Finite element analysis of a frame connection of a girder with a rack under beyond design basis impact

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Abstract. Over the past decade, the number of accidents in steel-framed buildings has been decreasing thanks to advanced approaches to cause analysis. In the presented article, a brief overview of the existing common design solutions of frame joints of the rack with the crossbar is made. A finite element design model of the structure under consideration has been made in accordance with the most common design solutions based on the experience of designing construction design organizations. The analysis of the local buckling of a steel structure element, which had cases of collapse in real life, was carried out. The results of the structural analysis of the structure without the presence of any defects were assessed, and the dependence of the bearing capacity of the structure on the presence of defects and the degree of their development was presented in a graphical form. The presence of a sensitive parameter of the structure under study was determined and the direction of further research of the frame connection of the rack with the girder was determined.

1. Introduction

Analysis of the causes of failures in building structures allows you to learn more about the design flaws of the solutions used, as well as expand the list of potential risks that can be taken into account in the design. The process of investigating the causes of accidents in building structures is carried out in accordance with the Regulations on the Procedure for Investigating the Causes of Accidents in Buildings and Structures, Their Parts and Structural Elements in the Territory of the Russian Federation (approved by Order of the Ministry of Construction of Russia dated 06.12.1994 No. 17-48).

In the course of the investigation, including the state of the collapsed structure, a search for defects, design errors are carried out, the current loads and the excess of their design values are determined. This process plays an important role in the improvement of modern calculation methods, in particular, by the method of limiting states. This is justified by the fact that exceeding the criteria of the limiting state of structures leads either to a decrease in the bearing capacity of the element (exceeding the ultimate stresses of the material), or to a significant change in the design scheme of the structure as a whole (exceeding the limiting deformations). The work of many scientists is devoted to this topic. Grozdo V.T., Ledenev V.V., Dobromyslov A.N. made a significant contribution to the illumination and study of this problem. and others. In any case, the presence of defects can become a critical factor.
There are many works by different authors dealing with the topic of inspection of buildings and structures, detection of defects and unsatisfactory strength of building structures, such as B.I.Belyaev, V.S.Kornienko, G.F. Deev, I.R.Patskevich, V.Meshechek. V., Kocherzhenko V.V., Albrecht R. and others.

2. Review of the investigated structure
Among other works, one can single out [1], where, in addition to chronological information on the facts of the accident, there is also discussion about possible ways to prevent collapse. It is proposed in this work to highlight the part where we are talking about the frame nodal connection of the steel structure of the column with the girder (figure 1).

![Figure 1](image)

**Figure 1.** Options for mating the frame girder to the outer rack.

This type of connection is widespread in the construction of warehouse buildings. An important feature of such nodes is a complex stress state both in the nodes themselves and in the areas of the crossbar and rack adjacent to them. The use of the curved beam theory to determine the stresses in broken joints of I-beams leads to extremely large errors and cannot be applied in practical cases. The pliability of flange connections, which, as a rule, pass through the assembly or are located near the assembly [4], introduces additional difficulties in determining the stress-strain state of the assembly.

In general, the tasks of calculating the mating nodes of the end posts and girders include the following:
- Determination of the stress-strain state of the unit and the adjoining zones of the girder and the rack for calculating the strength of the web, shelves, ribs and welds connecting them;
- Calculation of the elements included in the assembly for local stability;
- Calculation of nodes when the web is in the supercritical stage of work.

An example of using such a profile is shown in figure 2.
3. Analysis of construction
According to [1, 2], cases of collapse of structures with the mentioned nodal connection are documented. The reason was beyond design basis loads, as well as design errors. A design error is considered to be the absence of transverse stiffening ribs in the places indicated in figure 3. It is argued that because of this, the structure in the place of stress concentration lost its local stability.

![Figure 3. The structure of the frame unit of the collapsed building.](image)

Since the works [1, 2] do not indicate the exact information about the mentioned structure, design solutions for the calculation were taken according to the experience of designing the most massively constructed frames of warehouse buildings (figure 4). For the calculation, a frame made of welded rigidly supported frames of constant cross-section (I-beam 25B2 according to the Russian assortment [3], steel S345) was chosen. The frame span is 18 m. The frame pitch is 6 m. The roof slope is 5%. The calculation is based on the load corresponding to the 3rd snow region, which corresponds to the location of Moscow.
According to the design scheme, in the section under consideration, the bending moment is the main force factor. Also, a torque can act in the section for the extreme frames. The torque is due to the presence of bending moments in the floor beam resulting from the action of the distributed load, which are not balanced for the outer frames of the frame. A diagram of stresses in section 1-1 from the action of a bending moment, as well as a diagram of the action of shear torsion stresses are shown in figure 5.

\[
\sigma_{\text{equ}} = \sqrt{\sigma^2 + 4\tau^2};
\]
\[
\sigma_1 = \frac{M_{\text{max},y_1}}{I_x}; \quad \tau_1 = \frac{M_{t}r_1}{I_p};
\]

Based on the calculation, the shear stresses at point 1 make up a smaller, but significant part of the equivalent stress value, therefore, we assume that the loading conditions are the most critical for the extreme frame.

The calculation of the local buckling of the considered section of the structure in the design organizations is carried out in accordance with the Russian regulatory documentation [26].

It is assumed that the following factors will influence the critical stress of the I-beam web:

- web thickness;
- web height;
- the length of the web section between the stiffening ribs.
At the same load, the stresses at point 1 will differ depending on the "L" dimension (figure 3). Accordingly, this parameter also affects the local buckling of the I-beam web in the joint under consideration. Since in the case under consideration, the structure consists of a welded I-beam, the influence on the magnitude of the force factors acting in the web is also exerted by deviations in size, which form the eccentricities of the forces.

According to the analysis of buckling in the finite element model, the first eigenvalue of the structure, corresponding to the buckling of the I-beam web at the expected location (figure 6), has a margin of 1.60 at the design load. The second and third eigenvalues of web buckling have margins of 2.00 and 3.10, respectively.

![Figure 6](image)

**Figure 6.** Graphical representation of 1, 2 and 3 eigenvalues of structure buckling. The color gradation corresponds to the nodal displacement in the direction normal to the I-beam web. The borders of the color bar are responsive.

Considering that the stresses at design loads in places of geometric concentration already exceed the tensile strength of the steel used, it becomes clear that before the I-beam web becomes unstable, the metal will collapse, which does not correspond to the case under consideration. As an option for weakening the structure, the displacement of the I-beam web due to manufacturing inaccuracy is considered. The force scale factor vs displacement diagram is shown in figure 7.
Figure 7. Dependence of the scale factor of the force on the displacement of the web of the welded I-beam.

It can be seen from the presented graph that the displacement value has the greatest influence on the ultimate load on the third eigenvalue of the web buckling (figure 6), which most closely corresponds to the web buckling due to the action of increased stresses in the connection zone of the lower I-beam.

Corrosion of the I-beam web near the weld is considered as another weakening factor (figure 8). In the design model, corrosion is performed by reducing the thickness of the group of elements corresponding to the heat-affected zone (1-2 sheet thicknesses).

Figure 8. Welded I-beam web corrosion.

The dependence of the force scale factor on the web weakening value is shown in figure 9.
It can be seen from the presented graph that the value of the weakening of the I-beam web due to corrosion has the greatest effect on the ultimate load on the third eigenvalue of buckling of the web (figure 6), the decrease is 10-15% per millimeter. This repeats the conclusion from the analysis of the effect of displacement of the I-beam web due to the inaccuracy of manufacture presented above.

Testing the assumption about the influence of the “L” dimension (figure 3) on ultimate load by the stability criterion yielded more ambiguous results presented in figure 10.

**Figure 9.** Dependence of the scale factor of the force on the corrosion of the welded I-beam web corrosion

**Figure 10.** Dependence of the scale factor of the force on the «L»-dimension.
It can be seen from the presented graph that an increase in the size “L” has a positive effect on the ultimate load for the first two eigenvalues of buckling - about 17%. However, the ultimate load for the third eigenvalue of buckling decreased by 6%.

4. Conclusion
From the results proposed above, it follows that the investigated design of the unit has a low probability of reaching the limiting states, provided that there are no installation defects, welding and compliance with the structural characteristics of the structure adopted in the calculation. However, the conclusions from the calculations indicate that for the situation under consideration it is necessary to study the influence of many parameters on the strength of the structure, since even a minimal change in the section parameters (web thickness) led to a significant change in the results. The next step in this study is to determine the parameters that most affect the bearing capacity of the considered frame connection of the girder to the rack. The obtained results of the study will make it possible to judge what causes and beyond design basis effects were most likely to lead to the loss of stability of the unit found in the collapsed building.

Acknowledgments
The reported study was funded by RFBR, project number 20-38-90056/20.

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