Determination of the dynamic coefficient by the local damage of the element of steel trusses

Maria Berger and Alexandr Tusnin

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia

E-mail: marieberger@yandex.ru

Abstract. An important role in the robustness analysis of damaged structures, is played by time during which local damage of the elements of the system occurs. Numerical studies have shown that the shorter the failure time of a particular farm element, the greater the dynamic forces arising in the structure. The time from the beginning of destruction to the complete failure of an element, which consists either in destruction or in loss of stability, is called the time of exclusion. The article describes the results of a series of numerical calculations of steel trusses as part of the building frame with local damage of individual truss elements. The influence of the time of exclusion of the element and the location of its damage on the value of dynamic coefficient was studied. The frame of the building is considered as a space frame, including not only trusses with local damage and the columns on which it relies, but also neighboring trusses, columns, bracing and purlins. This approach allowed to study the effect of local damage on the behavior of intact bearing structures. Based on the calculations, dynamic factors were established for the load acting on the truss with local damage and for the load on adjacent structures of the space frame. Recommendations are offered on constructive measures to increase the robustness of a building with steel trusses. The most unfavorable options for local damage of the trusses have been established. Recommendations are given on the assignment of dynamic coefficient for conducting a static calculation that takes into account the dynamic effects in the building frame with local damage of the truss.

1. Introduction

When designing buildings and structures, the problem of preventing the progressive collapse of buildings or ensuring the robustness of structures in case of damage has to be solved. Regulatory documents of many countries contain instructions for calculations related to ensuring the load-bearing capacity of structures in case of accidental actions [1-6]. However, in Russian Federation there is still no methodology for calculating damaged structures approved and adapted for widespread use. A large number of studies are devoted to the problem of protecting high-rise buildings from progressive collapse. The bearing capacity of damaged steel frames of industrial buildings has been less studied, despite the fact that the destruction of many industrial buildings also leads to significant social, environmental and material losses [7].

At the moment, several main areas of research on the problem of safety of buildings and structures can be distinguished [8]:

- elimination of the potential danger of accidental exposure through the use of preventive or organizational measures;
- reserving the strength of structural key elements or creating alternative ways of transferring loads from accidental impacts;
- accounting for the spatial work of the constructive system;
- dynamic forces arising in the structure when any element (unit, section) is damaged;
- accounting for operational wear and structural damage;
- assessment of structures in terms of catastrophe theory. In the framework of catastrophe theory, the process of supercritical behavior of system elements is studied. At the onset of a supercritical state, elements fail and affect other elements of the system, giving rise to internal negative effects. External and internal influences lead to a sequence of failures of system elements that initiate its transition to an emergency state.

A large number of studies to ensure the stability and reliability of structures is devoted to methods for protecting structures from the consequences of accidental actions [9-17]. In the framework of the study, the dependence of the bearing capacity of the damaged steel truss of an industrial building on the time of local damage is studied. The causes of the damage of an element may be errors in design, manufacture, installment or operation. In this paper, terrorist impacts and technological explosions are not considered as causes of destruction.

2. Methods
Local damage of a structural element of the system (element failure) leads to a change in the design scheme and the occurrence of dynamic effects, which requires consideration when performing structural analysis. In some cases, a dynamic calculation can be replaced by a static one, performing the calculation taking into account the dynamic coefficient [18]. When using this analysis method, a load multiplied by a dynamic coefficient is applied to the calculation scheme with a damaged element. In the general case, two main dynamic coefficients are applied [19]:

1. The dynamic coefficient of displacement, which is the ratio of maximum dynamic displacement to maximum static.
   \[ k_d = \frac{w_d}{w_c} \]  
   where \( w_d \) is the maximum displacement of the system under the action of dynamic load; \( w_c \) - maximum movement of the system caused by the action of static load.

2. The dynamic coefficient of the load, which is the ratio of dynamic to static forces.
   \[ k_d = \frac{P_d}{P_c} \]  
   where \( P_c, P_d \) are the values of static and dynamic loads.

The value of the dynamic coefficient depends on a number of factors - the location of the damaged element in the structure, the time of failure of the element and the current load. If an instantaneous failure of an element is assumed, the value of the dynamic coefficient, as a rule, is taken \( k_d = 2 \). However, for some structures, local damage that occurs (even with an instant failure) does not always lead to the appearance of dynamic effects corresponding to \( k_d = 2 \). Therefore, the determination of dynamic coefficients for simple structures with various damages is of great practical importance.

The solution can be divided into several main stages:

1. The study of the influence of the time of failure of the element (time of exclusion) on the value of the dynamic coefficient;
2. The study of the dependence of the value of the dynamic coefficient on the location of the damaged truss element (lower belt, upper belt, support brace, stretched or compressed brace);
3. The study of the dynamic coefficient of the load on the bearing structures of the spatial frame of a one-story building with local damage of the truss element.

The operation of damaged steel trusses as part of the framework of a large-span building was studied using the Femap with NX Nastran. The analysis model of the building was constructed by the rod elements, type “beam”. Dynamic calculation was performed using the module 3..Transient Dynamic / Time History. The load was applied to the purlins according to the graph shown in Figure 1 - the load increases from 0 to its full value within 10 seconds and then remains unchanged. A damaged
The rod is modeled as follows - the rod is removed from the design scheme and replaced by the forces corresponding to the forces in this element when calculating the undamaged structure. The forces in the removed rod increase from zero to the full value within 10 seconds, then decrease to zero over the time interval $\Delta t$ in accordance with the graph shown in Figure 2. The coefficient of structural damping is assumed to be 0.1, the number of calculation steps is 3000, and the calculation step is 0.01 sec. The frequency of determining the equivalent viscous damping coefficient for each option is taken to be equal to the first natural frequency of the damaged structure.

**Figure 1.** Graph of external load for purlins.

**Figure 2.** Graph of changes in the forces of a damaged rod over time.

Numerical calculations were carried out for the following options for damage to the farm:
1. damage to the most loaded element of the lower belt;
2. damage to the most loaded element of the upper belt;
3. damage to the support brace;
4. damage to the most loaded compressed brace;
5. damage to the most loaded stretched brace.
The dynamic behavior of the frame structure with a damaged truss is investigated for the following exclusion periods $\Delta t$, during which the efforts in the rod are reduced, sec.: 0.01; 0.1; the period of the first waveform; 2.0. In addition, based on the results of previous experiments [20, 21], the exclusion time $\Delta t = 0.12$ s for stretched elements and $\Delta t = 1$ s for compressed elements was considered. The maximum displacements and forces in the damaged structure determined by dynamic calculations were compared with the corresponding parameters determined by the static calculation of the damaged structure. Figure 3 shows a spatial model of the calculated large-span building with a damaged farm.

**Figure 3.** A spatial model of a large-span building.

### 3. Results
As a result of the calculation, the distribution of the dynamic coefficient is obtained depending on the time of exclusion and the place of local damage to the truss element. Table 1 shows the maximum values of the dynamic coefficients of the load for a damaged steel truss.

**Table 1.** The values of the dynamic coefficient at different time of exclusion of element

| Place of local damage of the truss | Time of exclusion $\Delta t$, s | 0.01 | 0.1 | 0.12 | 1 |
|-----------------------------------|--------------------------------|------|-----|------|---|
| Lower belt                        |                               | 1.735| 1.714| 1.657| 1 |
| Upper belt                        |                               | 1.814| 1.779| 1.702| 1.239 |
| Support brace                     |                               | 1.325| 1.287| 1.216| 1.174 |
| Stretched brace                   |                               | 1.148| 1.118| 1.102| 1.067 |
| Compressed brace                  |                               | 1.121| 1.106| 1.099| 1.046 |

Previous experiments with damaged flat trusses showed that for compressed elements the failure time depends on the flexibility of the rod and exceeds 1 s. For elements with flexibility greater than $\lambda = 120$, the failure time is not limited, because the rod continues to maintain stability at a constant value of the load. Based on this, the exception time for the damaged compressed element is $\Delta t = 1$ s.
Dynamic forces smaller in magnitude than in a damaged truss develop in neighboring trusses. Figures 4 and 5 show a diagram of the distribution of the dynamic coefficient for the entire coating of a building. Figure 4 refers to the option of damaging the farm belt, Figure 5 – damaging one of the braces. A longitudinal section of the building along the digital axes is shown in the lower part of the figure. Bearing roof trusses are located along the letter axes. A dynamic coefficient value is given above each farm. Damaged farms are located and highlighted in the diagram by solid hatching. Above the numerical values, a diagram of the distribution of the dynamic coefficient is constructed.

**Figure 4.** Diagram of the distribution of the dynamic coefficient in case of damage to the belts.

**Figure 5.** Diagram of the distribution of the dynamic coefficient in case of damage to the braces.

The figures show that the maximum value of the dynamic coefficient corresponds to a damaged farm, for two neighboring farms, the dynamic coefficients ranged from 1,055 to 1,036. For subsequent farms, the dynamic forces remain virtually unchanged and range from 1.053 to 1.013.

4. **Discussion**

When modeling the local destruction of an element, different authors set differently the exclusion time of the damaged element. In [22, 23], the authors specify the exclusion time in fractions of the period of natural oscillations. In [24], the authors considered several design situations and assumed an exclusion time of 1 s, while a failure time exceeding 1 s does not significantly affect the forces and deformations. In the framework of this study, numerical calculations did not reveal the dependence of the exclusion time on the period of natural oscillations.

In [20, 21], the time of exclusion was experimentally investigated. In [20], a series of tests of steel rods of a solid square section was performed. During the experiment, part of the rods was stretched to failure, while others were centrally compressed until the bearing capacity was exhausted due to loss of stability. In [21] the results of experimental studies of flat trusses with damage to individual truss rods are presented. Three experiments were carried out: in the first, the work of a compressed belt was studied with a loss of flexibility, in the second and third, the redistribution of efforts in the truss when
the element of the lower and upper belts was damaged. Based on the data obtained, the time of exclusion and the redistribution of efforts to neighboring elements of the farm were calculated.

The exclusion time for damaged stretched rods and elements of flat trusses according to the results of experimental studies was 0.341 ÷ 0.429 and 0.12, respectively. The exclusion time for damaged compressed rods and truss elements was 1 ÷ 4.194 and 2.9, respectively. For compressed rods, the exclusion time depends on the flexibility of the damaged rod; the greater the flexibility, the longer the exclusion time.

The final value of the time for damage truss elements is proposed to be assigned taking into account the obtained experimental data.

5. Conclusions
Based on a comprehensive study of the work of damaged steel trusses covering an industrial building, it can be concluded that the most unfavorable option for damage is failure of the most loaded belt element (upper or lower). Taking into account the data of experimental studies, it is permissible to take the most unfavorable exclusion time: for stretched elements - 0.12 s, for compressed elements - 1 s. For the selected time, Figures 6, 7 show diagrams of the distribution of the dynamic coefficient.

Figure 6. Diagram of the distribution of the dynamic coefficient in case of damage to the stretched element of the truss.

Figure 7. Diagram of the distribution of the dynamic coefficient in case of damage to the compressed element of the truss.

The figures show that for the accepted exclusion time, the values of the dynamic coefficients in damaged farms are reduced by 1.2÷1.4 times, for farms adjacent to the damaged one, the dynamic coefficient values remain almost unchanged.

To increase the stability of the building frame against progressive collapse, the following design measures can be proposed:
1. Installation of vertical bracing in each panel of the truss (Figure 8).
Figure 8. Scheme of the spatial frame of the building with additional vertical bracing.

Such a constructive solution based on the multivariate calculations is the most effective and cost-effective method. Vertical bracing redistribute the load from the damaged truss to neighboring ones. It slightly increases the metal consumption of the coating structure. It is possible to install vertical bracing not in each panel of the truss, but through one panel. However, this option requires additional verification calculation.

2. Inclusion of purlins (purlins begin to function like cable roof) (Figure 9).

Figure 9. Scheme of the spatial frame of the building with purlins work like cable roof.
Such a constructive solution requires a device that is different from conventional connections of purlins. The modified connection should be capable of perceiving the strut that occurs when the purlins work like a cable roof. This complicates the design of the connections, increases its material consumption, increases the complexity of installation and requires additional control over the construction process.

3. Installation of horizontal bracing along the upper and lower belts of the truss (Figure 10).

![Figure 10. The spatial framework of the building with horizontal bracing along the upper and lower truss belts.](image)

Such a constructive solution is convenient, because nodes of the device of horizontal bracing are widespread and do not require special calculations, are simple and convenient to install. It does not increase the metal consumption of the coating structure. Also, the arrangement of horizontal ties along the coating coincides with the layout of ties for coating with cranes, which makes this option to increase the robustness of the coating more economical and advantageous especially for buildings equipped with cranes.

Based on the numerical and experimental studies, the following calculation algorithm is proposed:
1. calculation of loads;
2. static analysis of the space frame of building;
3. determination of the most loaded element of the truss and its removal from the design scheme;
4. multiplying the load by the value of the dynamic coefficient in accordance with the above distribution diagrams;
5. receiving efforts and selection of sections.

The proposed algorithm allows to simplify the analysis procedure for resistance to progressive collapse and reduce the metal consumption of the building.

References
[1]  EN 1991-1-7 2006 Eurocode 1: Actions on structures - Part 1-7: General actions - Accidental actions (The European Union) p 67
[2]  UFC 4-023-03 2013 Design of buildings to resist progressive collapse (USA: Department of Defense) p 245
[3]  ASCE/SEI 7-10 2010 Minimum Design Loads for Buildings and Other Structures (American Society of Civil Engineers) p 658
[4]  2011 Code of practice for the structural use of steel (The Government of the Hong Kong Special
Administrative Region) p 388

[5] NISTIR 7386 2007 Best Practices for Reducing the Potential for Progressive Collapse in Buildings (U.S. Department of Commerce / Technology Administration / National Institute of Standards and Technology) p 216

[6] AS/NZS 1170.0:2002 2002 Australian/New Zealand Standard. Structural design actions. Part 0: General principles (SAI Global Limited) p 42

[7] Arutyunyan G 2015 J. Vestnik MGSU 9 16-27

[8] Klyueva N 2009 Fundamentals of robustness theory of reinforced concrete structural systems with accidental actions (dissertation for the doctor of technical sciences) (Orel) p 454

[9] Kudishin Y 2009 J. Vestnik MGSU 2 28

[10] Perelmuter A 2007 Selected problems of reliability and safety of building structures (Moscow: ASV) p 256

[11] Rastorguev B 2003 J. Earthquake engineering construction safety 4

[12] Tour V 2009 Proc. Int. Symp. on modern metal and wooden structures (rationing, design and construction) (Brest) p 302

[13] Shapiro G, Eisman Y and Travush V 2006 Recommendations for the protection of high-rise buildings against progressive collapse (Moscow: Moskomarchitektura) p 74

[14] Shapiro G, Eisman Y and Zalesov A 2005 Recommendations for the protection of concrete buildings from progressive collapse (Moscow: Moskomarchitektura) p 59

[15] Shapiro G, Korovkin V, Eisman Y and Strugatsky Y 2002 Recommendations for the protection of frame buildings in emergency situations (Moscow: Moskomarchitektura) p 20

[16] Shapiro G, Korovkin V, Eisman Y and Strugatsky Y 2002 Recommendations for the protection of buildings with load-bearing brick walls in emergency situations (Moscow: Moskomarchitektura) p 24

[17] Strugatsky Y, Shapiro G and Eisman Y 1999 Recommendations for the prevention of progressive collapse of large-panel buildings (Moscow: Moskomarchitektura) p 55

[18] Belyaev M 1976 Strength of materials (Moscow: Nauka) p 608

[19] Korenev I and Rabinovich M 1972 Reference on the dynamic of structures (Moscow: Stroyizdat) p 511

[20] Berger M and Tusnin A 2018 J. IOP Conf. Ser.: Mater. Sci. Eng. 365 052020

[21] Berger M and Tusnin A 2019 J. Industrial and Civil Engineering (PGS) 10 12-18

[22] Elvira E, Mendis P and Whittaker A 2011 J. Civil Engineering Dimension 13 29

[23] Petrov I 2013 Evaluation of the effectiveness of vibration protection systems with nonlinear characteristics (dissertation for the candidate of technical sciences) (Moscow) p 119

[24] Zoli T and Woodward R 2007 J. International Journal of impact engineering 32(1) 39