one [32], [33], [34], [35].

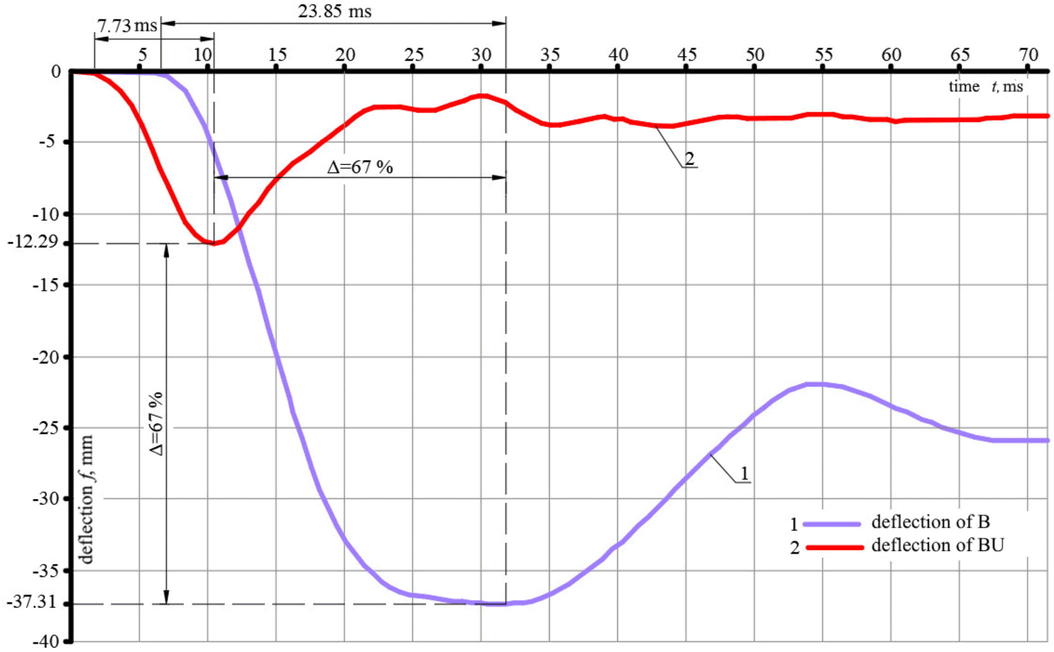

Fig. 5 – Graph of changes in the sample deflections in the middle of the span over time: 1 – for a conventional bendable element; 2 – for a cage-reinforced bendable element

Numerical studies. Next, in the environment of the Ansys software package, the same tests of conventional and cage-strengthened reinforced concrete elements under the action of short-term dynamic load were simulated.

The programme of numerical studies involved the modelling and calculation of three variants of structures. The first calculation option was performed for a conventional bendable element (B marking).

The second calculation option included bendable element strengthened with a reinforced concrete cage (BU marking). The third option assumed the calculation of the reinforced element with the existing cracks in the concrete of the sample before the reinforcement (BUT marking).

The geometric dimensions of the calculated models were assumed to be the same as for experimental studies (Figure 6). The calculations were carried out in the explicit dynamics module.

The concrete of the sample and the cage was modelled using hexahedral elements, which are eight-noded finite elements of regular and irregular shapes.

The elements of the longitudinal and transverse reinforcement of the sample and the cage were modelled using linear two-noded beam elements.

Cracks in concrete were modelled by removing the final elements of their design in the zone of pure bending.

The pitch of the cracks was 100 mm, the height of the cracks was 120 mm. The width of the cracks is conventionally assumed to be 3 mm. The sample models are shown in Figure 7.

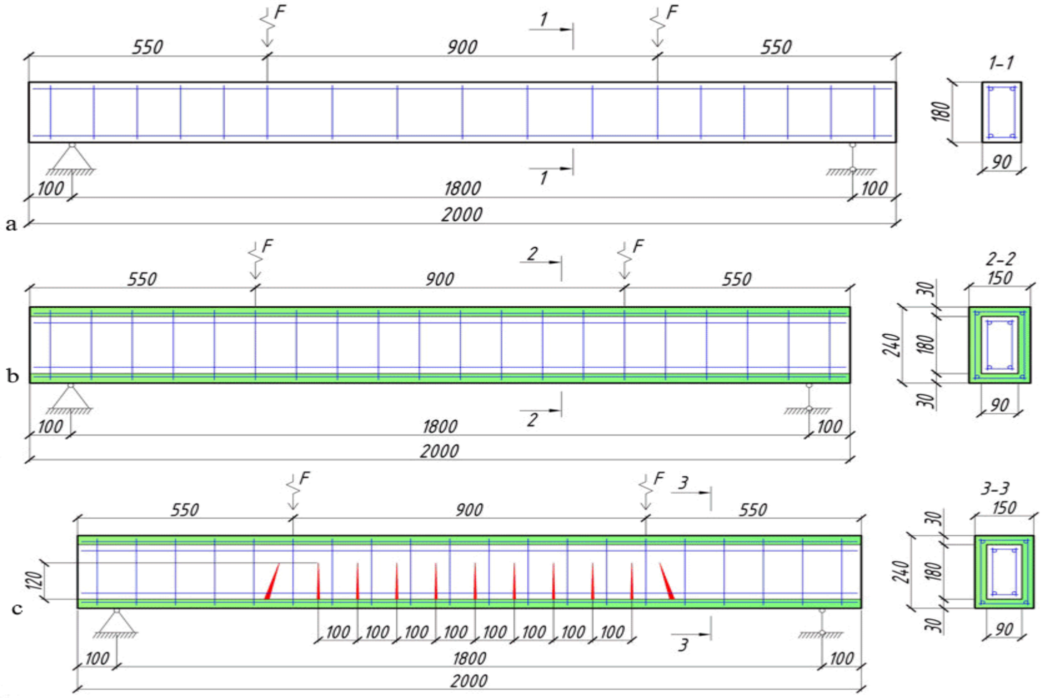

Fig. 6 – Diagrams of samples for numerical studies: a – ordinary bendable element; b – cage-reinforced bendable element; c – cage-reinforced bendable element with cracks

The model of the sample with the B marking contained 1,206 hexagonal eight-noded bulk elements, as well as 502 linear two-noded beam elements, the total number of nodes was 2,980 pcs. The model of the sample with the BU marking contained 2,680 hexagonal eight-noded volumetric elements, as well as 1,206 linear two-noded beam elements, the total number of nodes was 7,464 pcs.

The model of the sample with the BUT marking contained 3,958 hexagonal eight-noded bulk elements, as well as 1,206 linear two-noded beam elements, the total number of nodes was 9,508 pcs.

For the contact of reinforcement and concrete, the type of interaction "reinforcement type" was set. This type of interaction of bodies assumed that all linear bodies bounded by an object are transformed into discrete reinforcement.

For the contact of the concrete and the cage, the type of interaction "bonded type" was set. The supports were modelled by absolutely rigid bodies of semicircular cross-section at a distance of 100 mm from each edge of the sample (similar to the experiment). A hinged support was implemented [36], [37].

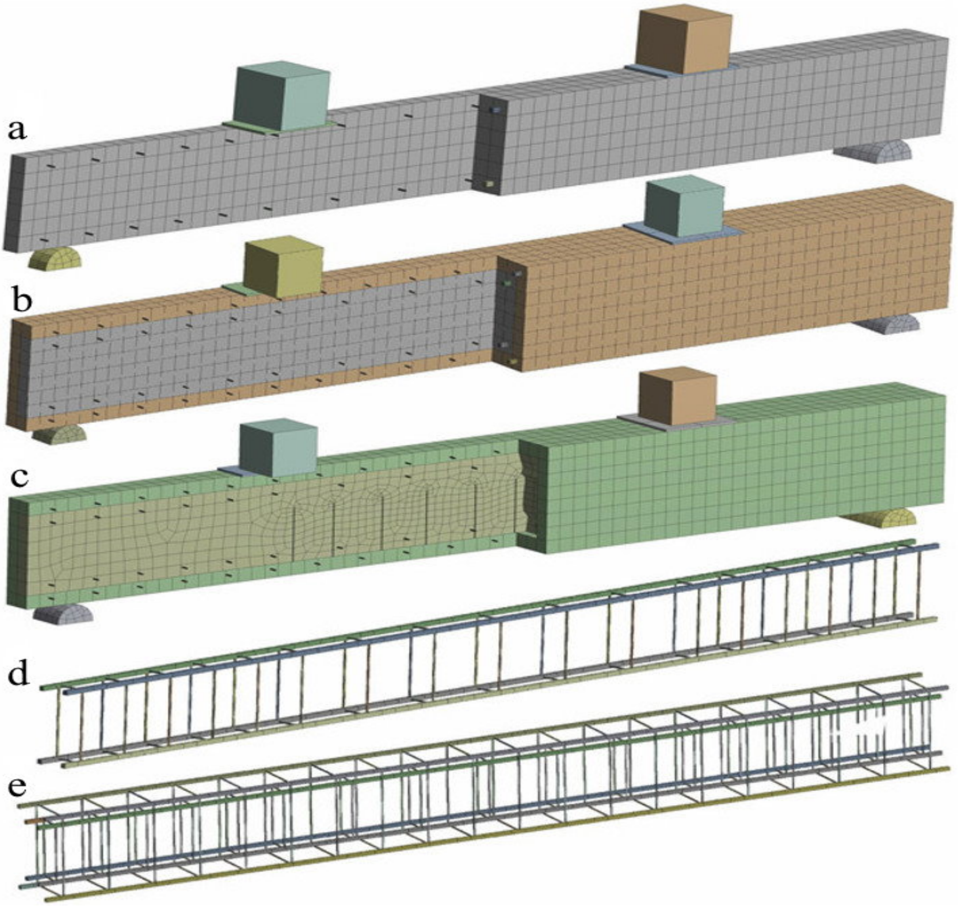

Fig. 7 – Sample models: a – ordinary bendable element; b – cage-reinforced bendable element; c – cage-reinforced bendable element with cracks; d – model of the frame of an ordinary sample; e – model of the frames of reinforced samples

The load on the sample was modelled similarly to a physical experiment – that is, it was equivalent to a weight of 430 kg falling on it from a height of 500 mm.

A minor difference was the exclusion from the models of the distribution traverse on top of the samples, in numerical studies, the load was applied at two points in the quarters of the sample span.

The cubes transmitting the load to the beam had a velocity of 3.15 m/s at the moment of contact with the metal plates (similar velocities were obtained in a physical experiment). The drop test function of the software was used to simulate loading.

The cubes and metal plates themselves had the property of absolutely rigid bodies. The following material models were used.

The model of the CONC-35MPA material from the software library [38], [39], [40], [41] was used as the basis for the concrete material of the sample and the reinforcement. The Structural steel material from the software library was used as the basis for the reinforcement bodies of the sample and the reinforcement.

The calculations were carried out in the Lagrangian formulation, the counting time was 70 ms, similar to the load action time obtained experimentally. The overall schematic of the model is shown in Figure 8.

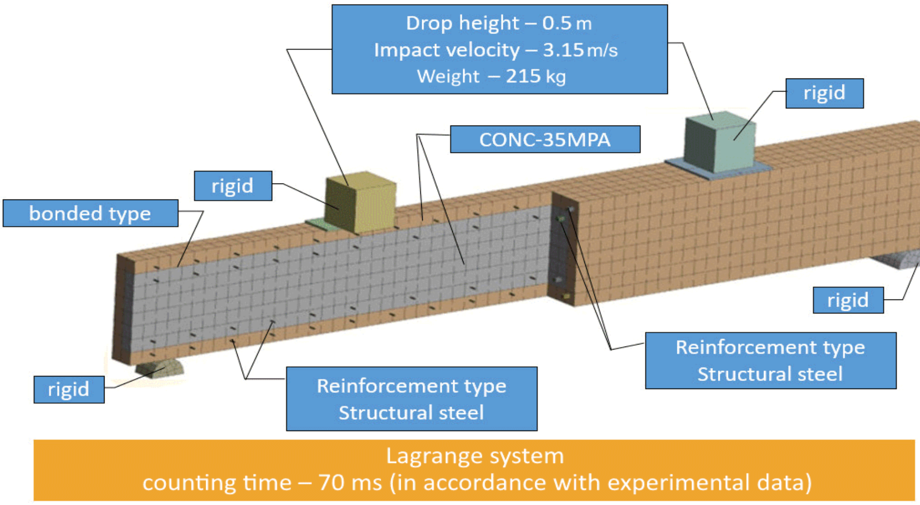

Fig. 8 – Overall schematic of the model

As a result of the performed calculations, the isofields of displacements of samples of all types (B, BU, BUT) were obtained. Figure 9 shows the isofields of the movements of the samples at the time they reach the maximum deflection.

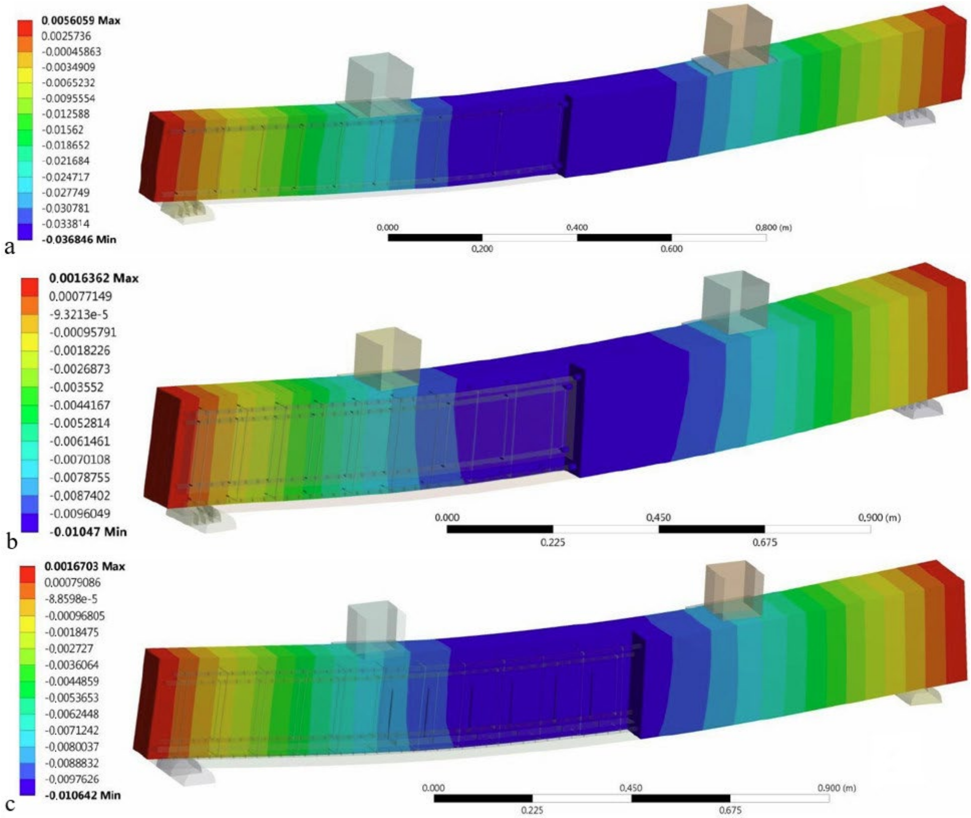

Fig. 9 – Isofield of movements of samples along the z-axis at the moment of reaching their maximum deflection: a – ordinary bendable element (18.2 ms); b – cage-reinforced bendable element (6.16 ms); c – cage-reinforced bendable element with cracks (6.02 ms)

The graphs of the development of deflections over time for all three variants of the samples (B, BU, BUT) were combined on the same coordination axes and are shown in Figure 10.

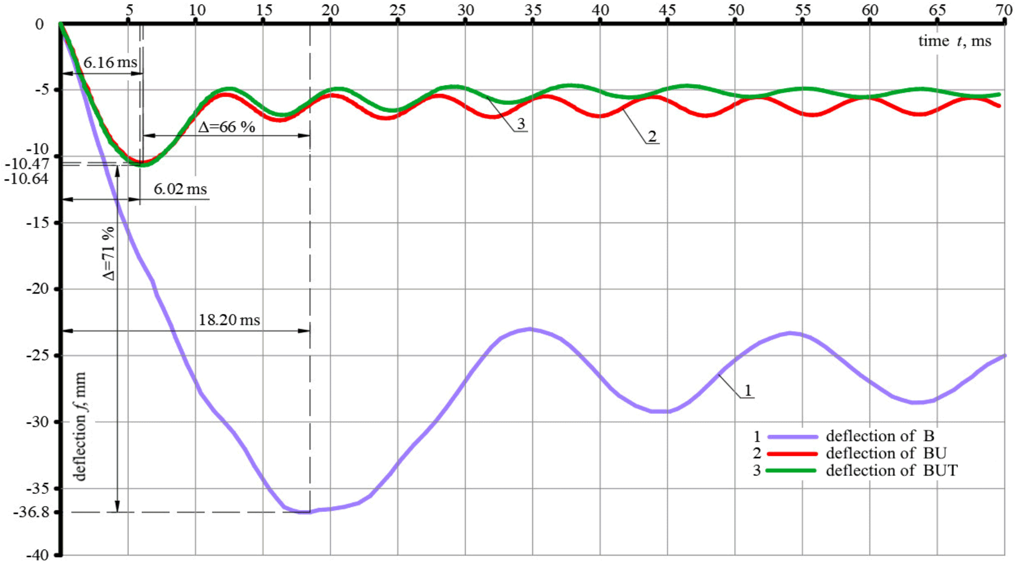

Fig. 10 – The development of deflections of samples over time: 1 – conventional bendable element (B); 2 – cage-reinforced bendable element (BU); 3 – cage-reinforced bendable element with cracks (BUT)

The analysis of the deflection graphs obtained from the results of numerical calculations in the Ansys software showed the following:

– the maximum deflection of the conventional sample (B) was 36.8 mm;

– the maximum deflection of the reinforced sample (BU) was 10.47 mm;

– the maximum deflection of the reinforced sample with cracks was 10.64 mm;

– the time to reach the maximum deflection for sample B – 18.2 ms;

– the time to reach the maximum deflection for the BU sample – 6.16 ms;

– the time to reach the maximum deflection for the BUT sample – 6.02 ms;

– the deviations in the maximum deflection values for conventional and reinforced samples were 71%, and the deviation in the time of reaching the maximum deflection was 66%.

The results of the calculation showed that for models of reinforced elements with and without cracks, the deviations in the maximum values and the time of their achievement were not significant and amounted to less than 3%. As a result of the performed physical and numerical studies, a comparative analysis of the resulting characteristics of the deflections of the samples under the action of short-term dynamic loading was performed (Table 1).

Table 1 – Results of comparative data analysis

Marking of the sample	Results of numerical studies in the Explicit Dynamics module of the Ansys software package	Results of experimental studies	Deviations in %
Maximum deflection value, mm			
B	36.8	37.31	1.36
BU	10.47	12.29	14.8
BUT	10.64	12.29	13.4
Time to reach the maximum deflection value, ms			
B	18.2	23.85	23.7

BU	6.16	7.73	20.3
BUT	6.02	7.73	22.12

Table 1 shows that the deviations of the results of numerical calculations from the experimental data for the maximum deflection do not exceed 15%, and for the time of its achievement – 25%, which is a satisfactory result when analysing the operation of a reinforced concrete structure under the action of a short-term dynamic loading. Notably, the maximum deflections obtained as a result of calculations were less than in experimental studies. Therefore, it is necessary to make some adjustments to the material model, for example, to vary the value of the elastic modulus, but in general, the calculation results are acceptable [42], [43], [44], [45], [46], [47], [48], [49], [50].

4. CONCLUSIONS

The possibility of using the calculation apparatus of the Ansys Explicit Dynamics complex to obtain deflections of reinforced concrete beams under short-term dynamic loading has been established by numerical and experimental studies. As a result of the performed calculations, the isofields of displacements of samples of all types (B, BU, BUT) were obtained.

On the examples of specific physical tests for short-term dynamic load and numerical calculations, a satisfactory convergence of the results on deflections was obtained. The results of the calculation showed that for models of reinforced elements with and without cracks, the deviations in the maximum values and the time of their achievement were not significant and amounted to less than 3%. As a result of the performed physical and numerical studies, a comparative analysis of the resulting characteristics of the deflections of the samples under the action of short-term dynamic loadings was carried out.

Deviations in the values of the maximum deflection were no more than 15%, and in the time of its achievement – no more than 25%. Notably, the maximum deflections obtained as a result of calculations were less than in experimental studies. Therefore, it is necessary to make some adjustments to the material model, for example, to vary the value of the elastic modulus, but in general, the results of the calculations are acceptable.

The results of numerical calculations of the deflections of reinforced concrete elements under short-term dynamic loading can be used to assess the survivability of building structures based on the survivability coefficient. It can be useful, for example, when assessing the effectiveness of systems on pliable supports to mitigate the dynamic impact on the reinforced concrete structures of buildings of ground space infrastructure under seismic, emergency shock or explosive loads. The development of these studies should be experimental and numerical studies of the deflections of bendable reinforced concrete elements that perceive short-term dynamic loads, with varying stiffness characteristics (classes of concrete and reinforcement, cross-section sizes, etc.) of samples.

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