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Experimental justification of the dynamic coefficient

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Abstract. Important part of the structural robustness analysis is the time period during which the elements of the bearing structure are destroyed. The researches show that the shorter the time of a failure of a particular rod is, the greater the dynamic forces in structure. In this article the problem of the experimental definition of the time lapse is considered. Solution of this problem will allow to justify failure time of the tension and compressed structural elements and to confirm the values of the dynamic coefficient experimentally. To solve this problem, a series of experimental studies of square solid rods was done. During the experiment, some of the rods were tensioned to destruction, others were centrally compressed until the load capacity was exhausted due to loss of stability. The experiment was carried out and funded by the Center of shared usage of equipment NRU MSUCE. Due to the obtained data on deformation mode of the tested rods (after their loss of stability and strength), time of failure can be calculated. An analysis of the obtained experimental data showed that for the tension elements, the average failure time was 0.37 sec. For compressed rods the operating time of the rod after the loss of stability depends on the flexibility and has an average value from 1 to 4 seconds. The obtained results make it possible to assign reasonable failure time of the bars of truss for making the correct dynamic calculation.

1. Introduction

An important problem of modern engineering is to ensure the robustness of construction and resistance to progressive collapse of buildings and structures. In the Russian regulatory documents, several options for determining the term "robustness" are given in GOST 27.002-89 "Industrial product dependability. General concepts. Terms and definitions " [1]: **Robustness** – 1) the property of the object, consisting in its ability to withstand the development of critical failures and damages with the established system of maintenance operations and repair; 2) the property of the object to preserve limited operational integrity under impacts not provided for in the application conditions; 3) the property of the object to preserve limited operational integrity in case of defects, damages of a certain type or failure of some components. In the Russian codes of practices this term does not occur, but there is a great number of scientific publications reflecting the subject of robustness of such authors as N P Abovskiy, G I Shapiro, V I Travush, A V Perelmuter, P G Eremeev, B S Rastorguev, Y I Kudishin, V O Almazov etc. [2-12].

Among foreign authors dealing with the development of the topic of structure robustness are B Crowder, J Crawford, J Gilmour, U Starossek, T Canisius, B Ellingwood, etc. [13-18]. The term "robustness" is widely used in building codes of Europe, the USA, Great Britain and other countries. According to Eurocode EN 1991-1-7 "Actions on structures. General actions - Accidental actions" robustness – the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause [19]. To ensure this property, most of the building codes [20-24] prescribe to consider different variants of damage load-bearing framework. Structural analysis of damaged construction can be done in two versions: static analysis with multiplying the actual loading by the dynamic coefficient, or dynamic analysis.

A significant influence on the value of the dynamic coefficient is due to the failure time of the element or the time of elimination (Δt). Under the time of elimination of the element Δt we agree to understand the time interval for which the element loses its strength or stability, is excluded from the system operation and cannot further ensure the reliability and integrity of the structure. Depending on the cause of damage to the element (fire, corrosion, defect in the manufacture or installation of the structure, etc.), the time of failure will also differ. This report does not address the causes of damage, but examines the failure time of the tension and compressed structural elements and its effect on the dynamic factors of the load applied to the damaged structure.

The dynamic analysis show that with decreasing Δt, the forces in the damaged structure increase and, consequently, the value of the dynamic coefficient increases. Calculations were made for a flat long-span farm with different variants of damaged elements. The truss belts were made of rolled I-bars, a truss members - of square pipes. Figure 1 shows the graphs of the change in the dynamic coefficient (y-axis) relative to the failure time of the element (the x-axis). Color lines indicate changes in the value of the dynamic coefficient for various elements of a damaged farm: the lower and upper belts, the truss members. As can be seen, the shorter the failure time of the element Δt, the greater the dynamic coefficient. If the elements of the belts and the support brace are damaged (green, purple and pink lines on the graph), the dynamic coefficient value reaches 1.75-1.85, for damages of the truss members (blue and blue lines), these values are lower: 1.6-1.5. However, with an increase of Δt to 2 s, the value of the dynamic coefficient decreases by 20-40% for all variants of damage.

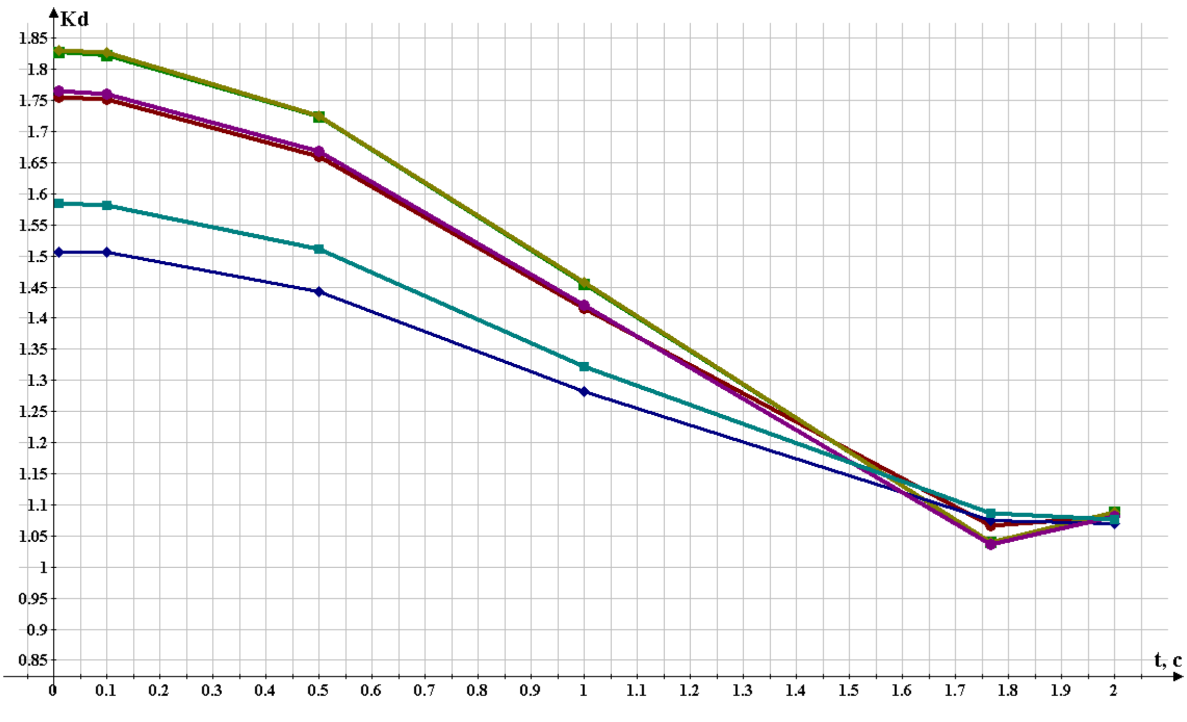

Figure 1. Graphs of the change in the dynamic coefficient (y-axis) relative to the failure time of the element (the x-axis)

2. Experimentation

For the experimental justification of Δt a series of experimental studies of tension rods and compressed rods were done. The research was aimed at obtaining data on the operation of the rods after the beginning of destruction (for stretched rods) or loss of stability (for compressed rods). The obtained results allow to determine the time of failure of damaged rods.

For the experiment were chosen square solid rods according to GOST 2591-2006 [25]. Three samples were tested for stretching, and four samples for compression (Figure 2).

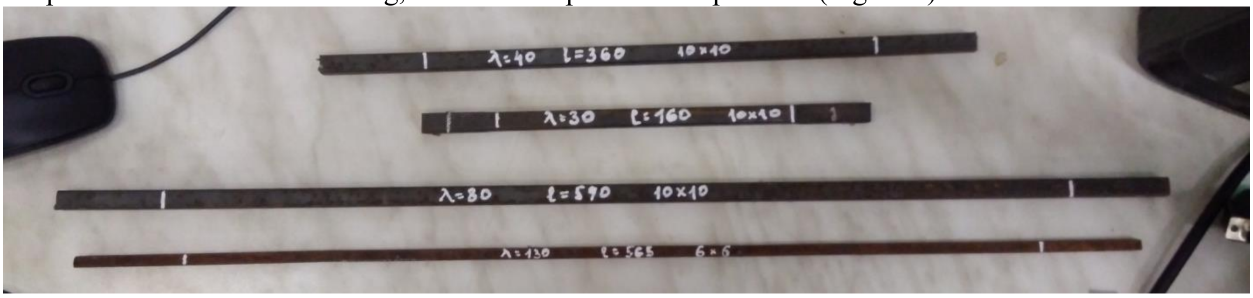

Figure 2 a. Compression test specimens

Figure 2 b. Tensile test specimens

Samples for stretch test had a cross-section 8x8mm. The rod was attenuated by a "V"-shaped notch on two opposite sides (Figure 3). Concentrators were arranged with a device used in the testing of steel for impact strength. This allowed to simulate the most unfavorable process of destruction without the development of plastic deformations.

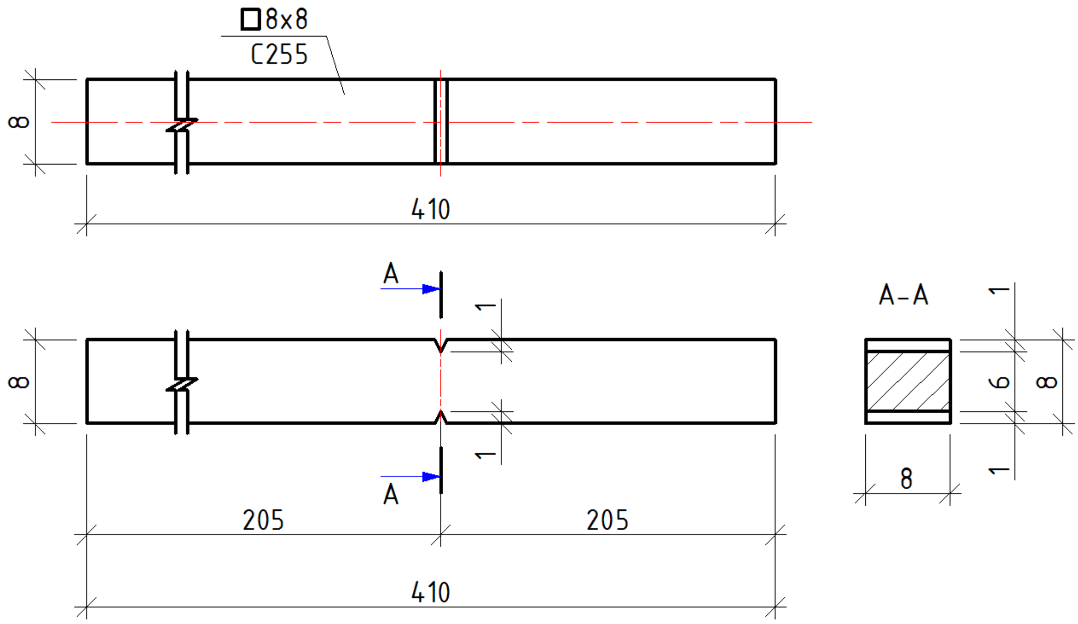

Figure 3. The scheme of the location of the V-shaped notch

For compression, four samples with different cross sections and flexibility were tested. The parameters of centrally compressed samples are presented in Table 1.

Table 1. The parameters of centrally compressed samples

	1 sample	2 sample	3 sample	4 sample
Length, mm	160	250	480	455
Cross-section, mm	10x10	10x10	10x10	6x6
Flexibility, λ	30	40	80	130
Steel grade	C255	C255	C255	C255

The tensile test specimens are made of unalloyed structural steel of ordinary quality type VSt5sp. Steel VSt5sp refers to medium-carbon steels (carbon content 0.28-0.37%) with a relative yield line, ultimate tensile strength σ_B = 620MPa, yield point $\sigma_{0.2}$ = 570MPa. According to international standards ISO 630:1995 and ISO 1052:1982, this steel corresponds to the types E-355-C (Fe 510-C) and Fe 490. In figure 4 red line shows the load-extension diagram, obtained from the results of verification tests for determination steel type. Green line is a graph of stress versus deformation for one of the tensile samples with a weakened section. It can be seen that it practically does not have a horizontal segment correspond to plastic response of the steel. Thus, during the tests it was possible to simulate an almost brittle fracture.

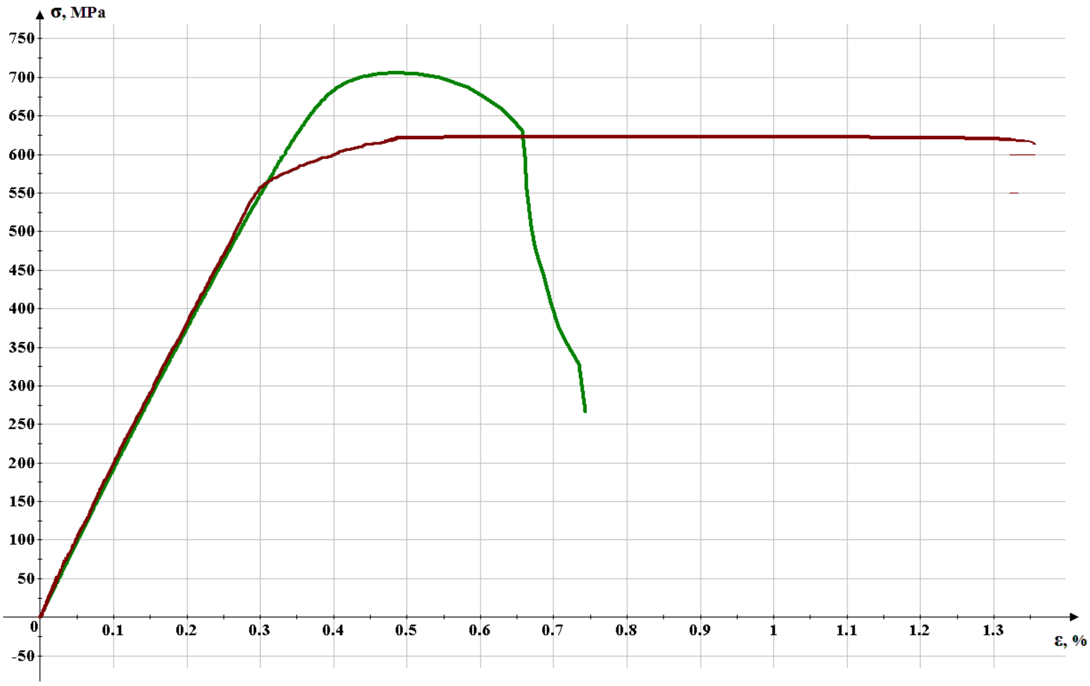

Figure 4. Deformation, % vs. stress, MPa graph (tensile sample)

The compression test specimens are made of unalloyed structural steel of ordinary quality type VSt2kp. The foreign analogue of this steel is USt34-2 steel according to DIN, WNr (Germany). The load-extension diagram, obtained from the results of verification tests for determination steel type, is shown in Figure 5 in red. Ultimate tensile strength σ_B = 320MPa, yield point $\sigma_{0.2}$ = 320MPa. Green line shows the stress-strain curve for a sample for compression with a flexibility of λ = 30. It can be seen that the beginning of the loss of stability of the sample practically coincides with the beginning of the destruction of the rod.

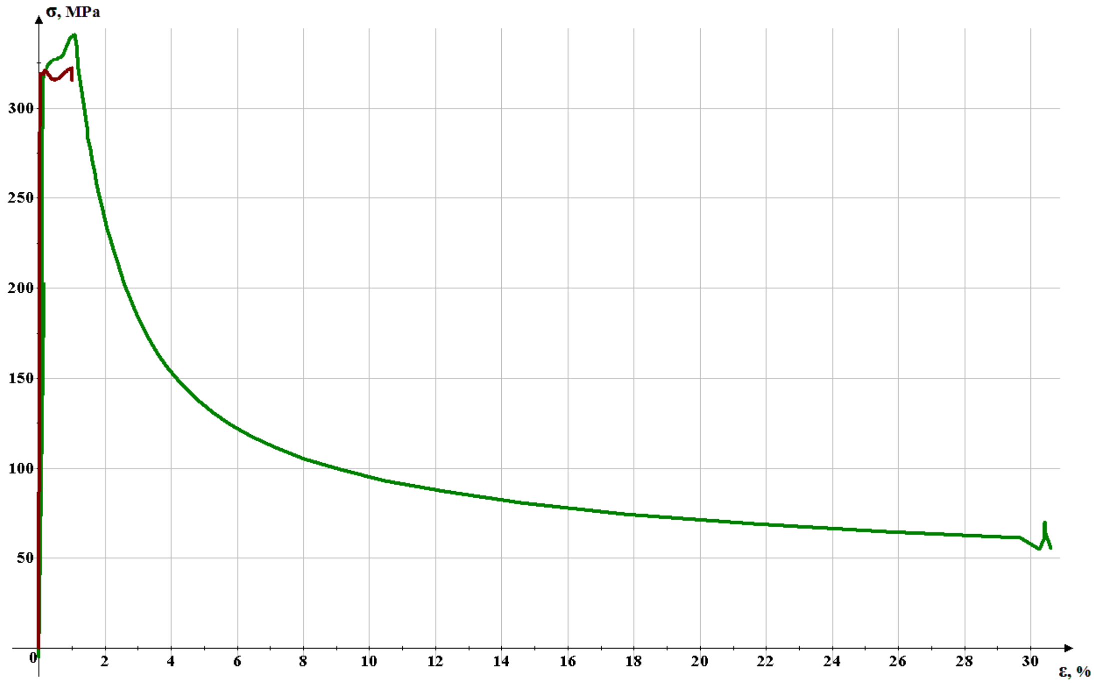

Figure 5. Deformation, % vs. stress, MPa graph (compressed sample)

The experiment was carried out and funded by the Center of shared usage of equipment NRU MSUCE, on a servohydraulic machine for static and dynamic testing (Instron 8802). During the tests movements, deformations and forces for each sample were measured. The choice of test equipment is due to the possibility to change the speed of the load application, which allowed after the exhaustion of the bearing capacity to follow the moving end of the rod and to investigate the process of rod failure.

The conducted experiments were aimed to determine the failure time of the rods from the beginning of the loading to the end of the destruction of the stretched rods or loss of stability of the compressed rods in order to determine the time of elimination.

3. Analysis of experimental results

The failure time of the specimens was determined as follows. A graph of the dependence of the load on displacements was constructed. On the graphs yellow markers indicate the beginning of the destruction of each of the tested rods (Figure 6-7). The marked points correspond to the maximum values of the load perceived by the samples. Further, in the stretched rods, the process of destruction of interatomic bindings begins and complete destruction corresponds to the end of the test. With the elastic behaviour of the material in the structure, the time of transition from the elastic to the plastic stage of the material operation (blue markers in Figure 6) can be taken as the start of exhaustion of the bearing capacity.

In the compressed bars (Figure 7), the yellow marker marks the beginning of the loss of stability. During the entire experiment, the load applied to the sample remains unchanged as long as the sensors fix the "resistance" of the element. Since the beginning of the loss of stability, the value of the load is sharply reduced. The end of the experiment means that the test sample no longer perceives the applied load, the rate of loss of stability has reached critical and the stoppers in the test machine have worked.

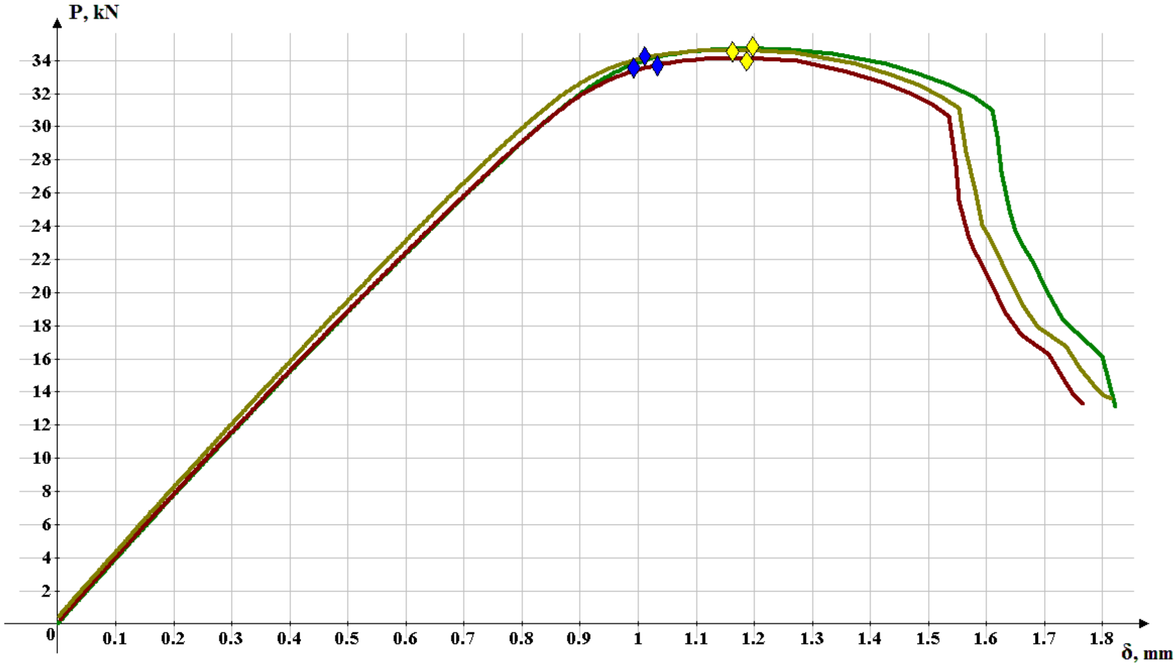

Figure 6. Load vs. displacement graph for stretched samples
Green line - sample number 1; red line - sample number 2; yellow line - sample number 3

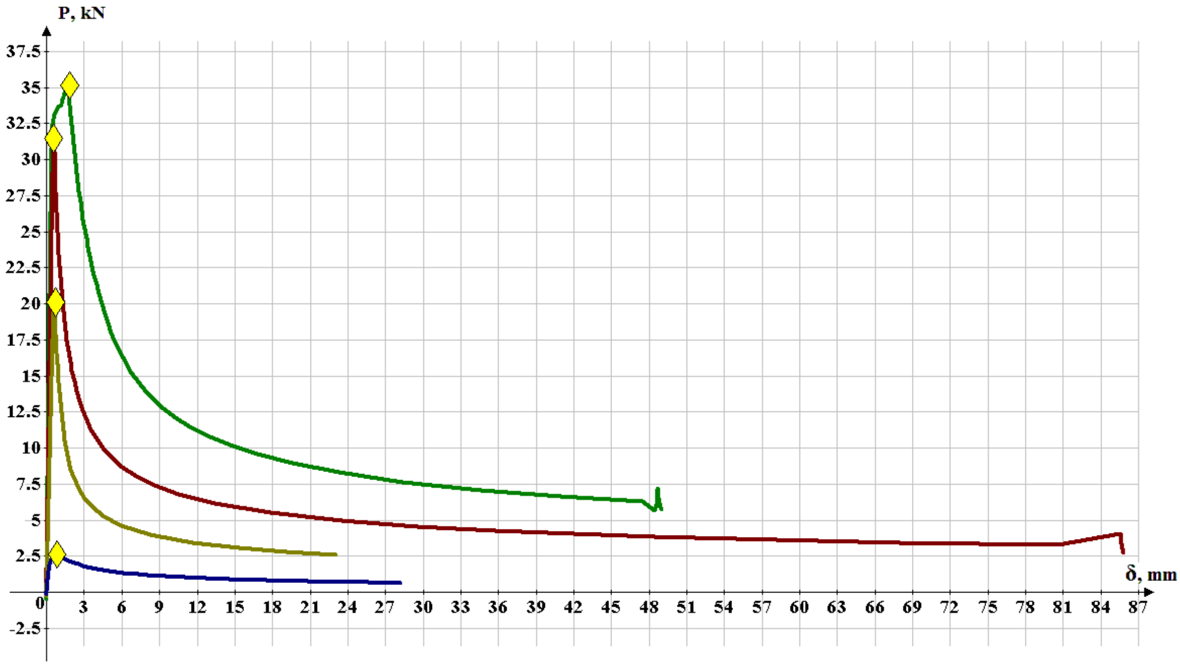

Figure 7. Load vs. displacement graph for compressed samples
Green line - sample number 1, λ=30; red line - sample number 2, λ=40; yellow line - sample number 3, λ=80; blue line – sample number 4, λ=130

Due to the experimental data, intervals Δt corresponding to the time interval from the beginning to the end of the loss of the bearing capacity were found.

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Table 2. Test results for tensile samples

Sample No.	Parameter	The beginning of destruction	The end of destruction	Δ
No 1, 8x8mm, l=410mm	Time, s	69.6	70.029	**0.429**
	Displacement, mm	1.184	1.821	0.637
	Deformation, %	0.483	0.743	0.260
No 2, 8x8mm, l=410mm	Time, s	68.1	68.441	**0.341**
	Displacement, mm	1.178	1.766	0.588
	Deformation, %	0.471	0.706	0.235
No 3, 8x8mm, l=410mm	Time, s	68.7	69.062	**0.362**
	Displacement, mm	1.171	1.815	0.644
	Deformation, %	0.476	0.738	0.262

Table 3. Test results for compressed samples

Sample No.	Parameter	The beginning of destruction	The end of destruction	Δ
No 1, 10x10 mm, l=160 mm, λ=30	Time, s	71.3	72.631	**1.331**
	Displacement, mm	1.707	48.985	47.278
	Deformation, %	1.067	30.615	29.549
No 2, 10x10 mm, l=250 mm, λ=40	Time, s	62.9	64.793	**1.893**
	Displacement, mm	0.597	85.785	85.188
	Deformation, %	0.239	34.314	34.075
No 3, 10x10 mm, l=480 mm, λ=80	Time, s	40.5	41.409	**0.909**
	Displacement, mm	0.629	23.009	22.380
	Deformation, %	0.130	4.7638	4.634
No 4, 6x6 mm, l=455 mm, λ=130	Time, s	6.2	10.394	**4.194**
	Displacement, mm	0.779	28.169	27.389
	Deformation, %	0.174	6.288	6.114

It should be noted that for stretched rods, despite the use of low-carbon steel, failure begins with a very slight development of plastic deformations, which amounted to no more than 15% of deformations of the yield strength. At the same time, with the free development of plastic deformations for C255 steel, destruction occurs when plastic deformations of the yield strength are 100-200 times more than deformations of the yield strength. This confirms that the destruction of stretched rods was practically brittle and the obtained failure time can be used to evaluate the process of destruction of stretched elements in the worst case of damage. An analysis of the experimental data showed that for tensile elements with a constrained development of plastic deformations, the mean failure time was 0.37 sec.

For compressed rods, the operating time of the rod after the loss of stability depends on the flexibility and varies significantly from 1 to 4 seconds. In Table 3, you can see that the failure time increases with increasing flexibility of the rod. The results of the test of sample No. 3 violate the established dependence, which agrees with the laws of mathematical statistics and the Gaussian distribution function. Nevertheless, the received time intervals allow to specify the time of failure of the stretched and compressed elements during the numerical calculation. The increase of the failure time from 0.01 s to 0.37 s (for stretched rods) reduces the magnitude of the dynamic coefficient by

10%, and for compressed rods for a time interval of 1 s to 4 s, the dynamic coefficient decreases by 20-40%.

When examining the behaviour of a damaged farm, as the element is switched off, the stresses from the damaged element are redistributed to neighboring rods. Therefore, during the analysis, it should be noted that the time for a complete redistribution of stresses may be less than the failure time of a single element. In the future it is planned to continue the investigation of the time of destruction of single elements and in the structure of the farm and carry out a series of experiments with rods of different sections, compare the results for different steel types, etc.

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