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## Deformations of steel roof trusses under shock emergency action

## Деформации стальных стропильных ферм при ударных аварийных воздействиях

**A.V. Alekseytsev,**  
*National Research Moscow State Civil Engineering  
University, Moscow, Russia*  
**N.S. Kurchenko,**  
*Bryansk State University of Engineering and  
Technology, Bryansk, Russia*

**канд. техн. наук, доцент А.В. Алексейцев,**  
*Национальный исследовательский  
Московский государственный строительный  
университет, г. Москва, Россия*  
**канд. техн. наук, доцент Н.С. Курченко,**  
*Брянский государственный инженерно-  
технологический университет, г. Брянск,  
Россия*

**Key words:** truss; technological equipment;  
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crate system; cable sensor; dynamic loads;  
displacements in time; strains in time

**Ключевые слова:** стропильная ферма;  
технологическое оборудование; аварийное  
воздействие; эксперимент; ударные  
воздействия; крейтовая система; тросовый  
датчик; динамические догружения;  
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времени

**Abstract.** The problems of experimental and theoretical research on the stressed and deformed state of steel structures under emergency actions are particularly relevant. This paper proposes experimental and theoretical research methodology, which is used on the basis of an example of research on a full-length truss as part of the frame for an industrial buildings workshop. Components of the stressed-strained state of the structure are determined experimentally in the course of a simulated emergency situation. As emergency impacts, this paper considers the detachment of the air-cooling unit attached to a node of the lower chord of the truss. Experimental data is gathered through the joint use of the crate system, cable sensor and PC. The finite-element modelling of the structure behavior is performed based on the direct integration of differential equations of motion of the system subject to the local dynamic effects, and a comparison of data obtained with experiments results. As a result of using the test methodology we obtained the maximum weight of technological equipment fastened to the roof truss, while ensuring its normal operation in case of an emergency related to the failure to affix the equipment.

**Аннотация.** Предлагается методика экспериментально-теоретических исследований стальных конструкций при не учитываемых в нормативных документах запроектных воздействиях, которая реализуется на примере стропильной фермы в составе каркаса цеха промышленного здания. Экспериментальным путем определяются компоненты напряженно-деформированного состояния конструкции при моделировании аварийной ситуации. В качестве запроектного воздействия рассматривается отрыв воздухоохладительной установки, закрепленной к узлу нижнего пояса фермы. Сбор экспериментальных данных осуществляется при совместном использовании крейтовой системы, тросового датчика и персонального компьютера. Выполняется конечно-элементное моделирование поведения конструкции на основе прямого интегрирования дифференциальных уравнений движения системы, подверженной локальным динамическим воздействиям, и сопоставление полученных данных с результатами экспериментов. В результате определена максимальная масса технологического оборудования, закрепляемого к стропильной ферме, при обеспечении ее нормальной эксплуатации в случае возникновения ненормируемой аварийной ситуации, связанной с отказом крепления оборудования.

## Introduction

The most important requirement when designing construction facilities is to ensure the mechanical safety of buildings and structures. Many researchers consider issues aimed at improving structural systems at ability to endure local damage. Of particular importance is the design of facilities with high level of responsibility, for which it is necessary to take into account actions that are not covered under buildings normal operation (so-called beyond-design actions). Incomplete or inadequate research on such action may result in severe socio-economic consequences. Research related to the design of safety design systems is one of the priority areas in the development of architectural engineering. Much attention is paid to the study of concrete and steel structures. As an example of emergency situations, a number of authors [1–6] have considered the processes of dynamic added stress on concrete systems, when excluding individual support links. An analysis of the ultimate static and dynamic effects in steel structures under emergency action, related to the maximum permissible loading or the exclusion of individual elements or supports from the design scheme, is reflected in papers [7–13].

Experimental and theoretical research on full-sized steel trusses and beams are of particular interest. In this case, experimental research is carried out both on designed [14, 15] and reconstructed [16] facilities. Through experiments, such basic observed values as the deformation of the rods [15], prestress levels of elements [14], and the parameters that describe the behaviour of nodal joints under static and dynamic loads [13, 17] are simulated for the designed structures. Much attention is awarded to emergencies. The most common beyond-design actions on building structures involve localised damage to one element or a group of elements as a result of fire exposure [18], ultimate loading [9, 19], removal of individual supports (pillars of the post-and-beam system) [13], or a number of scenarios involving mechanical local damage [12], dynamic pressure pulsations born by the structure, or [20] the actual load on the damaged system [21].

There is considerable interest in the theoretical and experimental analysis of beyond-design actions on structures. It should be noted that the literature has rather neglected the description of methodologies and the instrument basis for experimental research on building structures under local dynamic actions. In this paper, we propose a method for experimental research on dynamic displacements and deformations in steel structures under emergency impact, set forth using the example of testing of a steel truss spanning 18m as part of the building frame. This method determines the value of the dynamic added stress and the structure's dynamic displacement. Local dynamic actions were modelled using methods for analysing damaged structures, the main provisions of which are set out in [22].

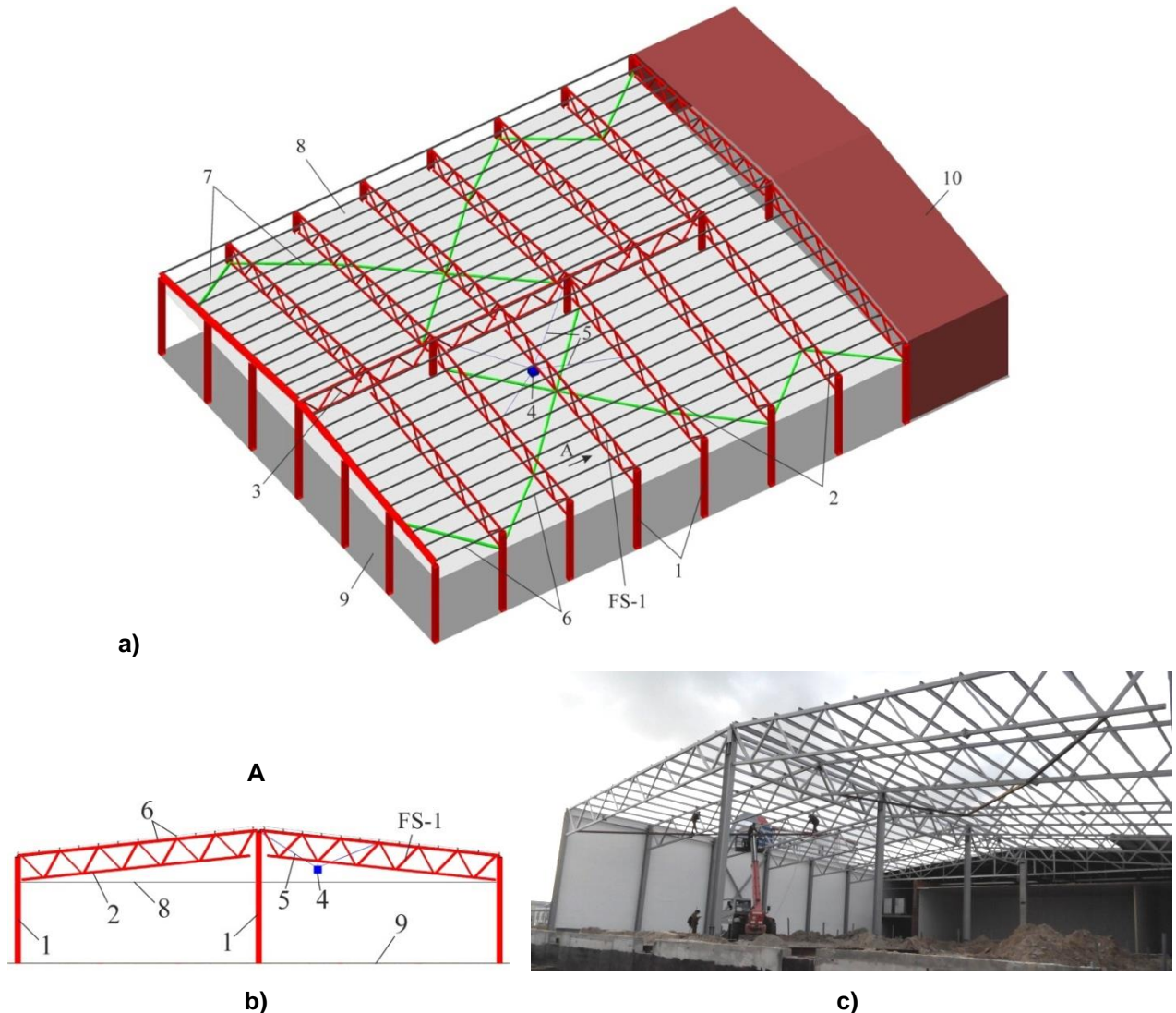
## Methods

When designing various industrial facilities, the safety of production and technological processes must be ensured. At the same time, in some cases, the normative documents do not take all possible types of production-related accidents into account. Thus, safety requirements shall be established in accordance with client's technical requirements. To implement such requirements, when considering the operating conditions of structural engineering objects, we propose that the following steps be taken:

- identify and classify possible emergency actions;
- develop and actually implement the test scheme, simulating an emergency situation. In this case, the structure or design system used in the building shall be tested.
- perform a finite-element simulation and design calculation in the dynamic formulation for the considered beyond-design actions, and calculate natural oscillations in the linear and non-linear formulations;
- determine the simulated level of emergency loading. The size of the experimental quasi beyond-design basis load (intensity, duration and other action parameters) shall be determined, taking the scale factor into account, and making it possible to avoid real damage to the structure. For example, the load on the structure (foundation subsidence) should be small enough that, when loading, no substantial plastic strain (deformation) occurs, and that system returns to its original state following quasi beyond-design actions;
- conduct an experiment simulating a possible accident. Determine the experimental values of coefficients of structural and inertia (if any) damping. Gathering data on the dynamic behaviour of these structures must be performed using modern industrial systems to record the values of the monitored parameters with a frequency of at least 50 Hz.

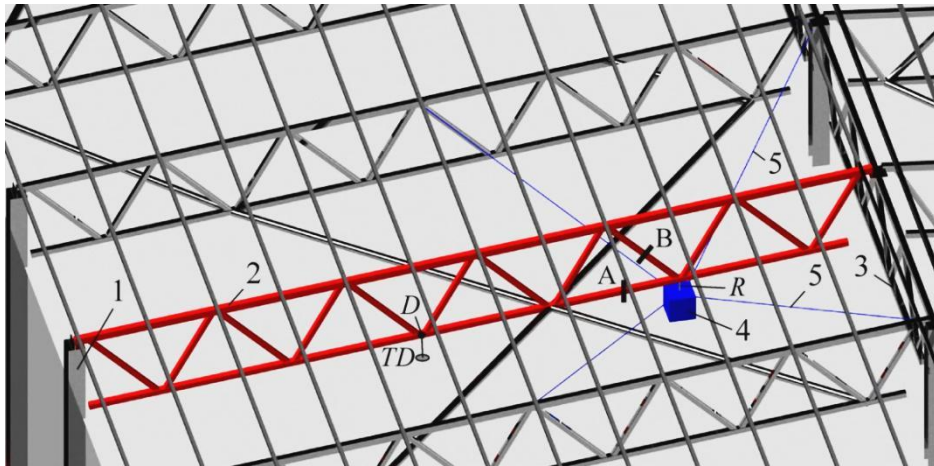
- conduct a structural analysis, taking into account the damping of vibrations and comparison of the results obtained with the experimental data, and a debugging test scheme with a calculation scheme that is adjusted if necessary;
- determine the parameters required, according to the security conditions, for the supporting frame system and equipment during beyond-design actions.

**Setting tasks for experimental investigations.** It is necessary to perform a dynamic analysis of roof truss FS-1, which is in extremely stressed-strained condition and is installed in the meat product storage building frame of the meat industry (Fig. 1). As beyond-design actions, it is necessary to consider the breakage of rope R (Fig. 2) connected to the node of the lower chord of the truss and with a load 4, while simulating the presence of the air-cooling device.



**Figure 1. Object of the experiment: a – solid model: 1 – column 2 – roof trusses, 3 – secondary truss, 4 – load, 5 – safety ropes, 6 – girders, 7 – braces on bottom chord of a truss, 8 – suspended ceiling of the sandwich panels, 9 – polymer floor of the shop, 10 – operated additional building; b – view A on the row of transverse frame, c – a photo of the object in the course of erection at the stage of installation of braces on bottom chords of trusses**

In this case, it is necessary to measure values of the dynamic *displacement* in the span and deformation of the individual structural elements and determine the values of the arising dynamic effects. According to the experiment's results, it is necessary to determine the maximum weight of the air-cooling device in ensuring the elastic behaviour of a truss in the event of an emergency situation under consideration.



**Figure 2. The scheme of tests: 1 – column 2 – truss FS-1 investigated, 3 – secondary roof truss, 4 – load, 5 – safety ropes, R – cut rope, RD – cable sensor, A, B – the location of the sections of rods with strain gauges installed**

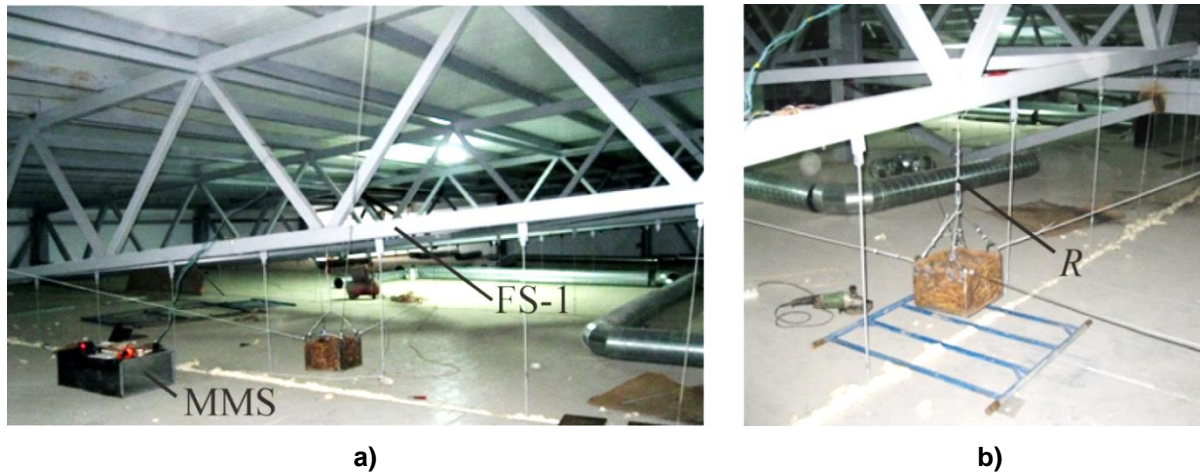
**Description of the structural system to be tested.** The object of the experiment is a flat roof truss FS-1 spanning 18 m as part of the frame of an industrial building workshop (Fig. 1a). The truss is made of square and rectangular pipes as per Russian State Standard GOST 30245-2003: the bottom chord of a profile is 140x6, the upper one is 180x6, and the grille is 100x4. The node for connecting rods is welded. The truss connections with the column and secondary truss are made of joint-fixed support nodes. From the plane, the truss is fastened with braces on the upper and bottom chords. At the level of the upper chord, the braces are located in the middle third of the truss span. At the level of the bottom chord, they are situated according to the scheme of the support braces' location, as shown in Fig. 1, pos. 7, and the one node is fastened. During the tests, the coating weight was taken into account and there was no snow load, but in the final calculation of the stress-deformed state, it was ultimately taken into account.

Load 4 is suspended using rope R in the assembly of the bottom chord (Fig. 3). In addition, safety ropes 5 are attached to the load in order to ensure the load transfer to the adjacent trusses in the case that rope R breaks. The safety ropes and suspension rope were used according to DIN 3055 with a diameter of 5/6 mm, type of stranding 6x7 + FC with a breaking force of not less than 11.2 kN. The load was made as a steel box, which is filled with steel plates. The total weight of the load is 180 kg. The picture of the truss test scheme fragment and assembly with a load is shown in Figure 3. The weight of the load was determined on the basis of preliminary calculations in a dynamic setting, taking into account the condition that the additional dynamic added load associated with emergency impact did not cause the appearance of plastic deformations in the structure.

### *Result and Discussion*

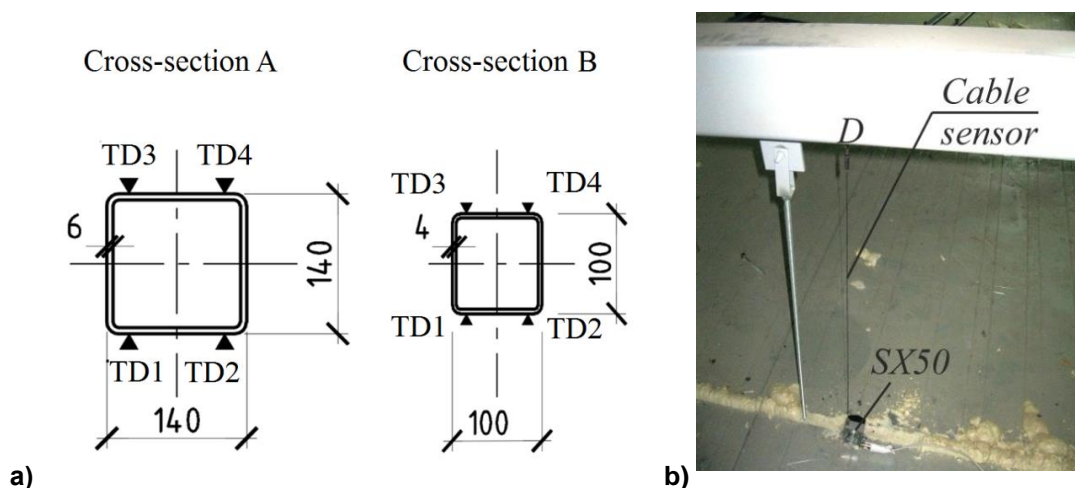
**Experiment plan.** The dynamic test of the truss was planned by the quick mechanical destruction of rope R with a load (Fig. 3,b). The state of the truss, through which operational loads were formed, including the structure's own weight and that of the girders and coating, load and safety system, was considered as the initial. In this state, it was planned to activate data collection systems for the measured values, and using the angle grinder to exclude rope R of the load from loading. According to the results of the preliminary dynamic calculation for the impact considered by us, it is necessary to measure displacements in time in node D of the truss (Fig. 2), and relative deformations in time in two rods: on the bottom chord and in the diagonal member, connected to the assembly from the side of the rest onto the column (cross-sections A, B on Fig. 2). Based on the results of measurements, it was planned to determine the level of maximum dynamic added loading (increase stress) in rods and maximum increase in displacements in case of emergency situation related to the breakage of the real technological equipment (air-cooled devices) with different weights.



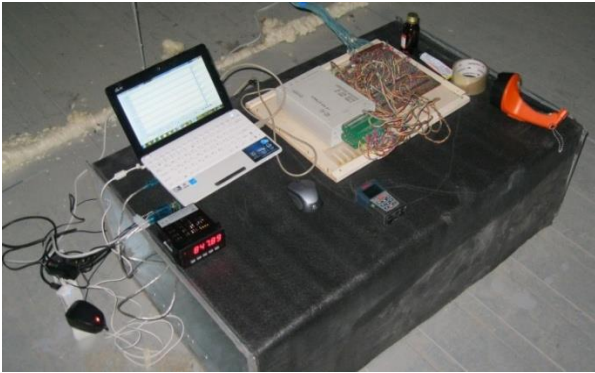


**Figure 3. Photo of preparing a design for testing: a – general scheme: FS-1 – the truss tested in span of 18 m; MMS – mobile measuring station; b – the load on the suspension R and safety ropes**

**The measurement scheme, devices and equipment.** In each of the cross-sections A, B (Figs. 2, 4, 6), a group of strain gauges TD1-TD4 of the type KF 5P1-3-200B12 with a base of 5 mm and a resistance of  $200 \text{ ohm} \pm 0.2$  were installed. Resistive strain gauge bases were placed in parallel to the longitudinal axis of the rod. To affix gauges on the truss, the glue of cold hardening cyanoacrylate “Tsiakrin AO” was used. Output signals of the strain amplifier were recorded using a crate data acquisition system L-CARD LTR EU-2 with chips ADC LTR-212, allowing to carry out a survey of gauges with frequency up to 3,000 Hz. The mode information collection with a frequency of 1,536 Hz was used in the experiment. Data obtained by the crate system was transmitted to a computer and processed by an electronic recorder Lgraph 2.0, which has the ability to visualize the measured deformations in time. At point D (see Fig. 2), vertical displacements were measured using the cable sensor SX50-1250-16-L-SR with the accuracy of 524 pulses within 1 mm of the cable stroke ( $2 \cdot 10^{-3} \text{ mm}$ ), a digital indicator PAX-I, and video camera with a recording frequency of 60 frames per second. This cable sensor was attached to a steel rod that passed through cover 8 (Figure 1) and attached to a ladder standing on floor 9 of the shop. The diagrams of displacements were based on a non-interlaced scan of a video file with the recording of the readings of the indicator PAX-I in each of the frames and their further processing. Discrete data obtained about the displacements and deformation of the frame were processed in the soft MATLAB 2015a with use of the one-dimensional wavelet transform using Meyer wavelet, which allowed the removal of noise and maintained continuous dependencies corresponding to the main frequency of the truss’ own vibrations. The mechanical properties of steel, which the truss is made from, were taken from the test report attached to the steel certificate. Yield stress of the material  $\sigma_m = 340 \pm 20 \text{ MPa}$ , relative deformations  $\varepsilon_m = 0.0015 \pm 0.0004$ .



**Figure 4. Location of strain gauges in sections A, B (a) and scheme of installation of the cable sensor (b)**



**Figure 5. MMS: crate system, cable sensor and an indicator connected to a computer**



**Figure 6. Installation of strain gauges on the truss rods**

At the emergency impact considered, the additional loading of the truss has not caused a significant formation of permanent deformations. The view of the load 4 (Fig. 2) after the rope R breakage is shown in Figure 7.

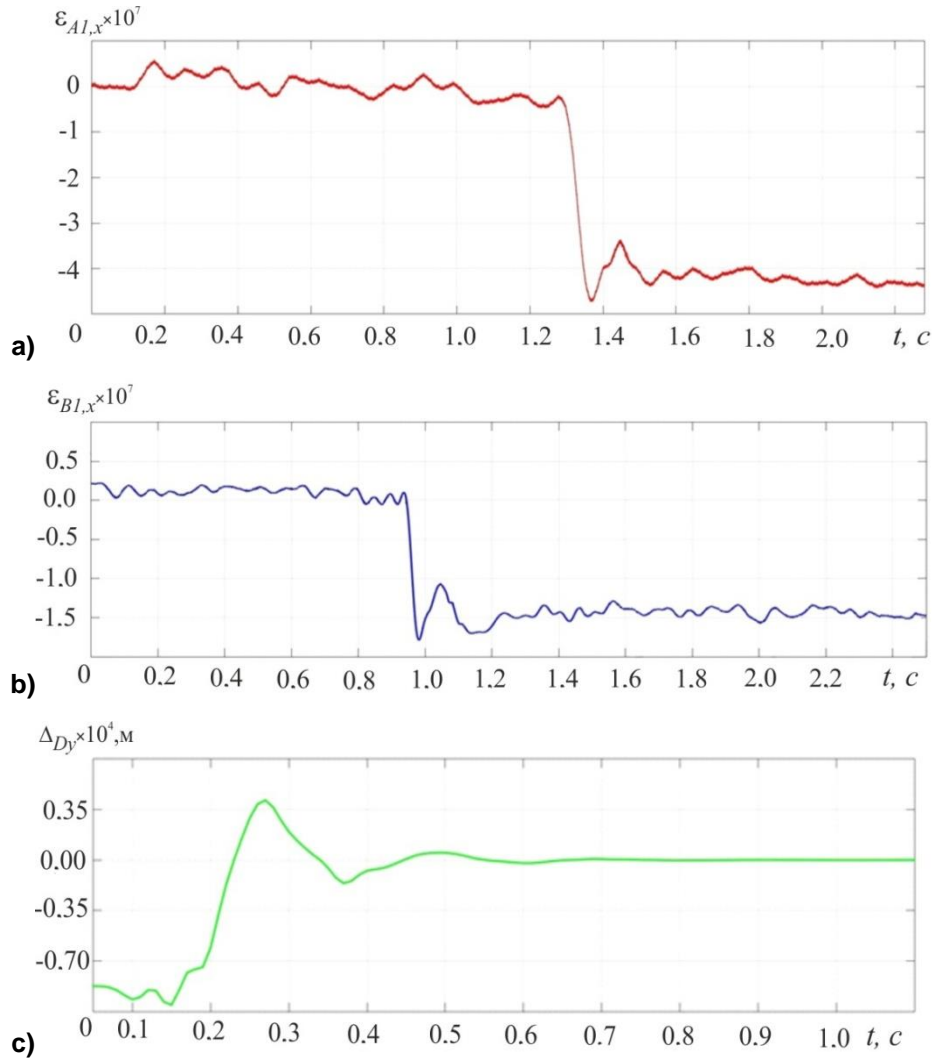


**Figure 7. The load on the safety ropes**



**Figure 8. Installed air-cooling devices**

The damping of the structure's vibrations was observed for 0.4–0.7 seconds after the emergency impact. Figure 9 shows the data of the measured values of longitudinal deformations  $\varepsilon$  and the vertical displacement of point D (see Fig. 3, 4, b), which shows that the maximum modulus of the values of displacements and deformations are achieved in the first quarter of the period for the main form of vibrations.



**Figure 9. Graphs of changes of deformations in time:**  
**a – deformations registered by the strain gauge TD1 on the lower chord;**  
**b – readings of the gauge TD2 on the diagonal member compressed;**  
**c – the vertical displacements of the point D measured using the cable sensor**

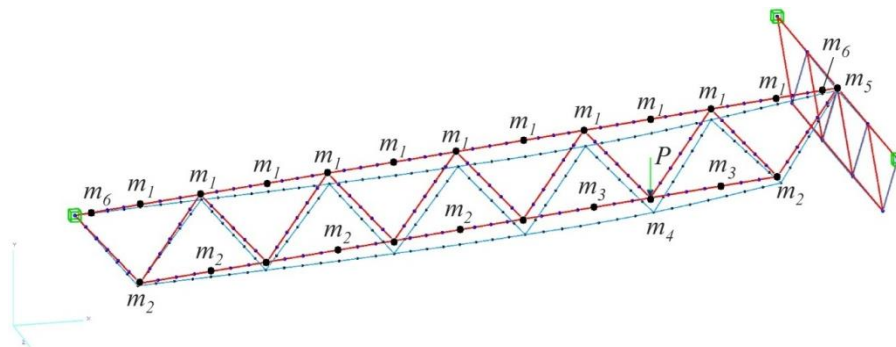
**Calculation of beyond-design actions.** The truss calculation was performed in a dynamic setting, taking into account the material's linear-elastic behaviour and based on the methodology described in [22]. To analyse the dynamic behaviour of the truss system, the equation was used:

$$[M(\{Z\})]\{\ddot{Z}\} + [C(\{Z\})]\{\dot{Z}\} + \{R(\{Z\})\} = \{F(t)\} + G\chi(t), \quad (1)$$

where  $[M(\{Z\})]$ ,  $[C(\{Z\})]$  – matrices of the masses and damping;  $\{R(\{Z\})\}$ ,  $\{Z\}$  – vectors of nodal reactions and generalized nodal displacements;  $\{F(t)\}$  – vector of loads acting on the normative actions;  $G$  – vector, defined by gravity forces of drop;  $\chi(t)$  – Heaviside function.

On the basis of applying the method of the peaks set forth in the paper [23], the value of the structural damping coefficient  $\beta = 0.02$  was calculated. In the case of load impact, the dynamic yield limit  $\sigma_m^D$  shall be determined in a simplified way according to the recommendations of [23]:  $\sigma_m^D = 1.1 \cdot \omega^{1/17} \cdot \sigma_m$  where  $\omega$  is the lowest frequency of the structure's vibrations. According to experimental measurements, it is  $\omega = 27.1 \text{ Hz}$  for the investigated structure. Then we have  $\sigma_m^D = 1.1 \cdot 27.1^{1/17} \cdot 320 \approx 427 \text{ MPa}$ . We introduced single supporting fastenings at the joints with braces at the upper and bottom chords of the adjacent trusses. The object's deformations were described

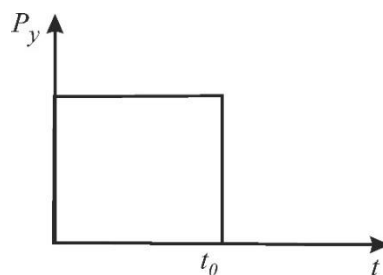
by the rod finite elements. The secondary roof truss was discretised in a simplified way, as its stress-deformed state was not considered in detail (Fig. 10).



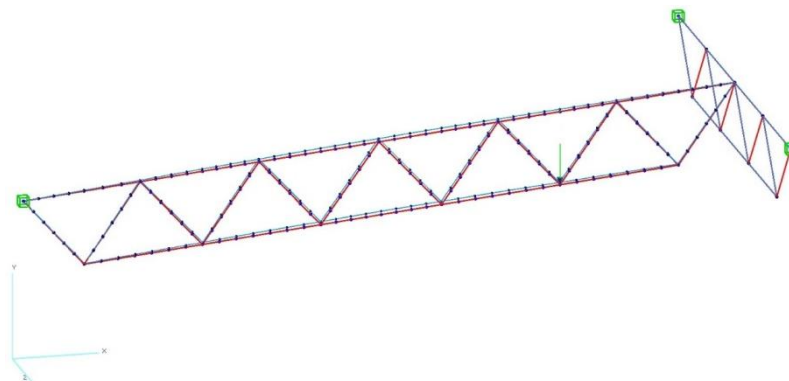
**Figure 10. Design and deformed scheme of the truss at time  $t_0$  before removing the load**

The actions from operating loads on the truss were taken into account in the form of concentrated nodal masses  $m_1 - m_6$  on vertical degrees of freedom. The mass  $m_1$  takes into account the presence of girders and cover structures of the shop,  $m_2$  – the ceiling affixed on suspensions (see Figure 3,a),  $m_3 = m_2 + m_4$ ,  $m_4$  – one-third of the weight of the installer cutting the rope,  $m_5$  – mass born by the secondary roof structure from the action of the truss and structures resting on it in a nearby span,  $m_6 = m_2 / 2$ . The force of gravity of the load  $P_y = -1765$  N (Fig. 11) was taken into account. The value  $t_0$  was determined under the condition of damping for vibrations of the system after the load is affixed on the structure. After this time, the load was removed.

Figure 12 reflects the truss deformation according to beyond-design actions at  $t = 0.375$  s, which corresponds to its maximum bending. The scale of movements has increased 100 times in comparison with the scale of the object image. The graph of the point  $D$  movement is shown in Fig. 13. The table compares the results of theoretical analysis of the truss with experimental data, according to the values of the modulus of maximum vertical displacement in time at the point  $D$  ( $|V_D|_{\max}$ ) and the maximum in time stresses in the rods. Table 1 shows that calculated and experimental data are satisfactorily matched. The results of the actual additional loading on the truss, depending on the weight  $m_{\max}$  of refrigeration systems, are shown in Table 2. Here,  $\Delta\sigma_{\max}$  is the truss margin of safety.



**Figure 11. Change in force in time**



**Figure 12. The design and deformed scheme of the truss at time  $t=0.375$  s after removing the load**



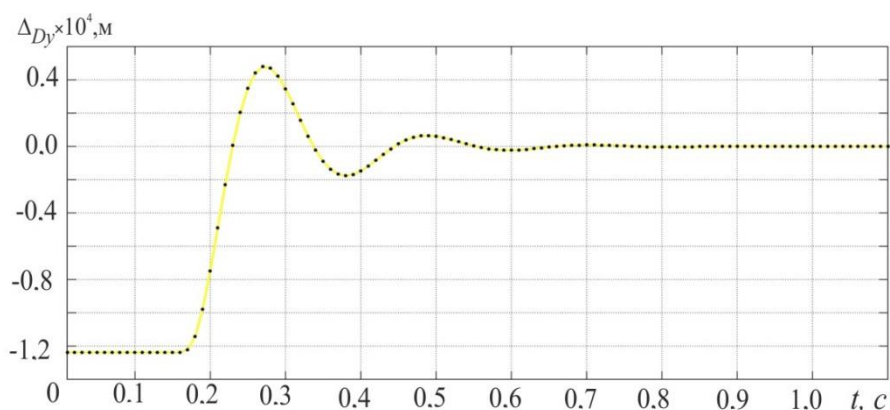


Figure 13. Results of the theoretical calculation of point D displacement in time

Table 1. Results of experimental and theoretical research on truss FM-1

| Measurements using a cable sensor and strain gauges (Figs. 2, 4) |     | $ V_D _{\max} \cdot 10^4, \text{ m}$ |             | $\sigma_{S1}, \text{ kPa}$ |             | $\sigma_{S2}, \text{ kPa}$ |             |
|--|-----|--------------------------------------|-------------|----------------------------|-------------|----------------------------|-------------|
|  |     | Experiment                           | Calculation | Experiment                 | Calculation | Experiment                 | Calculation |
| Node   | TD  | 1.340                                | 1.678       | -                          | -           | -                          | -           |
| Lower chord rod  | TD1 | -                                    | -           | 9500                       | 11000       | -                          | -           |
|  | TD2 | -                                    | -           | 4400                       | 7900        | -                          | -           |
|  | TD3 | -                                    | -           | 7300                       | 11000       | -                          | -           |
|  | TD4 | -                                    | -           | 6100                       | 7900        | -                          | -           |
| Diagonal member  | TD1 | -                                    | -           | -                          | -           | 3100                       | 4100        |
|  | TD2 | -                                    | -           | -                          | -           | 8400                       | 4600        |
|  | TD3 | -                                    | -           | -                          | -           | 5500                       | 4100        |
|  | TD4 | -                                    | -           | -                          | -           | 2100                       | 4600        |

Table 2. Results of experimental and theoretical research on truss FS-1

| Name                               | Values of dynamic additional loads at the breakage of the air-cleaning device at a mass $m_{\max}$ kg |     |     |     |      |      |      |      |
|------------------------------------|---|-----|-----|-----|------|------|------|------|
|                                    | 180*  | 200 | 500 | 800 | 1100 | 1400 | 1700 | 2000 |
| $\Delta\sigma_{\max}, \text{ MPa}$ | 11*   | 12  | 31  | 49  | 67   | 86   | 104  | 122  |

\* the value is obtained experimentally, and the remaining values obtained by the linear interpolation.

We did not find in the literature of similar facilities to compare the results of experimental studies. However, the overall behavior of the object under emergency exposures, which are considered, perfectly corresponds to the dynamics of structures, studied in the works [11, 12, 21], with similar effects.

### Conclusions

This paper has proposed a method for experimental and theoretical research on the stressed and deformed state of steel structures under emergency actions not taken into account in design standards.

1. We have established that calculations and tests on the truss as part of the building frame under actual impact have confirmed the efficiency of the proposed methodology of the investigation designs in emergency situations, as well as the accuracy of the paper proposed by the authors [22] about modifying the method for calculating systems damaged by directly integrating equations for objects' motion.

2. We have found that, for the considered beyond-design impacts on the truss, the maximum values of displacements and deformations were observed in the first quarter of the period of the main form of vibrations, which can be used in assessing such structural systems' ability to survive.

3. When solving the problem of determining the mass of the air-cooling device, the breakage of which has had an impact on the design of the truss, we found that the level of dynamic additional loading in the rods, at the values of this mass not exceeding 500 kg, has had no significant effect on the support system's stress-strain state.

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#### References

#### Литература

- Kolchunov V.I., Skobeleva Ye.A., Klyuyeva N.V. Experimental researches of deformations and crack resistance of reinforced concrete structures with composite section strain. *Structural Mechanics of Engineering Constructions and Buildings*. 2008. No. 1. Pp. 54–60. (rus).
- Bondarenko V.M., Klyuyeva N.V., Degtyar A.N. Optimizatsiya zhivuchesti konstruktivno nelineynykh zhelezobet-onnykh ramno-sterzhnevyykh sistem pri vnezapnykh strukturnykh [The optimisation of the survivability of structurally nonlin-ear reinforced concrete frame-bar systems at sudden structural loads]. *Izvestiya-Orel GTU. Seriya "Stroitel'stvo. Transport"*. 2007. No. 4. Pp. 5–10. (rus).
- Klyuyeva N.V., Shuvalov K.A. Methods of experimental determination of parameters of deformation and destruction of statically indeterminate pre-stressed reinforced concrete beam systems in the out-of-limit state. *Vestnik MGSU*. 2012. No. 11. Pp. 61–66. (rus).
- Tamrazyan A.G. Rekomendatsii k razrabotke trebovaniy k zhivuchesti zdaniy i sooruzheniy [Recommendations to the development of requirements for survivability of buildings and structures]. *Vestnik MGSU*. 2011. No. 2. Vol. 1. Pp. 77–83. (rus).
- Kolchunov V.I., Perelygin S.S. Eksperimental'nyye issledovaniya ramno-sterzhnevyykh konstruktivnykh sistem s el-ementami sostavnogo secheniya pri vnezapnom vyklyuchenii svyazey [Experimental investigations of the frame-rod struc-tural systems with elements of the composite section at the sudden exclusion of braces]. *Stroitel'naya mekhanika inzhenernykh konstruksiy i sooruzheniy*. 2006. No. 2. Pp. 115–121. (rus).
- Schramm B., Richard H.A., Kullmer G. Theoretical, experimental and numerical investigations on crack growth in fracture mechanical graded structures. *Engineering Fracture Mechanics*. 2016. No. 167. Pp. 188–200.
- Gordon V.A., Klyuyeva N.V., Poturayeva T.V. Raschet dinamicheskikh usiliy v konstruktivno-nelineynykh elementakh sterzhnevyykh prostranstvennykh sistem pri vnezapnykh strukturnykh izmene-niyakh [Calculation of dynamic forces in structural and non-linear elements of spatial rod systems at sudden structural changes]. *Stroitel'naya mekhanika i raschet sooruzheniy*. 2008. No. 6. Pp. 26–30. (rus).
- Fedorov V.S., Mednov E.A. Vliyaniye iskhodnogo napryazhenno-deformirovannogo sostoyaniya i urovnya nagru-zheniya na voznikayushchiy dinamicheskiy effekt pri avariynom razrushenii opory v nerazreznykh stalnykh balkakh [The effect of initial stressed and deformed state and the level of loading on the dynamic effect occurring in case of emergency support destruction in solid steel beams]. *Stroitel'stvo i rekonstruktsiya*. 2010. No. 6. Pp. 48–52. (rus).
- Serpik I.N., Leletko A.A., Alekseytsev A.V. Evolyutsionnyy sintez metallicheskiy ploskiykh ram v sluchaye otsenki nesushchey sposobnosti po metodu predelnogo ravnovesiya [The evolutionary synthesis of metallic flat frames in the case of evaluation of the bearing capacity using the method of limit equilibrium]. *News of higher educational institutions. Construction*. 2007. No. 8. Pp. 4–9.
- Kolchunov V.I., Skobeleva E.A., Klyueva N.B. Экспериментальные исследования деформативности и трещи-нотойкости железобетонных конструкций составного сечения // *Строительная механика инженерных конструкций и сооружений*. 2008. № 1. С. 54–60.
- Бондаренко В.М., Ключева Н.В., Дегтярь А.Н. Оптимизация живучести конструктивно нелинейных железобе-тонных рамно-стержневых систем при внезапных структурных // *Известия ОрелГТУ. Серия «Строительство. Транспорт»*. 2007. № 4. С. 5–10.
- Ключева Н.В., Шувалов К.А. Методика экспериментального определения параметров деформирования и раз-рушения преднапряженных железобетонных статически неопределимых балочных систем в запредельных состо-яниях // *Вестник МГСУ*. 2012. № 11. С. 61–66.
- Тамразян А.Г. Рекомендации к разработке требований к живучести зданий и сооружений // *Вестник МГСУ*. 2011. № 2. Т. 1. С. 77–83.
- Колчунов В.И., Перельгин С.С. Экспериментальные исследования рамно-стержневых конструктивных си-стем с элементами составного сечения при внезапном выключении связей // *Строительная механика инженерных конструкций и сооружений*. 2006. № 2. С. 115–121.
- Schramm B., Richard H.A., Kullmer G. Theoretical, experimental and numerical investigations on crack growth in fracture mechanical graded structures // *Engineering Fracture Mechanics*. 2016. No. 167. Pp. 188–200.
- Гордон В.А., Ключева Н.В., Потураева Т.В. Расчет динамических усилий в конструктивно-нелинейных эле-ментах стержневых пространственных систем при внезапных структурных изменениях // *Строительная механика и расчет сооружений*. 2008. № 6. С. 26–30.
- Федоров В.С., Меднов Е.А. Влияние исходного напряженно-деформированного состояния и уровня нагруже-ния на возникающий динамический эффект при аварийном разрушении опоры в неразрезных стальных балках // *Строительство и реконструкция*. 2010. № 6. С. 48–52.
- Серпик И.Н., Лелетко А.А., Алексейцев А.В. Эволюционный синтез металлических плоских рам в случае оценки несущей способности по методу предельного равновесия // *Известия высших учебных заведений. Строи-тельство*. 2007. № 8. С. 4–9.
- Алексейцев А.В., Курченко Н.С. Поиск рациональных параметров стержневых металлоконструкций на основе адаптивной эволюционной модели // *Строительная механика инженерных конструкций и сооружений*. 2011. № 3. С. 7–14.
- Gade V.P. Sahoo D.R Evaluation of collapse-resistance of special truss moment frames as per FEMA969 ap-proach // *Engineering Structures*. 2016. No. 126. Pp. 505–515.
- Brunell G., Kim Y.J. Effect of local damage on the behavior of a laboratory-scale steel truss bridge // *Engineering Structures*. 2013. No. 48. Pp. 281–291.
- Bo Y., Kang H.T. Experimental tests of different types of

Alekseytsev A.V., Kurchenko N.S. Deformations of steel roof trusses under shock emergency action. *Magazine of Civil Engineering*. 2017. No. 5. Pp. 3–13. doi: 10.5862/MCE.73.1.

- (rus).
10. Alekseytsev A.V., Kurchenko N.S. Poisk ratsional'nykh parametrov sterzhnykh metallokonstruktsiy na osnove adaptivnoy evolyutsionnoy modeli [The search for rational parameters of the rod metal structures on the basis of adaptive evolution model]. *Stroitel'naya mekhanika inzhenernykh konstruktsiy i sooruzheniy*. 2011. No. 3. Pp. 7–14. (rus).
  11. Gade V.P., Sahoo D.R. Evaluation of collapse-resistance of special truss moment frames as per FEMA695 approach. *Engineering Structures*. 2016. No. 126. Pp. 505–515.
  12. Brunell G., Kim Y.J. Effect of local damage on the behaviour of a laboratory-scale steel truss bridge. *Engineering Structures*. 2013. No. 48. Pp. 281–291.
  13. Bo Y., Kang H.T. Experimental tests of different types of bolted steel beam–column joints under a central-column-removal scenario. *Engineering Structures*. 2013. No. 54. Pp. 112–130.
  14. Gosaye J., Gardner L., Wadee M.A., Ellen M.E. Tensile performance of pre-stressed steel elements. *Engineering Structures*. 2014. No. 79. Pp. 234–243.
  15. Theofanous M., Liew A., Gardner L. Experimental study of stainless steel angles and channels in bending // *Structures*. 2015. No. 4. Pp. 80–90.
  16. Farsi A., Keshavarzi F., Pouladi P., Mirghaderi R. Experimental study of a replaceable steel coupling beam with an end-plate connection // *Journal of Constructional Steel Research*. 2016. No. 122. Pp. 138–150.
  17. Andrade S.A.L., Vellasco P.C.G., Silva J.G.S., Lima L.R.O., D'Este A.V. Tubular space trusses with simple and reinforced end-flattened nodes-an overview and experiments // *Journal of Constructional Steel Research*. 2005. No. 61. Pp. 1025–1050.
  18. Liu M., Zhao J., Jin M. An experimental study of the mechanical behavior of steel planar tubular trusses in a fire // *Journal of Constructional Steel Research*. 2010. No. 66. Pp. 504–511.
  19. Jankowska-Sandberg J., Kolodziej J. Experimental study of steel truss lateral-torsional buckling // *Engineering Structures*. 2013. No. 46. Pp. 165–172.
  20. Yuan Y., Tan P.J., Shojaei K.A., Wroble P. Large deformation, damage evolution and failure of ductile structures to pulse-pressure loading // *International Journal of Solids and Structures*. 2016. No. 96. Pp. 320–339.
  21. Attar M., Karrech A., Regenauer-Lieb K. A lattice spring model for dynamic analysis of damaged beam-type structures under moving loads // *European Journal of Mechanics - A/Solids*. 2016. No. 60. Pp. 196–207.
  22. Серпик И.Н., Курченко Н.С., Алексейцев А.В. Анализ в геометрически, физически и конструктивно нелинейной постановке динамического поведения плоских рам при запроектных воздействиях // *Промышленное и гражданское строительство*. 2012. № 10. С. 49–51.
  23. Deb K. *Optimisation for engineering design*. New Delhi: Prentice-Hall of India Private Limited, 2005. 383 p.
  24. bolted steel beam-column joints under a central column removal scenario // *Engineering Structures*. 2013. No. 54. Pp. 112–130.
  25. Gosaye J., Gardner L., Wadee M.A., Ellen M.E. Tensile performance of prestressed steel elements // *Engineering Structures*. 2014. No. 79. Pp. 234–243.
  26. Theofanous M., Liew A., Gardner L. Experimental study of stainless steel angles and channels in bending // *Structures*. 2015. No. 4. Pp. 80–90.
  27. Farsi A., Keshavarzi F., Pouladi P., Mirghaderi R. Experimental study of a replaceable steel coupling beam with an end-plate connection // *Journal of Constructional Steel Research*. 2016. No. 122. Pp. 138–150.
  28. Andrade S.A.L., Vellasco P.C.G., Silva J.G.S., Lima L.R.O., D'Este A.V. Tubular space trusses with simple and reinforced end-flattened nodes-an overview and experiments. *Journal of Constructional Steel Research*. 2005. No. 61. Pp. 1025–1050.
  29. Liu M., Zhao J., Jin M. An experimental study of the mechanical behaviour of steel planar tubular trusses in a fire. *Journal of Constructional Steel Research*. 2010. No. 66. Pp. 504–511.
  30. Jankowska-Sandberg J., Kolodziej J. Experimental study of steel truss lateral-torsional buckling. *Engineering Structures*. 2013. No. 46. Pp. 165–172.
  31. Yuan Y., Tan P.J., Shojaei K.A., Wroble P. Large deformation, damage evolution and failure of ductile structures to pulse-pressure loading. *International Journal of Solids and Structures*. 2016. No. 96. Pp. 320–339.
  32. Attar M., Karrech A., Regenauer-Lieb K. A lattice spring model for dynamic analysis of damaged beam-type structures under moving loads. *European Journal of Mechanics - A/Solids*. 2016. No. 60. Pp. 196–207.
  33. Serpik I.N., Kurchenko N.S., Alekseytsev A.V. Analysis of the dynamic behavior of plane frames at emergency actions considering geometrical, material and structural nonlinearities. *Promyshlennoye i grazhdanskoye stroitelstvo*. 2012. No. 10. Pp. 49–51. (rus).
  34. Deb K. *Optimisation for engineering design*. New Delhi: Prentice-Hall of India Private Limited, 2005. 383 p.

Anatoly Alekseytsev,  
+7(960)5643358; aalexw@mail.ru

Natalya Kurchenko,  
+7(920)602-32-40; ms.kurchenko@mail.ru

Анатолий Викторович Алексейцев,  
+7(960)5643358; эл. почта: aalexw@mail.ru

Наталья Сергеевна Курченко,  
+7(920)602-32-40; эл. почта:  
ms.kurchenko@mail.ru

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