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Bearing Capacity of Steel Trusses with Local Damage Considering the Exclusion Time

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Abstract: To ensure the safety of buildings and structures, they must maintain their bearing capacity in case of local damage. The article is devoted to the study of the robustness of damaged steel trusses, as well as the time during which local destruction of the trusses occurs. Finding a solution to this problem is one of the key stages in the development of a practical methodology for calculating steel trusses' resistance to the local destruction of elements. The time from the beginning of destruction to the complete failure of the element is proposed to be called the exclusion time. Based on the performed theoretical and numerical studies, for the quasi-static calculation it is recommended to use the values of the dynamic coefficient for the considered steel trusses. In the numerical formulation, the work of steel trusses as part of the building frame was investigated along with local destruction of individual elements of the truss. Numerical studies have shown that the shorter the failure time of the truss element, the greater the dynamic forces arising in the structure. The frame of the building is considered as a spatial system. A numerical dynamic analysis of the spatial coverage is carried out, taking into account the local failure of one of the truss elements. The distribution of the dynamic coefficient over the steel trusses is obtained. This made it possible to study the effect of local failure on the intact load-bearing structures. The article presents the results of a series of experimental studies of flat trusses aimed at determining the time of failure of a steel truss element. Based on the results obtained, the failure time of the damaged rod and the redistribution of efforts to the neighboring elements of the truss were calculated. In accordance with the calculated failure time, recommendations were formulated to reduce the value of the dynamic coefficient used in the static calculation, depending on the types of damage to the truss.

Keywords: the exclusion time; damaged steel truss; robustness; dynamic coefficient; progressive collapse

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1. Introduction

The issues associated with ensuring the safety of buildings and structures, including the protection of structures from progressive collapse, are one of the most relevant areas of research; regulatory documents and scientific research devoted to the topic of building resistance to progressive collapse are rapidly being supplemented and changed. Many publications [1–14] are devoted to the study of structural robustness and resistance of buildings and structures to progressive collapse. A review of the conducted studies demonstrated the presence of a large number of different numerical and theoretical methods for calculating structural robustness. A different period of publications shows that the problem has retained its relevance for many years.

A study of the regulatory documents of different countries showed that the definition and regulation of emergency impacts are similar in all reviewed documents. The building codes of different countries formulate general design requirements aimed at preventing progressive collapse in case of local damage [15–20]. The cause of progressive collapse can be not only an unfavorable external effect that was not foreseen in the design, but also changes in operating conditions, defects and damage to structures, errors in design, manufacture or installation, etc. A structural failure associated with the local destruction of one element, in the event of its insufficient survivability, can lead to the collapse of the entire structure, as well as the subsequent collapse of several adjacent structures. If the structure has sufficient robustness, local destruction does not lead to its collapse, which will ensure the safe evacuation of people.

To ensure resistance to the progressive collapse of buildings, additional studies are needed that take into account the characteristics of the damaged frame of a particular building. A significant part of the ongoing research is devoted to the problem of protecting high-rise buildings with a steel or reinforced concrete frame from progressive collapse. The bearing capacity of damaged steel frames of industrial buildings has been studied to a lesser extent, despite the fact that the destruction of industrial buildings also leads to significant social, environmental and material losses. Experimental studies have shown the effectiveness of the use of models of various designs, which were tested with the loss of the bearing capacity of individual elements.

This study is devoted to the problem of ensuring the robustness of steel trusses of industrial buildings. Within the framework of the article, the term "exclusion time" is used. It denotes the time from the beginning of destruction to the final failure of the element. Previous studies have shown that the time it takes to exclude an element from the system has a significant impact on the distribution and amount of forces in the structure. Considering the revealed features of the damaged structures operation, it is of considerable interest to study the influence of the exclusion time on the efforts in the trusses.

2. Materials and Methods

2.1. Theoretical Calculation

When studying how to protect buildings from progressive collapse, one of the important stages is the development of theoretical methods for calculating structures with local destruction.

For beams, the theoretical value of the dynamic coefficient can be determined by considering simple beam structures. Figures 1 and 2 show a continuous two-span beam loaded with point load P in the middle of each span.

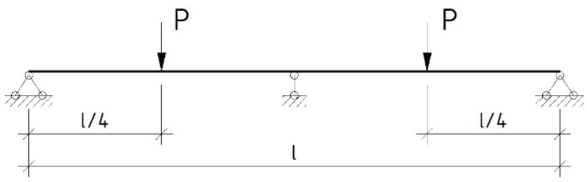

Figure 1. Continuous beam loaded with point load in the middle of each span. Intact structure.

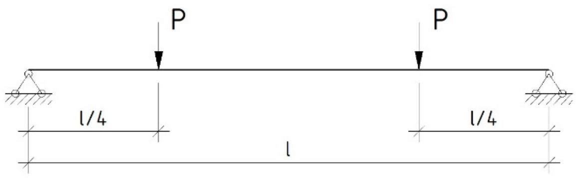

Figure 2. Continuous beam loaded with point load in the middle of each span. Damaged structure—middle support removed.

The theoretical calculation of a continuous beam was carried out using the energy method. With its use, the dynamic coefficient is determined as follows:

$$k_d = \frac{w_d}{w_c} \tag{1}$$

w_d is the maximum displacement of the system under the action of a dynamic load;

w_c is the maximum displacement of the system caused by the action of a static load.

The energy balance of the system:

$$U_o + A = U_d \tag{2}$$

In Equation (2), U_o is the energy accumulated in a continuous beam with point load P;
A is the work completed when the support is destroyed by the load P;
U_d is the energy accumulated in the beam when the middle support is removed.

The quantities included in Equation (2) are:

$$U_o = \frac{2Pw_0}{2} = Pw_0 \tag{3}$$

$$A = 2P(w_d - w_c) \tag{4}$$

$$U_d = \frac{2P_d w_d}{2} = \frac{2cw_d^2}{2} = \frac{2Pw_d^2}{2w_c} = \frac{Pw_d^2}{w_c} \tag{5}$$

In Equation (3). w_0 is deflection of the beam under each of the concentrated loads in an intact structure;
In Equation (5) P_d is dynamic load;
w_d is dynamic deflection of the beam at the points of concentrated loads, measured from the straight axis of the beam.

In addition, in Equation (5) the following equations described by Belyaev [21] are considered:

$$P = cw_c;\ P_d = cw_d \tag{6}$$

where c is the rigidity of the system (assumed to be the same for static and dynamic loadings).

After performing mathematical transformations, receive a quadratic equation:

$$w_d^2 - 2w_c w_d + w_c w_0 = 0 \tag{7}$$

Considering Equations (2) and (3), find the dynamic deflection as the roots of Equation (7):

$$w_{d1} = 1.9723w_c;\ w_{d2} = 0.02773w_c \tag{8}$$

The second root contradicts the meaning of the problem, therefore, $w_d = w_{d1}$ and the dynamic coefficient:

$$k_d = \frac{w_d}{w_c} = 1.9723 \tag{9}$$

For the theoretical determination of the dynamic coefficient in a damaged truss, consider a truss as a beam. For trusses, which are a structure consisting of several rods, failure of one rod does not lead to the collapse of the structure if the truss rods are designed in consideration of that the damage may occur. To determine the dynamic coefficient, consider the deformation of the truss with local destruction.

Let us denote the moment of inertia of the original truss is I and the moment of inertia of the truss after damage is I_0; thus, the decrease in the moment of inertia of the truss after its damage:

$$\Delta I = I - I_0 \tag{10}$$

Imagine a truss in the form of a conditional beam with the same span and boundary conditions as the truss. Imagine loading the conditional beam in the same way as the truss. After local destruction of the truss rod, the design scheme of the conditional beam would not change but its stiffness will decrease. Due to the decrease in stiffness, the conditional beam could absorb only a part of the acting load without additional deflection. Let us designate this part of the load q_0. With a load q on a conventional beam, the share of the load taken at the expense of the remaining part of the truss would be:

$$q_o = \frac{qI_0}{I} \tag{11}$$

As the rigidity of the truss and the conditional beam was less than the initial one then, for the perception of the full load, the truss must have additionally bent in order to absorb the unbalanced part of the load Δq. The unbalanced proportion of the load taken by the "damaged part" of the truss would be equal to:

$$\Delta q = \frac{q\Delta I}{I} \tag{12}$$

Suppose that after damage, only the proportion of the load Δq caused dynamic effects in the truss, such as an instantaneously applied load, and the dynamic coefficient was greater than one per ratio $\Delta q/q$. Analysis of Equations (11) and (12) allowed us to conclude that the lower the moment of inertia change during damage, the lower the proportion of the load perceived by the "damaged part" of the truss and the dynamic coefficient. In this regard, the highest values of the dynamic coefficient occurred in case of damage to the central panels of the chords; lower dynamic coefficients were expected with damage to the support braces and truss racks, while even lower dynamic coefficients occurred when the middle braces and racks were damaged.

To determine the ratio of the moments of inertia I, I_0, ΔI, the deflections obtained by the static calculation of the original and damaged trusses were used. In this case, the deflections of the truss were proportional to the moments of inertia.

Deflection of the original truss from load q:

$$w = \frac{k}{I} \tag{13}$$

Deflection of the damaged truss from the load q:

$$w_0 = \frac{k}{I_0} \tag{14}$$

The proportionality coefficient k in Equations (13) and (14) depended on the span, load and elastic modulus of the truss material. From Equations (13) and (14), the moments of inertia of the truss were equal:

$$I = \frac{k}{w} \tag{15}$$

$$I_0 = \frac{k}{w_0} \tag{16}$$

$$\Delta I = \frac{k(w_0 - w)}{ww_0} = \frac{I(w_0 - w)}{w_0} U_d = \frac{2P_d w_d}{2} = \frac{2cw_d^2}{2} = \frac{2Pw_d^2}{2w_c} = \frac{Pw_d^2}{w_c} \tag{17}$$

Substituting Equation (17) in Equation (12), we found the proportion of the load acting on the "damaged part" of the truss:

$$\Delta q = \frac{q(w_0 - w)}{w_0} \tag{18}$$

Then the dynamic factor:

$$k_d = 1 + \frac{\Delta q}{q} = 1 + \frac{w_0 - w}{w_0} \tag{19}$$

Using Equations (13) and (14), we obtained the following expression for the dynamic coefficient:

$$k_d = 1 + \frac{\Delta I}{I} \tag{20}$$

2.2. Experimental Research

The experimental research and tests were carried in several past studies [22,23] to compare the results of numerical calculations of structures for resistance to progressive collapse. In this work, experiments were carried out with regard to steel trusses with local damage.

To obtain data on the actual operation of the structure in case of damage, a series of experimental studies were carried out on models of trusses. One of the important tasks conducted during the tests was determining the time of exclusion of an element, taking into account its stress–strain state and location in the structure. The work of models of a flat truss with a damaged element within the upper or lower chord was studied. When analyzing the results of testing truss models, the experimental data obtained while testing the operation of individual compressed and stretched rods were considered [24,25].

Three experiments were carried out to test trusses impacted by local failure of chords to determine the exclusion time for compressed and stretched rods operating as part of a truss:

- In the first experiment, the operation of a truss was investigated, in which the local destruction consisted of the loss of stability of the compressed upper chord of great flexibility;
- In the second, the work of the truss was investigated, with local destruction in the form of a rupture of the stretched lower chord;
- In the third, the work of the truss was investigated, with local destruction of the upper compressed chord due to loss of stability and provoked by defects on the compressed element.

Geometric schemes of trusses and sections of elements are shown in Figures 3 and 4. Dimensions reflected on the drawings are given in mm. Truss elements are made of square steel pipe 60 × 60 × 2 mm, strip steel 80 × 6 mm and a round bar Ø 12 mm.

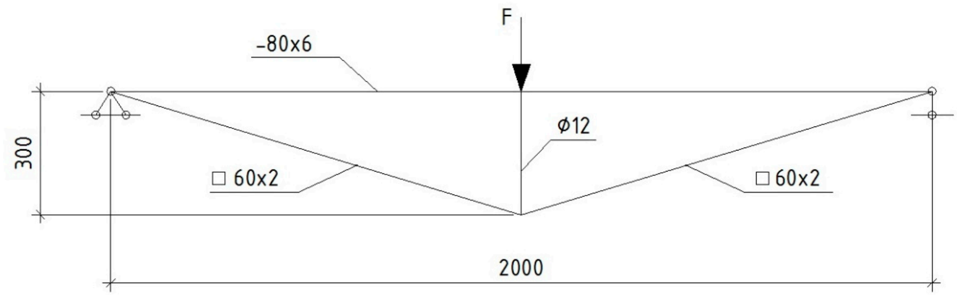

Figure 3. Geometric scheme of truss No. 1 (loss of stability and destruction of the upper chord).

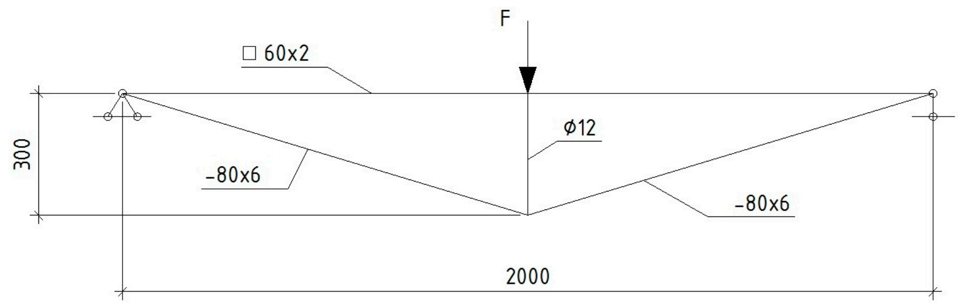

Figure 4. Geometric scheme of truss No. 2 (destruction of the lower chord).

To measure deformations, FLA-5-11 strain gauges with a base of 5 × 1.5 mm and a resistance of 120 Ohm were glued to the truss. Strain gauges were installed in the middle of each element of the upper and lower truss chords on the upper and lower edges. The total number of sensors was 12 pcs. for each truss. Vertical displacements were measured using an inductive linear displacement transducer CDP-25 (rod stroke 0–25 mm) installed in the middle of the span of the upper chord of the truss and secured with a clamp. Additionally, during experiment No. 3 two more inductive linear displacement transducers CDP-25 were placed in the center of each of the panels of the upper chord. The arrangement and numbers of strain gauges and deflection gauges for truss No. 1 are shown in Figure 5. The numbers in brackets refer to the gauges glued to the underside of the element.

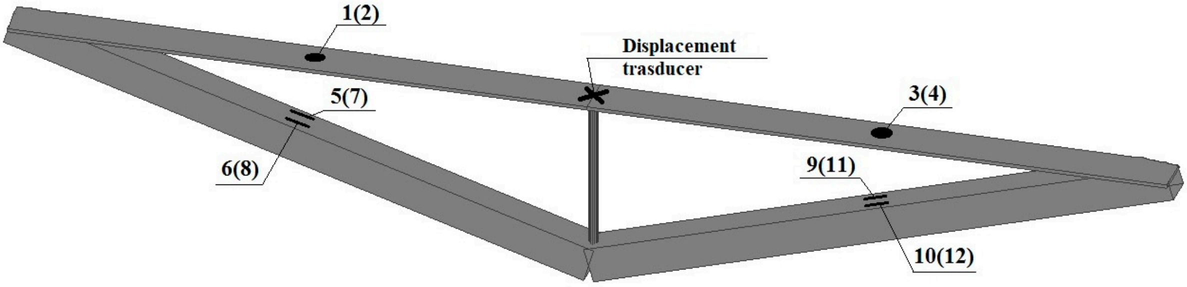

Figure 5. Layout and numbering of sensors on the truss in experiment No. 1.

The load was applied step-by-step by placing weights of 0.2 kN and 0.125 kN on a specially designed cargo platform suspended from the upper chord of the truss. The subsequent stages of loading began after the complete attenuation of the vibrations of the structure of the tested truss caused by the previous stage. The trusses were hinged on stationary inventory supports. Inventory supports were rigidly attached to the power floor of the laboratory. In the support nodes of the trusses, corners with a fixing plate were welded, which prevented the truss from displacing from the support when it was destroyed. The trusses were installed on supports so that there were 5–10 mm gaps between the vertical fixing plates at both ends of the truss (Figure 6).

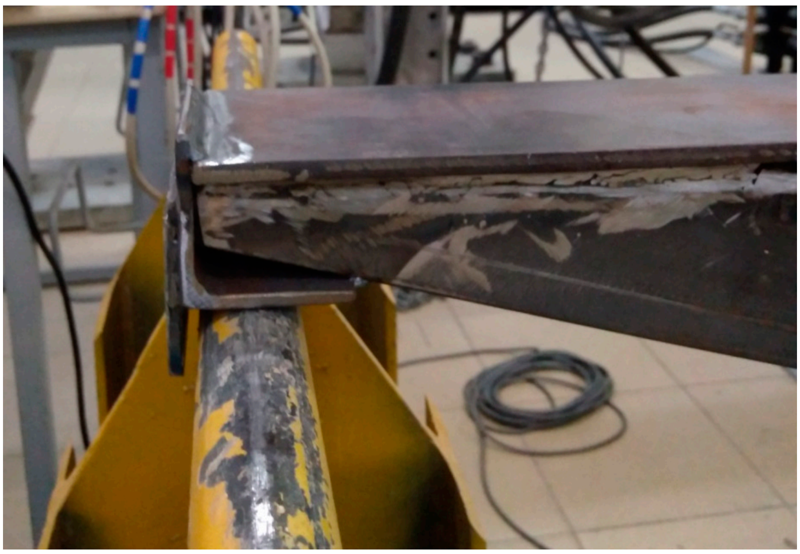

Figure 6. Installing the truss on stationary inventory support.

During the tests, the beginning of the loss of stability of the compressed upper chord (in the first and third experiments) and the beginning of the destruction of the lower chord (in the second experiment) were recorded. The behavior of the truss after buckling or breaking the chord was then studied. Observation of the behavior of a truss, which has local destruction in the form of rods and the bearing capacity of which has been exhausted, made it possible to determine the time interval of the operation of the damaged element in the structure of the truss. This time determined the final failure of the element and was known as the exclusion time Δt.

The test results are given in part 3 of the "Results" section of this article.

2.3. Numerical Calculation

Numerical studies were carried out for flat trusses with spans of 24 m and 78 m and a damaged truss as part of the spatial frame of a large-span building. The point load for a truss with a span of 24 m was P = 32 kN, while for a truss with a span of 78 m it was P = 35 kN. The sections of the truss elements are assigned in such a way that, in case of local destruction of one truss element, the bearing capacity is retained. The calculations were performed using the Femap with NX Nastran, ver. 11.1.0 in a dynamic setting according to the following method:

1. Determining the type of damage to the structure. When choosing options for damage to structures for studying resistance to progressive collapse, one should be guided by the recommendations of the current regulatory documents. For rod systems such as trusses, local destruction of one (any) truss rod is considered.
2. Performing a static analysis of an intact structure for the combination of loads, which is assigned in accordance with the current regulatory documents and by determining the forces in the removed element.
3. Removing the element corresponding to the considered variant of local destruction from the design model, changing of the design of the structure and applying forces to the nodes of the structure in the removed element.
4. Performing a dynamic calculation to determine the natural vibration frequencies of the damaged structure. The first vibration frequency is used to designate one of the considered time intervals when performing a dynamic calculation. The emphasis on the first vibration frequency allows one to consider the possible unfavorable distribution of forces in the system when the exclusion time of the destroyed element is equal to the period of the first frequency.
5. Performing a dynamic calculation of the damaged construction with a constant external load on the structure, and a time-varying load in the form of forces in the removed bar, taken with the opposite sign. An external load is a load combination based on current regulations.

During the calculations, the structural material was considered elastic, the elastic modulus corresponded to the elastic modulus of steel and the truss was modeled with rod finite elements of the "beam" type.

To simulate the failure of a rod, a time interval is assigned, during which the forces decrease to zero. The load on the damaged structure varied as shown in the graph in Figure 7. It increased from zero to full value in 10 s and remained constant thereafter. The magnitudes of the forces simulating the forces in the excluded rod increased from zero to the full value in 10 s and then decreased to zero over a certain set time interval. The choice of the time interval for the growth of the load and efforts to the full value of 10 s makes it possible to exclude the development of oscillations of the system until the destruction of the element.

During the dynamic calculations for all considered structures, the following exclusion times Δt were studied: 0.01 s, 0.1 s, 0.12 s, 0.16 s, T1, 1 s. T1 is the time corresponding to the first natural vibration frequency of the damaged structure. The exclusion times of 0.12 s and 0.16 s corresponded to the experimentally confirmed exclusion times for stretched and compressed damaged elements [21,22].

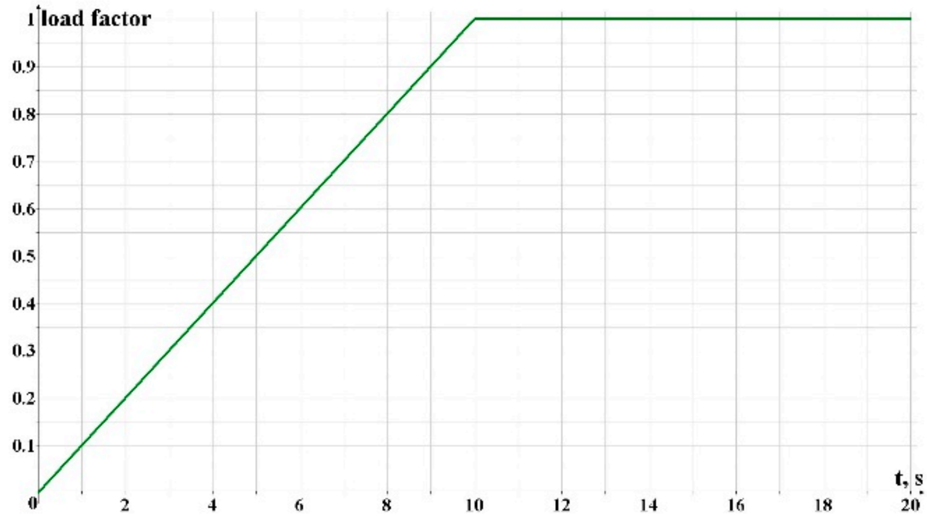

Figure 7. The graph of the application of an external load on the structure.

Figure 8 shows a graph of the change in the forces in the damaged element with the elimination time Δt = 0.01 s.

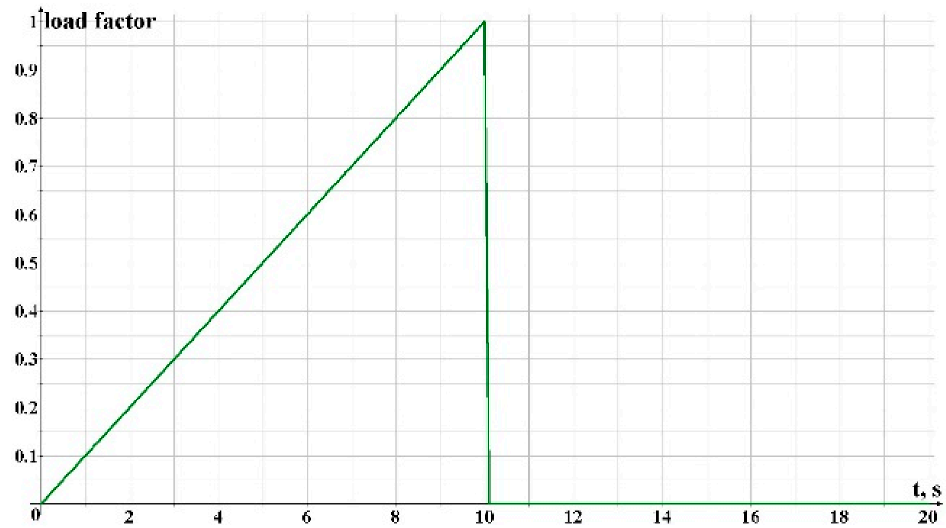

Figure 8. The graph of the change in the forces in the damaged element with the exclusion time Δt = 0.01 s.

The following design situations were considered:

1. The element of the upper chord of the truss was damaged;
2. The element of the lower chord of the truss was damaged;
3. The element of the truss support brace was damaged;
4. The middle compressed or stretched brace was damaged.

The schemes of trusses with a span of 24 m and 78 m with a damaged element of the lower chord are shown in Figures 9 and 10, respectively. Dimensions on the drawings are given in mm. Elements of truss with a span 24 m were designed from I-beams I35 (depth 350 mm) and I23 (depth 230 mm), as well as square steel pipes with dimensions 80 × 80 × 4 mm and 100 × 100 × 4 mm. Elements of truss with a span 78 m were designed from I-beams I40K19 (depth 668 mm, width 435 mm) and I40K5 (depth 429 mm, width 400 mm), as well as square steel pipes with dimensions 350 × 350 × 15 mm and 500 × 500 × 25 mm.

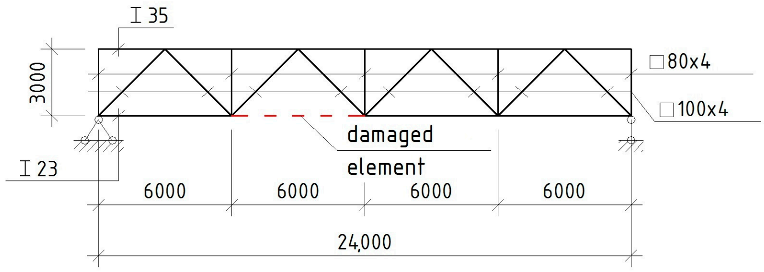

Figure 9. Truss with a span of 24 m and a damaged lower chord.

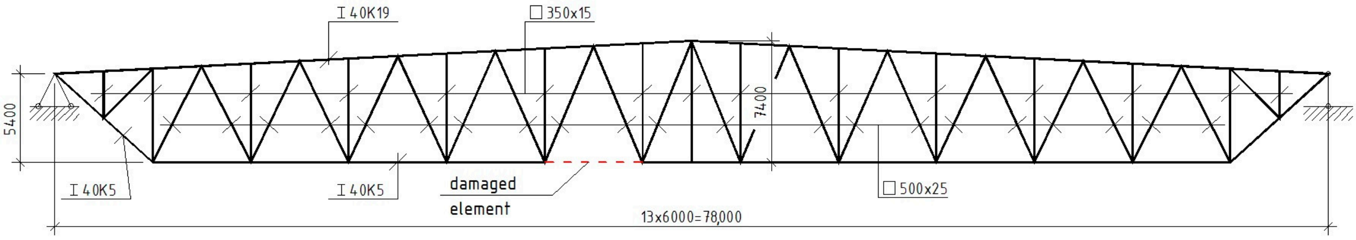

Figure 10. Truss with a span of 78 m and a damaged lower chord.

As part of the numerical study, a one-story industrial building was considered. The structural scheme was frame in the transverse direction, connecting in the longitudinal direction. The transverse frame was single-span with a span of 78 m, while the spacing of the frames was 6 m. The frame girder was a trapezoidal truss. The truss was hinged to the columns. Two variants of the structural scheme of the building covering were considered:

1. Horizontal links along the upper and lower chords of trusses and the vertical backbone truss (in the middle of the span);
2. Longitudinal vertical braces in each truss panel.

The spatial model with a typical arrangement of ties along the coverage is shown in Figure 11.

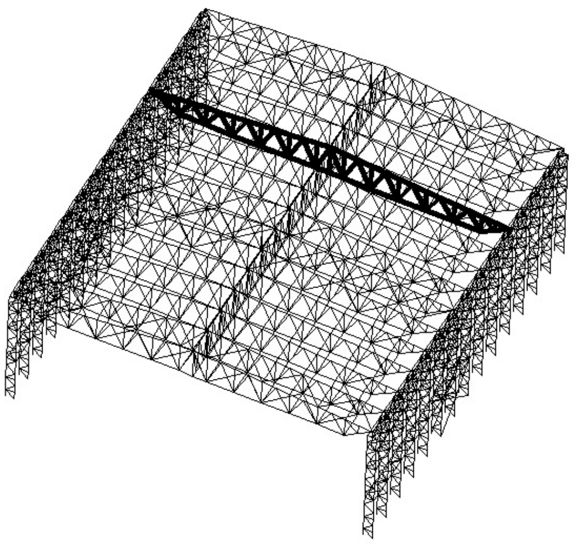

Figure 11. Spatial model of a large-span building. Structural scheme, var. No.1.

For the listed options, numerical calculations were performed and the dynamic coefficients for the damaged truss and neighboring trusses were determined. The assessment and comparison of the work of the frame for each of the options, in the case of local destruction of a truss element, was carried out.

3. Results

3.1. Theoreticalcalculation

Figure 12 shows a truss with a span of 24 m, loaded at the nodes of the upper chord with concentrated forces P = 30 kN.

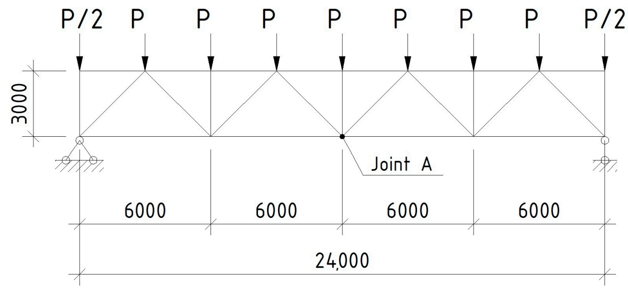

Figure 12. Truss with a span of 24 m.

All joints in the farm are rigid. The cross-sections of the truss rods are chosen in such a way that the load-bearing capacity of the truss is preserved under the considered variants of local destruction. The considered options for local failure of chord and brace elements are shown in Figures 13–16. Dimensions on the drawings are given in mm. Cross-sections of truss elements shown in Figures 13–16 are: I-beam I35 (depth 350 mm); I-beam I23 (depth 230 mm); I-beam I55 (depth 550 mm).

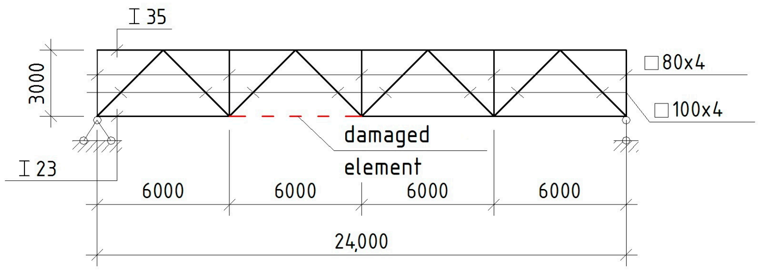

Figure 13. Truss with a damaged lower chord.

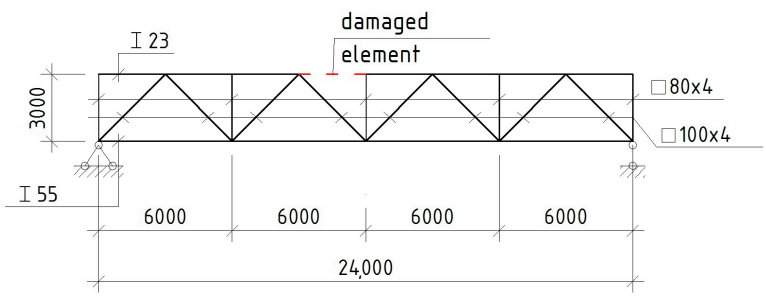

Figure 14. Truss with a damaged upper chord.

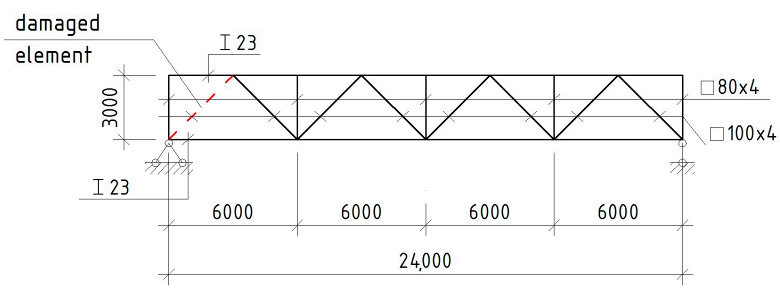

Figure 15. Truss with a damaged support brace.

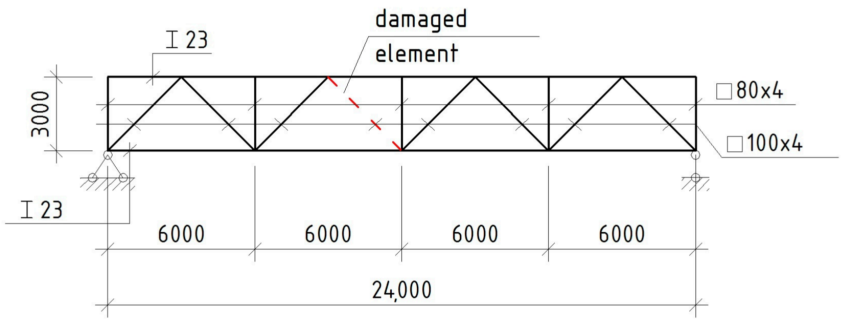

Figure 16. Truss with a damaged middle brace.

Deflections are defined at joint A in the middle of the truss span. The theoretical values of the dynamic coefficient are presented in Table 1.

Table 1. Theoretical dynamic coefficients for a truss with a span of 24 m.

Place of Local Damage of the Truss	Deflections, mm		k_d
	w	w_0	
Lower chord	16.8	371	1.955
Upper chord	15.3	152	1.899
Support brace	8.25	48.8	1.831
Middle brace	20.7	26.5	1.219

Based on the results of theoretical studies, the dependence of the dynamic coefficient for local damage to a truss on deflections in the original and damaged trusses was obtained (Equation (19)). Table 2 compares the theoretical and numerical dynamic coefficients for a truss with a span of 24 m. The error given for the exclusion time is Δt = 0.01 s.

Table 2. Dynamic coefficients obtained by numerical and theoretical calculations.

Place of Local Damage of the Truss	Dynamic Coefficient at Exclusion Time					Theoretical Calculation Equation (19)	Error, %
	0.01 s	0.1 s	0.12 s	0.16 s	1 s		
Lower chord	1.992	1.607	1.595	1.570	1.050	1.955	0.15
Upper chord	1.786	1.643	1.637	1.624	1.350	1.899	5.95
Support brace	1.573	1.363	1.355	1.341	1.045	1.831	14.09
Middle brace	1.032	1.030	1.030	1.029	1.001	1.219	15.34

The analysis of the results showed that the dynamic coefficients, obtained theoretically under the assumption of instantaneous failure of the element, correlate closely with the numerical data for the exclusion time (Δt = 0.01 s). On average, the theoretical values are higher than the numerical ones chords (by 1–6%) and braces (by 15%). A good agreement between the numerical and theoretical data allows us to conclude that the proposed numerical method is operable and can be used in practical calculations, considering the actual time of element elimination.

3.2. Experimental Research

Tests of truss models made it possible to establish the exclusion time when the bearing capacity is exhausted and local destruction of the elements of a flat truss occurs.

In the first experiment, the final load on the truss was 4.1 kN. At the time of the installation of the last pair of weights, the loss of stability of the upper chord of the truss was visually recorded. Figure 17 shows a graph of the movement of the truss over time. The horizontal sections during loading exist due to the holding of the structure after the application of the load until the vibration of the structure stops.

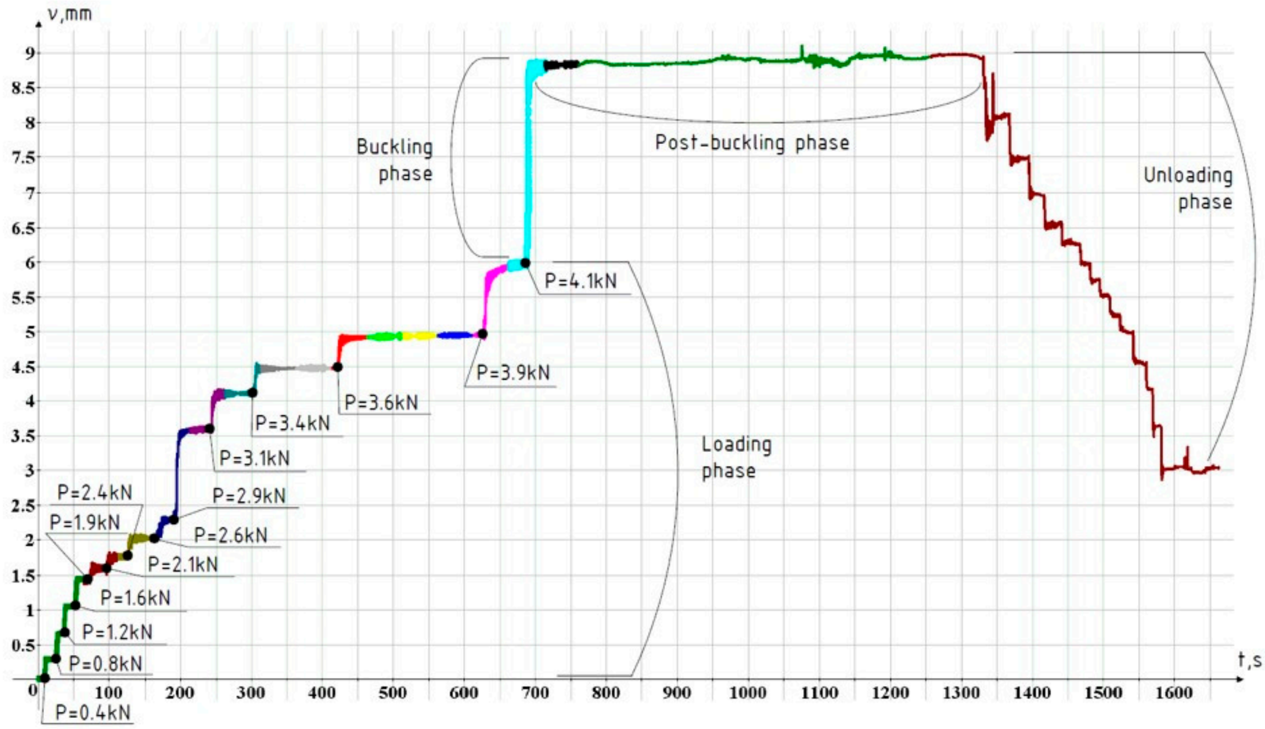

Figure 17. Dependence of deflections, mm (y-axis) on time, s (x-axis). Experiment No. 1.

The sharp jump in the deflections in Figure 17 corresponds to the buckling phase of the upper chord. At this stage, the curvature of the upper chord occurred. It should be noted that with great flexibility after the loss of stability of the upper chord, the truss as a whole retained its bearing capacity. The next horizontal section corresponds to the phase of the truss post-critical operation, which was characterized by the absence of growth of the truss deflections after the loss of stability while maintaining the load on the truss.

After loss of stability of the upper chord, the model was kept under maximum load for 70 s, after which the truss was completely unloaded and the deformations of the upper chord were measured. Measurements showed that after complete unloading, the upper chord of the truss, which had lost its stability, returned to its original rectilinear state without residual deformations; this result indicates the loss of stability of the chord in the elastic stage of the structure's operation.

In the second experiment, the destruction of the lower chord of the truss was investigated. At the junction of the lower chord with the central rod, the lower chord was weakened by V-shaped notches and transverse cuts in the neck of the notch on both sides of the chord. The presence of V-shaped notches and a reduced thickness of the chord made it possible to achieve local brittle fracture when testing. The destruction of the lower chord of the truss occurred at a load on the truss of 4.85 kN (Figure 18).

Figure 19 shows a graph of the evolution of displacement over time. A sharp jump in displacements at the end of the graph corresponds to the moment of destruction of the lower chord of the truss.

Figure 20 shows an enlarged fragment of the graph of the dependence of displacements on the truss for the time interval corresponding to the destruction of the lower chord of the truss. In this graph, the times t_1 and t_2 denote, respectively, the beginning and the end of the fracture process.

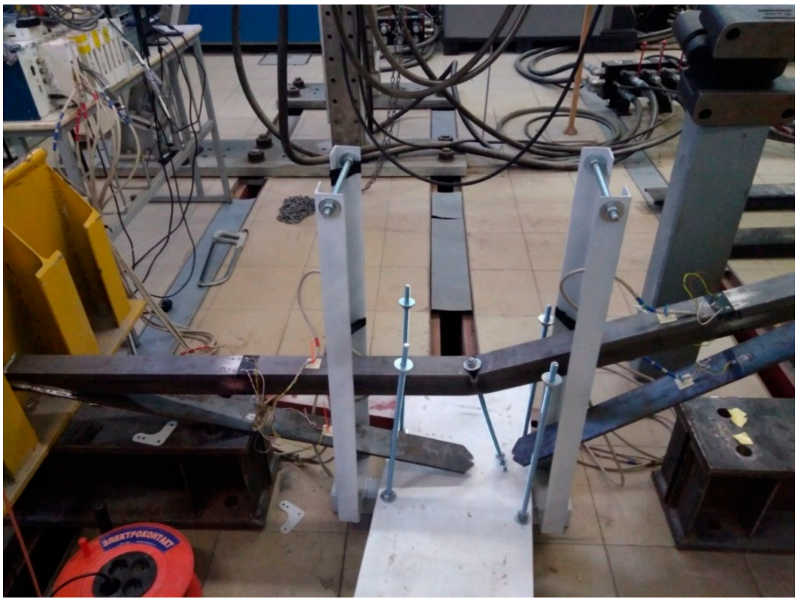

Figure 18. Truss after the destruction of the lower belt. Experiment No. 2.

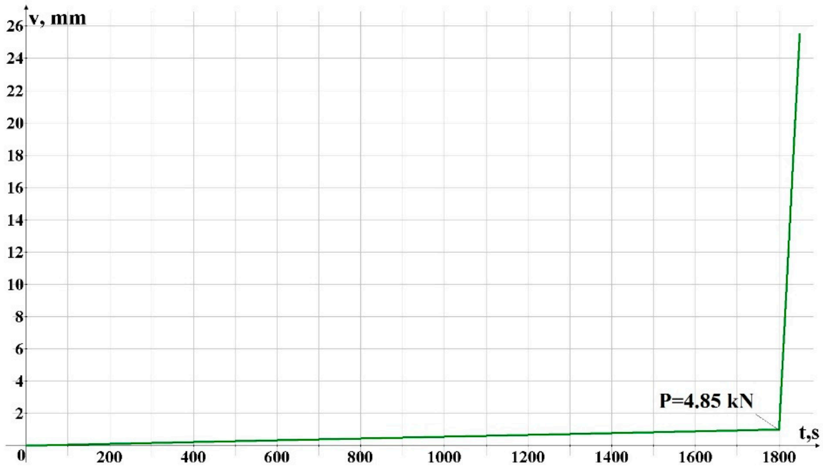

Figure 19. Change in the deflection of the truss, mm (y-axis) in time, s (x-axis). Experiment No. 2.

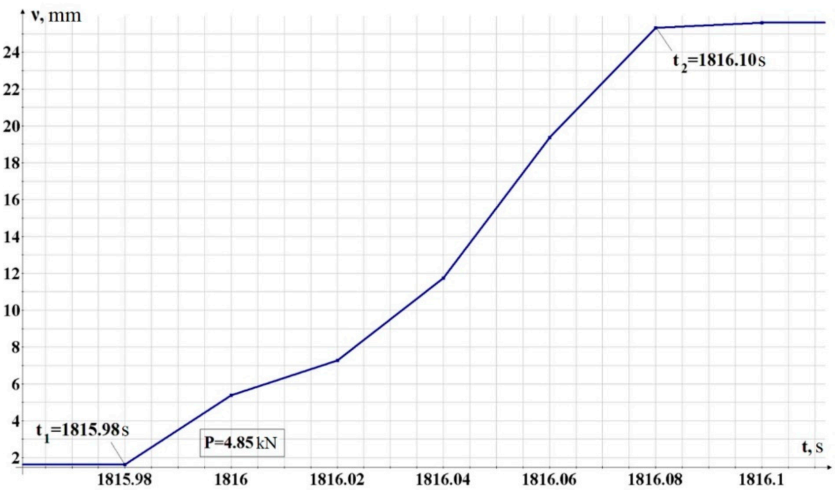

Figure 20. Change in the deflection of the truss, mm (y-axis) in time, s (x-axis) in the phase of destruction of the lower belt (P = 4.85 kN). Experiment No. 2.

According to the graph shown in Figure 20, the destruction time of the lower chord (with a weakened section) was 0.12 s. In accordance with the initial conditions, the chord collapsed in a brittle manner.

The objective of the third experiment was to achieve the destruction of the upper chord of the truss through loss of stability caused by the formation of a mechanism at a certain level of load, which very quickly leads to the exhaustion of the bearing capacity of the compressed bar. To accelerate the formation of plasticity hinges, cuts were made in the right panel of the upper chord, the locations of which were chosen in accordance with the assumed form of buckling. Before testing the weakened upper chord panel, a preliminary deflection of 7 mm was reported in the direction of the assumed buckling shape.

The destruction of the upper chord of the truss occurred at a load of 4.1 kN (Figure 21).

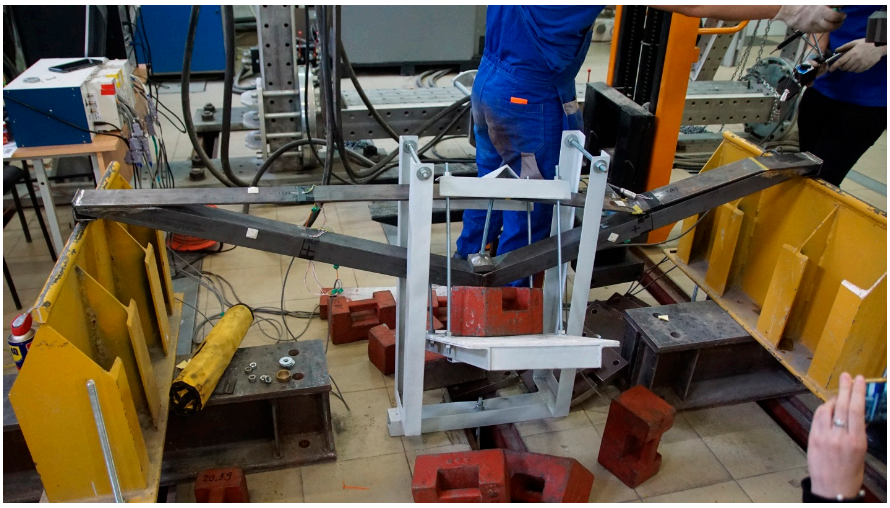

Figure 21. Truss after the destruction of the upper belt. Experiment No. 3.

Figure 22 shows a graph of displacement changes over time.

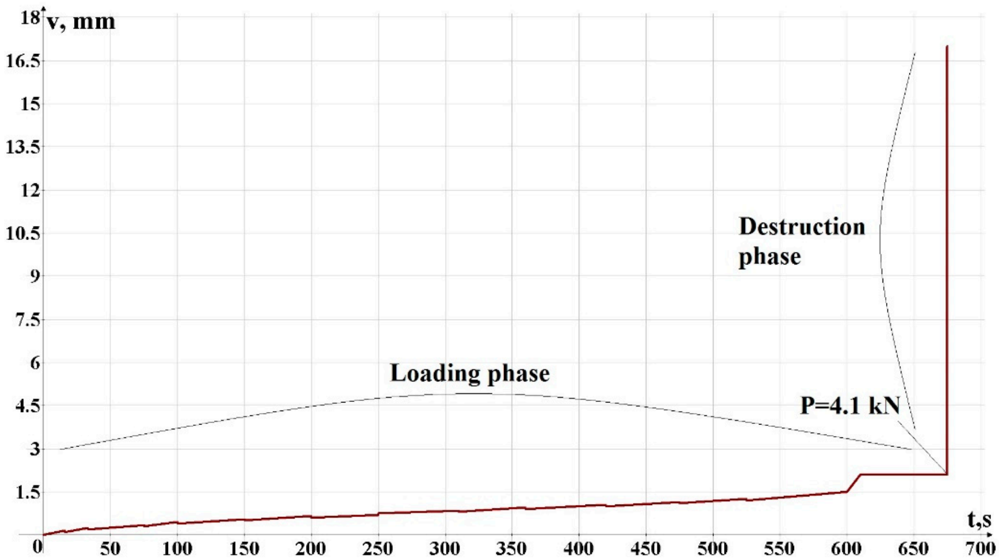

Figure 22. Change in the deflections of the truss, mm (y-axis) in time, s (x-axis). Experiment No. 3.

A sharp jump in displacements at the end of the graph corresponds to the moment of destruction of the upper chord of the truss. The destruction of the upper chord of the truss occurred after the formation of three plastic hinges in the places of preliminary weakening of the chord section.

Figure 23 shows a graph of the development of displacements at the time of failure.

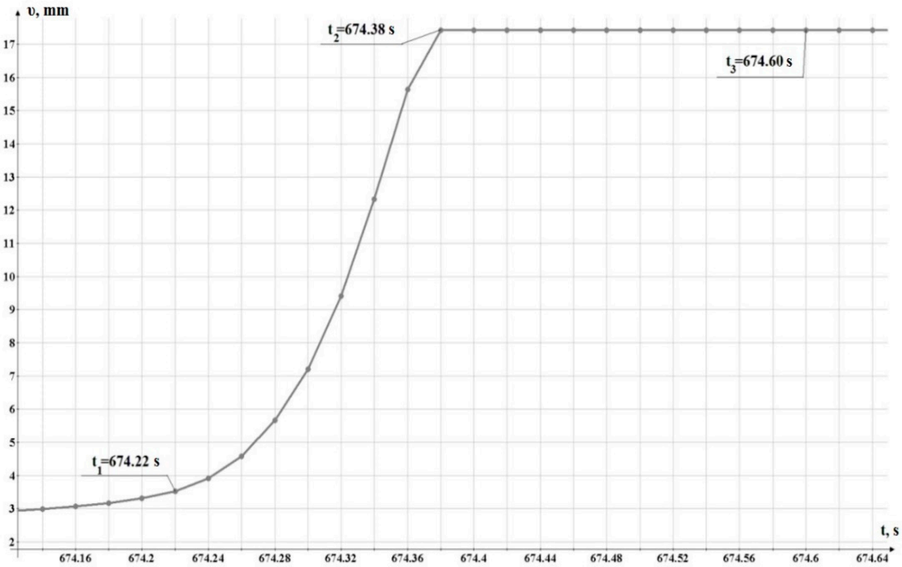

Figure 23. Dependence of deflections, mm (*y*-axis) on time, s (*x*-axis) in the phase of loss of stability of the upper chord of the truss (P = 4.1 kN). Experiment No. 3.

Based on the plotted graph, the destruction process can be divided into two stages. The first stage corresponds to the beginning of the destruction of the upper chord (time t_1) and is characterized by a sharp jump in displacements. Furthermore, from the moment of time t_2 to the moment of time t_3, the deflection of the truss remained constant; however, the truss continued to bear the acting load. After reaching the moment of time t_3, the truss lost its bearing capacity. For further calculations, the exclusion time $\Delta t = 0.16$ s, corresponding to the first stage of the destruction of the truss, was taken as a reserve of the bearing capacity for compressed damaged rods.

Based on a comparison of the obtained experimental data on the operation of individual rods and elements in the composition of a flat truss, the following exclusion time was adopted in the bearing capacity margin:

- for compressed rods with a slenderness ratio greater than proportionality slenderness, the exclusion time is not limited;
- for compressed rods: $\Delta t = 0.16$ s;
- for stretched rods: $\Delta t = 0.12$ s.

3.3. Numerical Calculation

For the studied trusses with spans of 24 and 78 m, an exclusion time $\Delta t = 0.01$ s and a variant of local destruction of chord elements, the values of the dynamic coefficient were $k_d = 1.75 \div 1.99$. The use of the experimentally confirmed exclusion time ($\Delta t = 0.16$ s for compressed and $\Delta t = 0.12$ s for stretched members) allows a reduction in the value of the dynamic factor by 13–20% for a truss of 24 m and 3–5% for a truss of 78 m.

Based on a comparison of the results obtained for both considered trusses, to unify further calculations, a larger value of the dynamic coefficients is taken (corresponding to a truss with a span of 78 m). Thus, taking into account the nature of the destruction of the element, the following values of the dynamic coefficient are taken as recommended when performing a static calculation of a truss with local destruction:

- an element of a stretched chord—$k_d = 1.744$;
- a compressed chord element—$k_d = 1.718$;
- a support brace—$k_d = 1.250$;
- an ordinary brace—$k_d = 1.108$.

Numerical calculations show that for the exclusion times $\Delta t = 0.16$ s and $\Delta t = 0.12$ s, the values of the dynamic coefficients differ insignificantly: for a truss with a span of 24 m by 0.1 ÷ 2.5%; for a truss with a span of 78 m by 1%. In this regard, the exclusion time $\Delta t = 0.12$ s is taken for both compressed and stretched elements in the bearing capacity margin.

It should be noted that with the loss of stability of compressed elements when the inequality Equation (21) is satisfied, the dynamic coefficient is equal to $k_d = 1$ due to the ability of a flexible rod after loss of stability and a constant force to perceive it for an unlimited time.

$$\lambda = \frac{l_{ef}}{i} > \lambda_{pr} = \pi\sqrt{E/\sigma_{pr}} \quad (21)$$

where λ is slenderness ratio, λ_{pr} is proportionality slenderness, l_{ef} is effective length of the rod, i is radius of gyration, E is modulus of elasticity and σ_{pr} is proportionality limit.

When installing additional vertical braces in each panel of the truss due to the redistribution of the load on the undamaged trusses, the dynamic coefficient for the damaged truss does not exceed $k_d = 1.080$. In this case, the same dynamic coefficient was assumed for neighboring farms.

Based on the results of the calculations of the spatial frame of the building, diagrams of the distribution of the dynamic coefficient for the entire building coverage were constructed. Considering the data of experimental studies and the previously obtained results of numerical calculations, the diagrams were plotted for the exclusion time $\Delta t = 0.12$ s. The lower part of the figure shows a longitudinal section of the building along the digital axes. The load-bearing roof trusses are located along the letter axes. Above each truss is given the value of the dynamic coefficient, which can be used in a static calculation to set the load applied to the corresponding truss. The damaged truss is highlighted in the diagram with solid shading. Figure 24 shows a diagram for a damaged element of the lower chord.

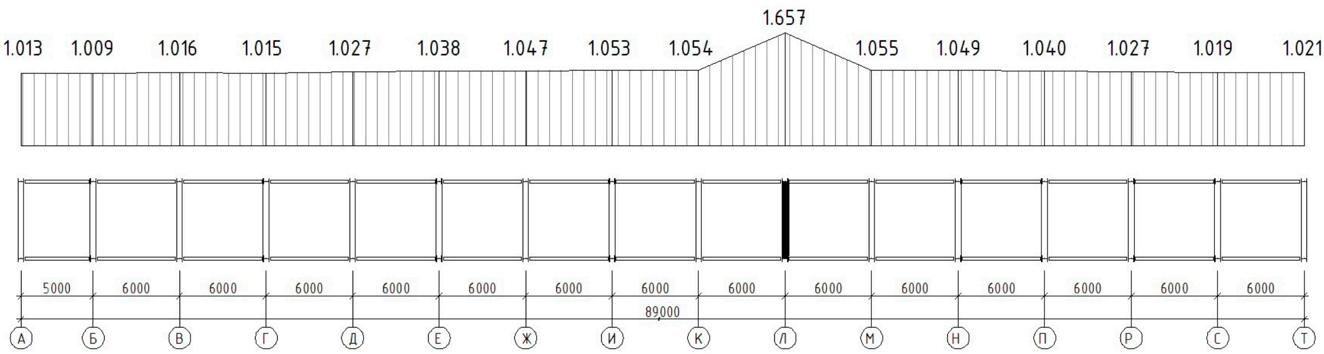

Figure 24. Diagram of the distribution of the dynamic coefficient in case of damage of the lower chord.

The figure shows that the maximum value of the dynamic coefficient corresponds to the damaged truss. The calculations showed that the dynamic coefficient in neighboring farms ranges from 1.036 to 1.075. For subsequent trusses, the dynamic forces practically do not change and range from 1.011 to 1.071.

Thus, in the considered structural scheme of the frame with local destruction of one of the elements of the truss, the redistribution of efforts occurs within the limits of the damaged truss. This explains the significantly lower values of the dynamic coefficients for neighboring farms. With this design scheme, an increase in the survivability of the frame is possible by increasing the cross-section of the elements of the rafter trusses, considering the possible local destruction of the elements. Taking into account the increased cross-sections of the truss elements, the metal consumption for the coating is 2.21 kN/m^2.

The spatial scheme of the frame with additional longitudinal vertical braces installed in each truss panel is shown in Figure 25.

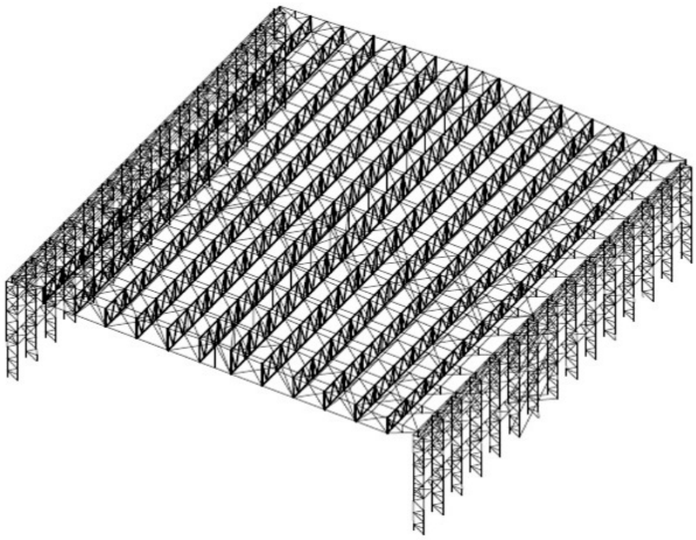

Figure 25. Long-span truss in a spatial frame with additional vertical bracing.

With this constructive solution, the difference between the values of the dynamic coefficient in the damaged and neighboring farms does not exceed 5%, while the value of the dynamic coefficient in the damaged truss is close to 1 (no more than 1.08 with an exclusion time Δt = 0.12 s). Figure 26 shows the distribution of the dynamic coefficient for the entire coverage of the building in case of damage to the element of the lower chord (exclusion time Δt = 0.12 s).

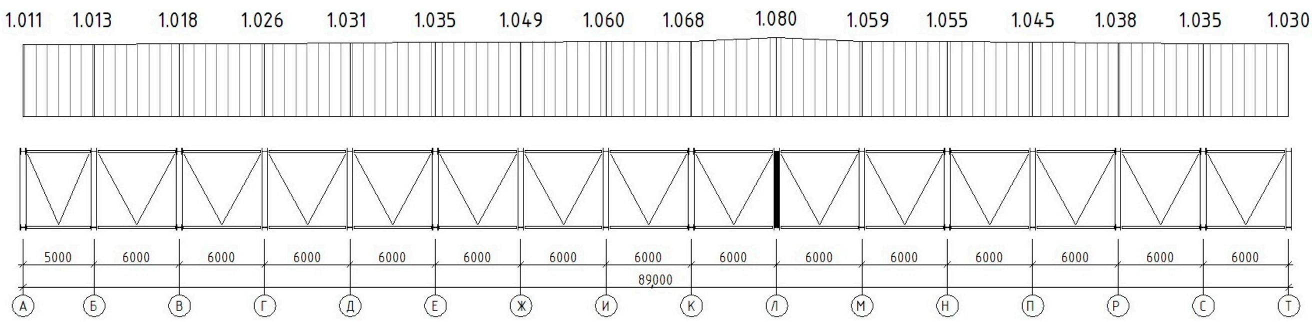

Figure 26. Diagram of the distribution of the dynamic coefficient in case of damage to the lower chord.

Due to the installation of additional longitudinal vertical ties, the load is redistributed from the damaged truss to the neighboring ones, which significantly reduces the efforts in the damaged truss and makes it possible to reduce the cross-sections of the elements of the truss trusses. At the same time, the consumption of steel for the coating, considering additional vertical ties, is 1.66 kN/m^2, which is 25% less compared to the first coating option.

4. Discussion

According to the results of experimental studies of the operation of flat damaged trusses, it was revealed that due to the redistribution of efforts, even after the damaged rod is disconnected from the operation, the truss retains its bearing capacity for a certain period.

Based on the data of the first experiment, it can be concluded that with a high slenderness of the compressed element of the upper chord (λ = 405), which loses its stability in the elastic stage of steel operation, the truss retained its bearing capacity during the entire duration of the test load (70 s). After the loss of stability, the initially rectilinear upper chord acquired a curved shape. Due to the elastic work of steel, the upper chord, after losing stability, continued to perceive the longitudinal force acting in it equally to the critical one during the entire period of the experimental load on the truss. In the truss, after the loss of stability of the flexible chord in the elastic stage of steel work, no oscillations arose and the load acted on the truss statically. During the tests, the post-critical phase lasted until the beginning of the unloading of the truss; for all this time, the truss retained its bearing capacity. The unlimited duration of the supercritical operation phase after the loss of stability of a truss element of great flexibility has been experimentally established. Tests of the truss with the loss of stability of the flexible chord confirmed the results obtained during compression tests of rod specimens, which outlined the possibility of taking into account the supercritical work of compressed rods that lose their stability in the elastic stage of material operation. Thus, it has been experimentally proved that the loss of stability of the flexible upper chord in the elastic stage of the material operation is not accompanied by the development of vibrations in the system; this result makes it possible to calculate the structure with the loss of stability of undamaged compressed flexible elements using the dynamic factor equal to unity.

In the second experiment, the presence of a weakening of the lower chord provoked the fragile nature of the destruction of the truss element. It has been experimentally established that even with brittle fracture, the elimination of a truss element does not occur instantly, but within a certain period. In the experiment, the exclusion time was $\Delta t = 0.12$ s. During this time interval, the truss retained its bearing capacity as the force is redistributed from the damaged element to the adjacent truss elements. Tests of the truss confirm the data of tensile tests of rod specimens, for which it was experimentally established that the destruction of rod elements does not occur instantaneously but within a certain finite period. The resulting exclusion time makes it possible to reduce the dynamic coefficient in case of local destruction of the truss in the form of a rupture of a stretched element.

Tests of the truss in the third experiment showed that the exclusion time of the compressed pre-weakened truss element was $\Delta t = 0.16$ s. The loss of stability of the upper chord with local fractures of the section participated in the formation of plastic hinges in places where the section weakened, as well as in the formation of a broken outline of the damaged chord panel.

Thus, for compressed rods, the most unfavorable time was taken to be the shorter exclusion time corresponding to the damage of the previously weakened compressed rod element. For tensile members, the difference between the obtained values of the exclusion time for individual members and members in a flat truss was up to 8%. Based on a comparison of the obtained experimental data on the operation of individual rods and elements in the composition of a flat truss, the following exclusion times were adopted in the bearing capacity margin:

- for compressed rods: $\Delta t = 0.16$ s;
- for stretched rods: $\Delta t = 0.12$ s.

The analysis of the numerical studies conducted regarding the damaged steel trusses operation showed that the most unfavorable damage option is the exclusion from the operation of the most loaded element of the upper or lower chord. Taking into account the small (up to 2.5%) difference in the values of the dynamic coefficients obtained with the exclusion times of 0.12 and 0.16 s, for simplification and unification of calculations in the bearing capacity, it is recommended that both compressed and stretched elements take the exclusion time $\Delta t = 0.12$ s. Based on the studies carried out on the operation of flat trusses with local destruction, the following dynamic coefficients can be recommended for practical calculations:

- for a stretched chord: $k_d = 1.744$;
- for a compressed chord: $k_d = 1.718$;
- for the support brace: $k_d = 1.250$;
- for braces: $k_d = 1.108$.

In a spatial frame with horizontal ties along the upper and lower chords of trusses and a vertical spine truss, the values of the dynamic coefficient turned out to be close to the dynamic coefficients for a flat truss. In this case, the dynamic coefficients for the damaged truss as part of the lattice frame were equal to:

- for a stretched chord: k_d = 1.657;
- for a compressed chord: k_d = 1.702;
- for the support brace: k_d = 1.216;
- for braces: k_d = 1.102;
- for farms adjacent to the damaged one: k_d = 1.075.

For intact farms, the dynamic factor is no more than 1.080.

5. Conclusions

Based on the study of the operation of trusses with local destruction of elements, the following conclusions can be drawn:

- Comparison of the data of theoretical and numerical studies showed that instant failure corresponds to the time of exclusion of the damaged element from 0.01 to 0.1 s. At the same time, the difference in the values of the dynamic coefficients determined by theoretical and numerical calculations does not exceed 5%. The dependence of the dynamic coefficient for a damaged truss on its rigidity is theoretically established. In this case, the value of the theoretical dynamic coefficient is greater than the value determined by the numerical dynamic calculation for chords (by 2–6%) and braces (by 15–20%).
- The exclusion time of damaged elements of a flat truss was experimentally determined. For the upper chord of high flexibility, the loss of stability did not lead to the development of oscillations and the exclusion time was not limited. For the stretched element of the lower chord, the exclusion time was Δt = 0.12 s. The exclusion time for the element of the compressed upper chord with local damage was at least Δt = 0.16 s. Rapid failure of the compressed element is due to the formation of plastic hinges in the places of section weakening and the formation of a broken outline of the damaged chord panel. Based on a series of experiments for further numerical studies, the exclusion time for compressed rods of low flexibility was taken as Δt = 0.16 s; for compressed rods of high flexibility, the exclusion time is not limited; and for stretched rods, the exclusion time was Δt = 0.12 s.
- It was numerically established that an increase in the exclusion time from 0.01 to 1 s is accompanied by a decrease in the dynamic coefficient for farms, depending on the location of local destruction, of 1.3–1.6 times.
- It was numerically established that for flat trusses, the difference between the values of the dynamic coefficients at exclusion times of 0.12 s and 0.16 s does not exceed 2.5%. In this regard, when numerically calculating damaged trusses in a dynamic setting, it was recommended to use the exclusion time for stretched and compressed (at $\lambda \leq \lambda_{pr}$) rods, which is Δt = 0.12 s.
- It was established that the most unfavorable damage option for steel trusses was the destruction of an element of the upper or lower chord. With an increase in the time of exclusion of a chord element from 0.01 to 0.12 s, the value of the dynamic coefficient decreased by 3–12% for flat trusses and by 4–7% for trusses as part of a spatial frame with a typical arrangement of the cover links.
- Based on the dynamic calculations of flat trusses with a span of up to 78 m, the accepted value of the dynamic coefficient was: 1.744 for a stretched chord; 1.718 for a compressed chord; 1.250 for a support brace; 1.108 for an ordinary brace. For large-span trusses, dynamic calculations were required.
- Numerical studies established that with a typical arrangement of the pavement ties, the damaged truss operates as a flat one. The difference between the values of the dynamic coefficients did not exceed 2.5%. For this type of frame and trusses with a span of up to 78 m, the obtained values of the dynamic coefficients, depending on the

type of damage, were: k_d = 1.702 for a chord element; k_d = 1.216 for the support brace; k_d = 1.102 for an ordinary brace. It was found that for any variants of local damage for farms adjacent to the damaged one, the value of the dynamic coefficient did not exceed k_d = 1.055.

- Numerical studies of the spatial frame with additional vertical braces in each panel of the truss established that the value of the dynamic coefficient for the damaged truss did not exceed k_d = 1.080. In this case, the same dynamic coefficient was assumed for neighboring farms.
- The developed method of quasi-static calculation proposed in this article could be used to perform calculations not only for steel trusses, but also for other structures. In this case, the values of the dynamic coefficients must be determined by dynamic calculation in each case, taking into account the exclusion time.

Prospects for the further development of the research topic are:

1. Investigation of the operation of damaged steel trusses of various shapes and spans, as well as determination of the dependence of the value of the dynamic coefficient on the geometric scheme of the truss and the size of the span;
2. Determination of the exclusion time of damaged steel elements of load-bearing structures, depending on the boundary conditions and the cross-section;
3. Development of a methodology for calculating steel frames of industrial buildings for resistance to progressive collapse from the point of view of using the dynamic coefficients in the calculation, obtained on the basis of the exclusion time of the damaged element.

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