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Bolted connections stiffness of steel trusses for bridge superstructures

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Abstract. The article assesses stiffness of main trusses bolted connections in the railway bridges metal superstructures. The generally accepted approach for trusses of bridge structures analysis is to replace joints with hinges. This technique simplifies finding the forces in structure elements, but reduces the reliability of the design model. In this study, the finite element method implemented in the Ansys Mechanical software package is used. The process of determining the stiffness of the high-strength bolts joint connection is described in detail. The paper proposes formulas to determine rotation angles of the truss elements joint sections according to the finite element model analysis results. For two joints of a standard design, superstructure stiffness was determined: kN_2 = 107183.06 kN×m/rad, kN_3 = 137605.56 kN×m/rad. Graphs of bending moment on the rotation angle dependence were also made. It was concluded that the beam model of the structure shows underestimated values of the joints stiffness, and the difference with the stiffness determined for the detailed finite element model can reach 5.635.

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1. Introduction

Nowadays, when designing new and reconstructing existing bridge structures on the Russian Federation territory, engineers are guided by the SP 35.13330.2011 "Bridges and Pipes" code specification, which allows replacing rigid joints in connections with hinges when analyzing lattice trusses, if the structure remains unchanged and the ratio of the truss element section height to its length is ensured to be not more than 1:15. If the last condition is not met, when analyzing the strength and fatigue behavior of the lattice trusses elements with high-strength bolts connections, it is necessary to take into account the joints stiffness, and the elements longitudinal forces can be determined according to the hinge scheme. However, there are no direct instructions on how to take into account the connections stiffness in the code specification. Note here, that this approach to the lattice trusses analysis can be found in all specification documents of the USSR since 1938: in TUPM-38 (Technical conditions for the design of bridges and pipes), in TUPM-47, in 1955 additions and changes to TUPM-47, as well as in SN 200-62. Therefore, it can be argued that the question of how to take into account the connection stiffness and its effect on the reliability and durability of the structure has not yet been finally answered.

However, there are publications on this topic that need to be mentioned here to represent the level of knowledge on this issue.

First, let us turn to foreign specification documents. According to the fourth edition of the AASHTO LRFD, a truss can be analyzed as hinged structure when loads are applied to the panel nodes. European norms introduce a classification of nodes according to two criteria: stiffness and strength. Note, however, that although Eurocode 1993-2-2009 refers to Eurocode 1993-1-8 in terms of connections modeling, the provisions given here are applicable more to the field of building design.

As shown in [1], a number of outstanding scientists of the second half of the 19th century were engaged in the elimination of the lattice trusses stress-strain state with rigid connections at the joints: Manderla, Engesser, Azimont, Winkler, Ritter and Landsberg, Müller-Breslau, Mor. At the beginning of the 20th century, the works of national researchers appeared – E.O. Paton, E.V. Zotikov, G.P. Peredery, K.M. Dubyaga, N.V. Nekrasov. But the obtained results contradicted each other in many ways, therefore, subsequently, this area practically did not develop.

The works [2–5] are devoted to the necessity of considering the connections as semi-rigid joints in the analysis of the wooden trusses state. Some methods of taking into account the real characteristics of connections are given, which show a good approximation to real structures.

Detailed analysis of joints of metal beams and columns of buildings have been carried out [6–12]. The obtained results indicate that the reliability and bearing capacity of the joints is influenced by a whole set of factors: the geometric dimensions of the joined elements, the configuration of the attachment unit, the bolts diameter.

The detailed stress-strain state analysis of four different systems taking into account the connection joints stiffness was carried out in [13]. Taking the stiffness of the hinge connection as 0, and the stiffness of an absolutely rigid connection as 100 %, the authors showed the presence of a relationship between the values of internal forces and displacements and the degree of restraint in the connection. Some continuation of this study can be found in [14], where the analysis of the relationship between the dynamic characteristics of railway bridge superstructure and the connections rotational stiffness was made.

As shown in [15–17], the most important characteristic of the joint connection is the graph with the "Angle of rotation" – "Moment" axes. In general, this is a curve that characterizes the dependence of the bending moment arising in the joint on the angle of rotation; the tangent of the slope of this curve to the abscissa axis characterizes the joint stiffness, which is expressed by the formula:

$$K_s = \frac{M}{\theta}, \tag{1}$$

where M is the bending moment, expressed in kN, and θ is rotation angle, expressed in radians.

Eurocode 1993-1-8 allows simplification of the non-linear relationship between the rotation angle and the bending moment; thus, bilinear approximation has become widespread (dashed line in Fig. 1).

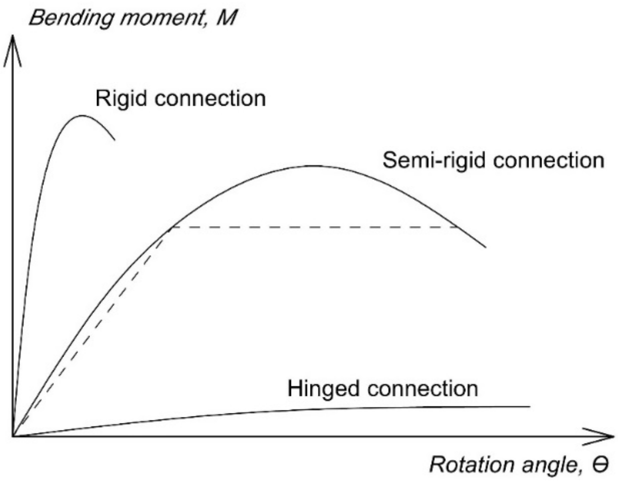

Figure 1. Dependence of the bending moment on the rotation angle at the joint.

The Eurocode approach to the truss joints classification has some drawbacks: firstly, stiffness and strength criteria are considered separately, what can lead to difficulties in the choice of a specific category. Secondly, the possibility of joint category changing at different stages of loading is not taken into account. In this regard, the need for development of a different classification system devoid of the indicated inaccuracies arises. The article [18] is devoted to this issue.

Articles [19–21] are devoted to the study of various aspects of the work of gusset plates as part of bridge trusses and building frames. Analysis of the gussets joints dimensions assigning approaches was made. A nonlinear model to take them into account when analyzing frame structures and assessed the stiffness of the attached elements, initial imperfections, eccentricity of load application impact on the stress-strain state of gussets was proposed.

According to [22, 23], detailed modeling of bridge structures makes it possible to identify reserves of bearing capacity, as well as alternative ways of forces distributing in case of bearing elements failure.

Works [24–27] describe various approaches of taking into account the joint connections stiffness when analyzing the frames of buildings. The authors paid great attention to the mathematical substantiation of the proposed procedures, and also gave specific examples of structural analysis.

Works [28–31] are devoted to the finite element method application in the study of the operation of joint connections for various purposes structures. Comparison of the results obtained by experimental and numerical methods is performed. It is shown that numerical modeling makes it possible to assess the stress-strain state of a structure with the required degree of accuracy; moreover, data become available that is not possible to obtain experimentally.

Connections of lattice structures of power transmission line supports were investigated in works [32, 33]. It is shown that bolted joints have a great influence on the deformed state of this type of structures.

Based on the performed review of scientific publications, we can conclude the following: in world practice, an approach to the consideration of bolted connections of building frames as semi-rigid joints has become widespread. At the same time, the concept of a semi-rigid connection is practically not used in the design of metal trusses for transport structures. Despite the external similarity of the aforementioned structures, the conditions of their operation are fundamentally different: while the columns and beams of buildings work mainly on static loads (compressive longitudinal force and bending moment, respectively), the elements of the bridge structures trusses experience a complex dynamic effect from the circulating moving loads with a predominance of longitudinal compressive and tensile forces. At the same time, as noted in [34, 35], the joint connection stiffness has an insignificant effect on the results of the static analysis of structures, but the dependence of their dynamic characteristics on the joints properties is much greater. The problem of correct determination of the bridge structures dynamic characteristics is becoming especially urgent now, with the advent of high-speed railways.

The connections of the bridge superstructures main trusses elements have a very complex composition. For through bridges, this connection, as shown in Fig. 2, represents the area of braces, chords, stands and crossbeams intersection. The elements are joined by overlapping with gusset plates, followed by the installation of high-strength bolts. Obviously, such a connection is neither hinged nor absolutely rigid; it has some intermediate properties, and therefore received the name "*semi-rigid connection*".

Moreover, there is no doubt that the stiffness of such assemblies depends on many factors: the connected elements geometry, the thickness and dimensions of the gusset plates, the number and degree of tension of high-strength bolts. Therefore, the problem of determining the stiffness of bridge superstructures metal trusses joints is practically insoluble from the point of view of structural analysis approaches.

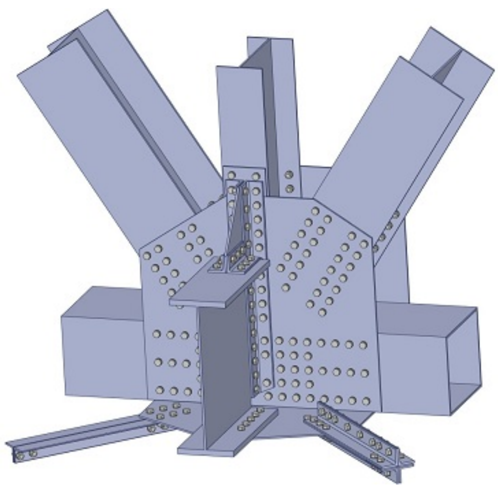

Figure 2. Joint of a standard design railway bridge superstructure.

In our opinion, the only possible way to solve the original problem is the finite element method implemented in software packages such as Ansys. With a certain degree of detail, the created mathematical model will make it possible to assess the influence of all the above factors on the joint properties.

When writing this article, we set a goal of assessing the bolted connections stiffness of main trusses for bridge steel superstructures. For this, the following tasks are being solved:

- a detailed finite element model of a fragment of the analyzed railway bridge lattice superstructure is being developed;
- stiffness of the main truss joint connections are determined;
- a comparative analysis of the superstructure beam and detailed finite element models are performed.

2. Methodology of numerical experiment

2.1. General information

Since the use of software packages implementing the finite element method in the investigation of complex detailed models requires large computational resources, it was decided to analyze the structure in two steps:

1. Beam model analysis. This stage is necessary to assess the general stress-strain state of the structure and to check the correctness of the assignment of general parameters, such as material properties, sections of elements, support fixings.
2. Within the framework of the beam model, the investigated elements are modeled in detail using shell finite elements.

2.2. Description of the superstructure under study

The structure under study is a metal superstructure with through trusses, manufactured according to standard design No. 3.501-30/75. The span of this single-track railway bridge is 55 m. The main elements of the superstructure are made of 15KhSND low-alloy steel. Lattice truss elements are welded as box-shaped and H-shaped sections with field connections on high-strength bolts. Box-shaped elements have a perforated bottom chord, perforation dimensions are 270 × 600 mm, the distance between perforation centers is 1200 mm. The chords connections are aligned with the main trusses joints and are located at 11 m intervals.

The main trusses are connected by top and bottom braces in the plane of the chords, portal frames in the plane of the outside braces and struts in the plane of the stands (Fig. 3).

Field connections are made on high-strength bolts with a diameter of 22 mm. All contact surfaces of the joints and connections are sandblasted before assembly. The standard tension force of a high-strength bolt is taken equal to 20 tons.

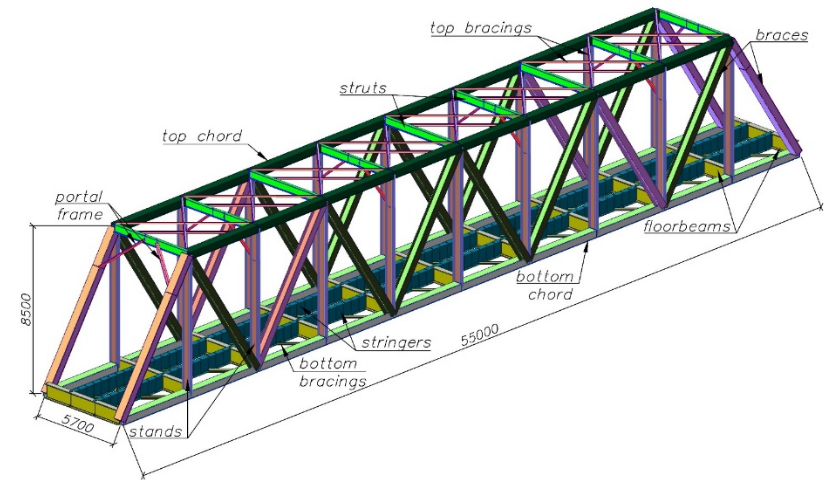

Figure 3. Superstructure beam model.

2.3. Beam model

General view of the superstructure model is shown in Fig. 3.

The analysis was carried out taking into account the linear work of the material, the elastic modulus and Poisson's ratio were set as E = 2.0×10^5 MPa and μ = 0.3, respectively. The specific gravity of steel was taken equal to ρ = 76.98 kN/m^3.

Each element of the beam model has its own type of cross-section with dimensions taken from standard design project. All joint connections are rigid. Supports are installed at the joints of the extreme braces and the lower chords intersections: fixed supports on one side and supports with displacements along the axis of the bridge on the other side.

Dead loads from the self-weight of the superstructure and the weight of the bridge deck and moving loads from passing trains were applied to the structure.

As a result of the structure analysis, the displacement values of the superstructure finite element model nodes were obtained for the position of the passing trains, at which the biggest longitudinal forces arise in the element under consideration. Optimization of the moving load position was performed in the Midas Civil software package.

2.4. Detailed model

In this work, the stiffness of the joints *N2* and *N3* of the lower chord of the superstructure main truss is assessed (Fig. 4).

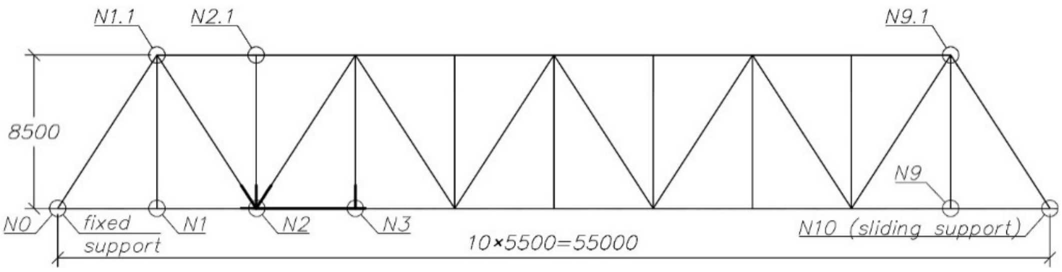

Figure 4. Main truss scheme.

As noted earlier, the actual joint connections of railway bridge trusses are complex assemblies of main elements and high-strength bolts. Therefore, to perform an accurate analysis, it is necessary to carry out a detailed modeling of the truss bottom chord panel between joints *N2* and *N3*, in which all the components that influence the behavior of the structure will be presented in an explicit form (Fig. 5). At the same time, the study of the stress state of the bolts themselves is not the purpose of this work; therefore, in the analysis they will be represented by equivalent beams, to which a tension force is applied. The main elements of the truss and elements of longitudinal bracings, as well as gussets and angles, are approximated by shell elements. Thus, the stress-strain state of the bottom chord section *N2-N3* depends only on the properties of the contiguous joints.

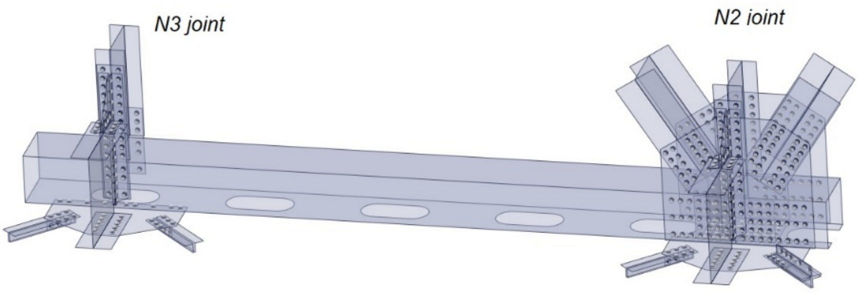

Figure 5. Fragment of the detailed analysis model in Ansys Mechanical.

For the structure material Bilinear Isotropic Hardening property was set with the following characteristics: Yield Strength σ_Y = 345 MPa and Tangent Modulus σ_T = 696.2 MPa. The material of high-strength bolts is 40Ch steel with Yield Strength σ_Y = 785 MPa and Tangent Modulus σ_T = 2029.7 MPa. All the contacts between elements are Frictional type;-+ Friction Coefficient is set equal to 0.58.

Truss bottom chord panel with *N2* and *N3* contiguous joints attached to the beam part of the model by Fixed Joints. All bolts are tensioned with 196.12 kN Preload force. The total number of high strength bolts in this model is 454 pcs.

The "Face Sizing" option has been applied to the shell elements with a finite element size of 6 mm. Total task size is 809748 nodes and 785004 elements.

2.5. Determination of the joint connections stiffness

As shown earlier, the numerical value of the joint stiffness is the quotient of dividing the bending moment by the angle of rotation of the section. To determine the latter, let us turn to Fig. 6, which shows the vertical displacements of a bottom chord panel between joints *N2* and *N3*. The solid line corresponds to the case of a hinged connection at the truss joints; since in this case only a longitudinal tensile force acts on the element, this line is straight. The dotted line corresponds to the case of a semi-rigid connection with real joint characteristics; this line has a certain curvature, which is due to the presence of fixing in the connections. The angle between the straight and dotted lines is the angle of the section rotation from the action of the bending moment in the plane of the truss (Fig. 7).

The data for the selected cross-sections required for calculating the stiffnesses of the joints, as well as the final result are shown in Table 1.

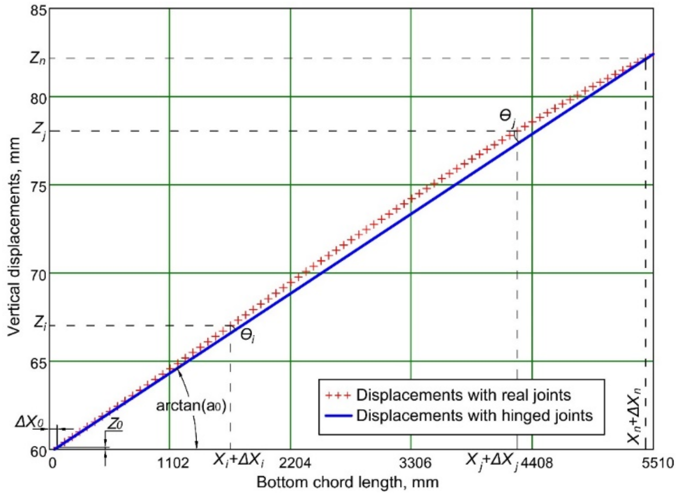

Figure 6. Vertical displacements of the N2-N3 bottom chord panel.

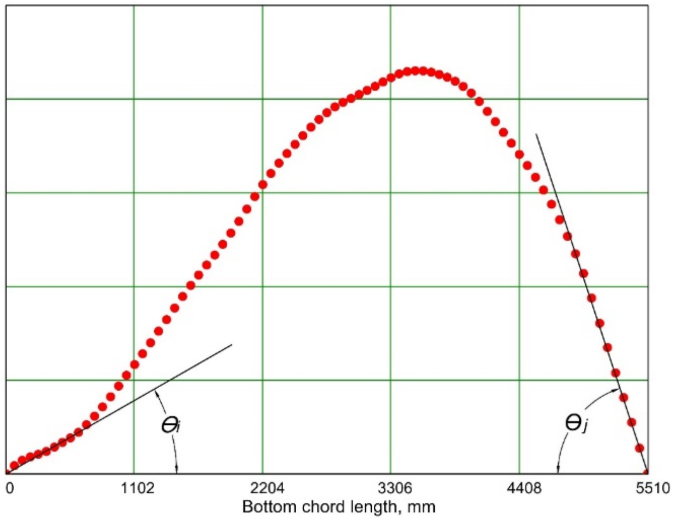

Figure 7. Scheme for determining the angles of rotation.

The angles of rotation θ_i and θ_j are determined based on the analysis of the curve in Fig. 6 using the formulas:

$$\theta_i = \arctan\left(\frac{Z_i - Z_0}{X_i + \Delta X_i - \Delta X_0}\right) - \arctan\left(a_0\right); \tag{2}$$

$$\theta_j = \arctan\left(a_0\right) - \arctan\left(\frac{Z_n - Z_j}{X_n + \Delta X_n - X_j - \Delta X_j}\right), \tag{3}$$

where $Z_0,\ Z_n,\ Z_i,\ Z_j$ are the coordinates along the vertical axis of the first, end, i^{th} and j^{th} points of the curve, $X_n,\ X_i,\ X_j$ are the initial coordinates along the horizontal axis of the end, i^{th} and j^{th} points of the curve, $\Delta X_0,\ \Delta X_n,\ \Delta X_i,\ \Delta X_j$ are displacements of the first, end, i^{th} и j^{th} points of the curve, obtained as a result of deformation from the action of applied loads, a_0 is the slope of the straight line connecting the first and end points of the curve on the graph.

Table 1. Data for determining the stiffness of joint connections

Joint	Angle of rotation, radians	Angle of rotation, degrees	Bending moment, kN×m	Joint stiffness, kN×m/rad
N2	0.0001406726	0.0080599478	15.078	107183.06
N3	0.0007581663	0.0434397292	104.328	137605.56

Note: rotation angle Θ_i corresponds to *N2* joint, Θ_j corresponds to *N3* joint.

3. Results and Discussion

Data on the stiffness of joints *N2* and *N3* is shown in Table 1. However, of greater interest are the dependence graphs of the bending moment and the angle of rotation in the joint, which clearly demonstrate the change in the connection stiffness depending on the magnitude of the applied loads. The graphs in Fig. 8 and 9 are derived from the structure load history analysis in Ansys Mechanical.

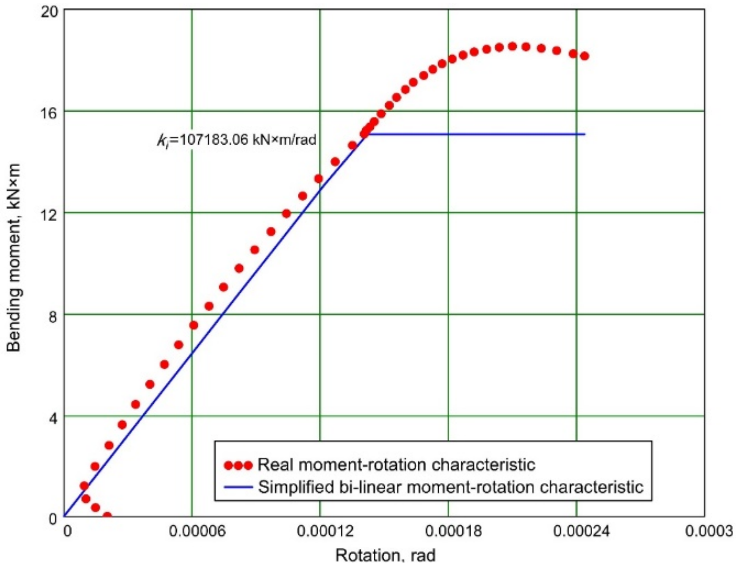

Figure 8. Graph of the N2 joint stiffness.

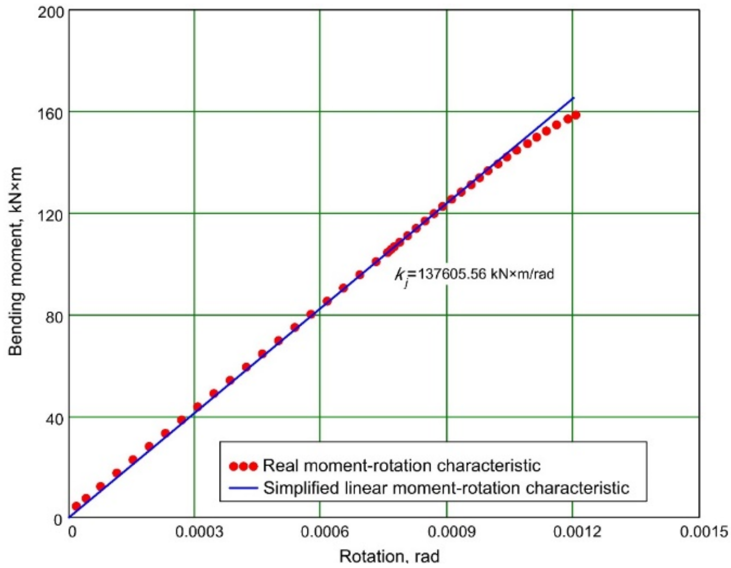

Figure 9. Graph of the N3 joint stiffness.

Let us remark here that the graph of the stiffness of the *N2* joint has the same form as the curves obtained in [24, 25, 28, 29, 36, 37]. However, despite the indicated external similarity, the obtained values are very different. Comparing the rotation angles of *N2* joint, shown in Fig. 8, and the values obtained in [28] for the Specimen SC7, we see that the beam-column connection of buildings steel frames are more flexible – the maximum rotation angles obtained within a numerical experiment differ by 250 times. The curve corresponding to joint *N3* requires further study as part of a separate finite element model.

Conspicuous is the fact that the *N3* joint stiffness is 1.284 times higher than the *N2* joint stiffness. The greater flexibility of *N2* joint can be explained by the fact that it is aligned with the truss lower chord connection, while in *N3* joint the lower chord is continuous.

An interesting question is how accurate the result on the joint connections stiffness can be obtained from the beam model analysis. Data on the stiffness of beam model joints *N2* and *N3* is shown in Table 2.

Table 2. Joint connections stiffness in beam model.

Joint	Angle of rotation, radians	Angle of rotation, degrees	Bending moment, kN×m	Joint stiffness, kN×m/rad
N2	0.0003222700	0.0184647119	6.13	19021.32
N3	0.0006856034	0.0392821833	50.05	73001.38

In this case, *N3* joint stiffness is also greater than *N2* joint stiffness, and the stiffness ratio is equal to 3.838.

At the same time, the stiffness of the *N2* joint for the case with detailed models of connections is 5.635 times higher than the corresponding characteristic for the case with a full beam model. For *N3* joint this ratio is equal to 1.885. Such a difference in the obtained results can be explained by the fact that the beam model does not consider the complex stress-strain state in the truss joint. It can also be concluded that the more complex the construction joint, the less accurate results obtained from the analysis of the beam model. Based on the above, we can argue that the beam model of the structure is not able to give an adequate assessment of the complex joint connections stiffness.

Let us note the difference in the graphs of the analyzed joints stiffness. For node *N2*, two stages of work are clearly traced: linear, up to the value of the rotation angle θ_i = 0.0001406726 radian, and nonlinear afterwards. For *N3* joint the stiffness is linear for all values obtained as a result of a numerical experiment.

4. Conclusions

1. This work presented an assessment of bolted connections stiffness in steel trusses of bridge superstructures. In the Ansys Mechanical software package it was analyzed a detailed finite element model of the truss bottom chord panel as part of the entire structure. This approach makes it possible, without additional constructions, to determine the joints stiffness when calculating the entire superstructure.

2. In the process of writing this work, formulas were obtained analytically to determine the angles of rotation θ_i and θ_j of the truss elements joint sections according to the finite element model analysis results.

3. After analysis of the created finite element model, the stiffness values of two connection joints were determined: k_{N2} = 107183.06 kN×m/rad, k_{N3} = 137605.56 kN×m/rad. The obtained results allow us to conclude that the continuity of the element itself in the connection has a great influence on its rigidity.

4. By comparing the analysis results of the beam and detailed finite element models, we can conclude that the beam model of the structure shows underestimated values of the joints stiffness. At the same time, the values of the joints stiffness for the two indicated cases may differ by a factor of 5.635.

5. Based on the analysis of the dependence of the bending moment on the angle of rotation, the graphs of the stiffness were made for the joints *N2* and *N3* of the superstructure under consideration. Linear and bilinear approximations of the obtained data were proposed.

6. Taking into account all the above, we can conclude the following: the connection stiffness is the joint generalized characteristic, largely dependent on its composition. With an increase in the joint complexity, the difference between the stiffness of the real connection and the stiffness determined for a beam model with absolutely rigid connections increases. Therefore, joint connections must be considered semi-rigid. The question of correct stiffness assessment of the bridge superstructures steel trusses connections is becoming especially urgent at the present time, with the appearance and development of

the high-speed railway system. However, in the existing standard documents there are no direct instructions on the method of determining stiffness of these structures joint connections, especially with respect to static and dynamic analysis. Therefore, further development of this area of knowledge is necessary.

References

1. Valiullin, D.A., Chizhov, S.V. Analysis of assessment methods of stress-strain state of lattice trusses with rigid connections in nodal joints. Vestnik Grazhdanskikh Inzhenerov [Bulletin of Civil Engineers]. 2019. 75 (4). Pp. 38–43. DOI: 10.23968/1999-5571-2019-16-4-38-43
2. Leichti, R.J., Hyde, R.A., French, M.L., Camillos, S.G. The continuum of connection rigidity in timber structures. Wood and Fiber Science. 2000. 32 (1). Pp. 11–19.
3. Masse, D.I., Salinas, J.J. Analysis of timber trusses using semi-rigid joints. Canadian Agricultural Engineering. 1988. 30 (1). Pp. 111–124.
4. Mam, K., Douthe, C., Le Roy, R., Consigny, F. Shape optimization of braced frames for tall timber buildings: Influence of semi-rigid connections on design and optimization process. Engineering Structures. 2020. 216. Pp. 1–15. DOI: 10.1016/j.engstruct.2020.110692
5. Sawata, K., Yasumura, M. Estimation of yield and ultimate strengths of bolted timber joints by nonlinear analysis and yield theory. Journal of Wood Science. 2003. 49 (5). Pp. 383–391. DOI: 10.1007/s10086-002-0497-3
6. Li, Z., Su, Y., Zhang, K. Numerical Analysis Of The T-stub Beam-to- Column Hysteretic Behavior Affected By Beam Height. The 2016 International Conference on Advances in Energy, Environment and Chemical Science. 2016. Pp. 0373–0376. DOI: 10.2991/aeecs-16.2016.70
7. Gomes, V., Silva, A.T., de Lima, L.R.O., Vellasco, P.C.G. da S. Numerical investigation of semi-rigid connection ultimate capacity. Revista Escola de Minas. 2018. 71 (4). Pp. 505–512. DOI: 10.1590/0370-44672018710031
8. Madjour, A., Soltani, M.R., Harkati, E.H. Numerical investigation into the ultimate strength of steel cellular beams with semi-rigid connections. Periodica Polytechnica Civil Engineering. 2018. 62 (2). Pp. 517–532. DOI: 10.3311/PPci.11304
9. Aydin, A.C., Ardalani, A., Maali, M., Kiliç, M. Numeric modelling of innovative semi-rigid connections under cyclic loading. Steel Construction. 2020. 13. Pp. 1–13. DOI: 10.1002/stco.201900037
10. Tusnina, V.M. Semi-rigid steel beam-to-column connections. Magazine of Civil Engineering. 2017. 73 (5). Pp. 25–39. DOI: 10.18720/MCE.73.3
11. Vatin, N., Bagautdinov, R., Andreev, K. Advanced Method for Semi-Rigid Joints Design. Applied Mechanics and Materials. 2015. 725–726. Pp. 710–715. DOI: 10.4028/www.scientific.net/amm.725-726.710
12. Babu, S.S., Sreekumar, S. A Study on the Ductility of Bolted Beam- Column Connections. International Journal of Modern Engineering Research. 2012. 2 (5). Pp. 3517–3521.
13. Kartal, M.E., Başağa, H.B., Bayraktar, A., Muvafik, M. Effects of semi-rigid connection on structural responses. Electronic Journal of Structural Engineering. 2010. 10. Pp. 22–35.
14. Patil, M., Pandey, A.D. Influence of Semirigid joints on fatigue life of steel truss railway bridge. International Journal of Civil and Structural Engineering. 2012. 3 (1). Pp. 44–56. DOI: 10.6088/ijcser.201203013005
15. Faridmehr, I., Tahir, M.M., Lahmer, T. Classification system for semi-rigid beam-to-column connections. Latin American Journal of Solids and Structures. 2016. 13 (11). Pp. 2152–2175. DOI: 10.1590/1679-78252595
16. van Keulen, D.C., Nethercot, D.A., Snijder, H.H., Bakker, M.C.M. Frame analysis incorporating semi-rigid joint action: Applicability of the half initial Secant stiffness approach. Journal of Constructional Steel Research. 2003. 59 (9). Pp. 1083–1100. DOI: 10.1016/S0143-974X(03)00031-2
17. Weynand, K., Jaspart, J.-P., Steenhuis, M. The stiffness model of revised annex j of eurocode 3. Connections in Steel Structures III1996. Pp. 441–552.
18. Nethercot, D.A., Li, T.Q., Ahmed, B. Unified classification system for beam-to-column connections. Journal of Constructional Steel Research. 1998. 45 (1). Pp. 39–65. DOI: 10.1016/S0143-974X(97)00064-3
19. Crosti, C., Duthinh, D. A nonlinear model for gusset plate connections. Engineering Structures. 2014. 62–63. Pp. 135–147. DOI: 10.1016/j.engstruct.2014.01.026
20. Crosti, C., Duthinh, D. Instability of steel gusset plates in compression. Structure and Infrastructure Engineering. 2014. 10 (8). Pp. 1–11. DOI: 10.1080/15732479.2013.786102
21. Court-Patience, D., Garnich, M. Buckling analysis of gusset plates with bolted connections using finite element modeling. Journal of Constructional Steel Research. 2021. 176. Pp. 1–15. DOI: 10.1016/j.jcsr.2020.106420
22. Butler, M.A., Swanson, J.A., Rassati, G.A., Dues, E.F. High Resolution Modeling and Modeling of Connections in Pony-Truss Bridges. Transportation Research Record. 2018. 2672 (41). Pp. 186–195. DOI: 10.1177/0361198118792126
23. Buitrago, M., Bertolesi, E., Calderón, P.A., Adam, J.M. Robustness of steel truss bridges: Laboratory testing of a full-scale 21-metre bridge span. Structures. 2021. 29. Pp. 691–700. DOI: 10.1016/j.istruc.2020.12.005
24. Ngo-Huu, C., Nguyen, P.C., Kim, S.E. Second-order plastic-hinge analysis of space semi-rigid steel frames. Thin-Walled Structures. 2012. 60. Pp. 98–104. DOI: 10.1016/j.tws.2012.06.019
25. Nguyen, P.C., Kim, S.E. An advanced analysis method for three-dimensional steel frames with semi-rigid connections. Finite Elements in Analysis and Design. 2014. 80. Pp. 23–32. DOI: 10.1016/j.finel.2013.11.004
26. Zlatkov, D., Zdravkovic, S., Mladenovic, B., Stojic, R. Matrix formulation of dynamic design of structures with semi-rigid connections. Facta universitatis – series: Architecture and Civil Engineering. 2011. 9 (1). Pp. 89–104. DOI: 10.2298/fuace-1101089z
27. Sagiroglu, M., Aydin, A.C. Design and analysis of non-linear space frames with Semi-rigid connections. Steel and Composite Structures. 2015. 18 (6). Pp. 1405–1421. DOI: 10.12989/scs.2015.18.6.1405
28. Shi, G., Shi, Y., Wang, Y., Bradford, M.A. Numerical simulation of steel pretensioned bolted end-plate connections of different types and details. Engineering Structures. 2008. 30 (10). Pp. 2677–2686. DOI: 10.1016/j.engstruct.2008.02.013
29. Girão Coelho, A.M. Rotation capacity of partial strength steel joints with three-dimensional finite element approach. Computers and Structures. 2013. 116. Pp. 88–97. DOI: 10.1016/j.compstruc.2012.10.024

30. Wang, G., Ding, Y. The interface friction in the friction-type bolted joint of steel truss bridge: Case study. Baltic Journal of Road and Bridge Engineering. 2020. 15 (1). Pp. 187–210. DOI: 10.7250/bjrbe.2020-15.467
31. Omar, R., Rani, M.N.A., Yunus, M.A. Finite Element Modelling and Updating of a Bolted Structure Using Elements Representing the Stiffness Members, Bolts and Affected Areas of the Joints. Journal of Physics: Conference Series. 2019. 1262 (1). Pp. 1–10. DOI: 10.1088/1742-6596/1262/1/012005
32. Jiang, W.-Q., Liu, Y.-P., Chan, S.-L., Wang, Z.-Q. Direct Analysis of an Ultrahigh-Voltage Lattice Transmission Tower Considering Joint Effects. Journal of Structural Engineering. 2017. 143 (5). Pp. 1–14. DOI: 10.1061/(asce)st.1943-541x.0001736
33. Baran, E., Akis, T., Sen, G., Draisawi, A. Experimental and numerical analysis of a bolted connection in steel transmission towers. Journal of Constructional Steel Research. 2016. 121. Pp. 253–260. DOI: 10.1016/j.jcsr.2016.02.009
34. Tran-Ngoc, H., Khatir, S., De Roeck, G., Bui-Tien, T., Nguyen-Ngoc, L., Abdel Wahab, M. Model updating for nam O bridge using particle swarm optimization algorithm and genetic algorithm. Sensors (Switzerland). 2018. 18 (12). Pp. 1–20. DOI: 10.3390/s18124131
35. Luong, H.T.M., Zabel, V., Lorenz, W., Rohrmann, R.G. Vibration-based Model Updating and Identification of Multiple Axial Forces in Truss Structures. Procedia Engineering. 2017. 188. Pp. 385–392. DOI: 10.1016/j.proeng.2017.04.499
36. Frye, M.J., Morris, G.A. Analysis of flexibly connected steel frames. Canadian Journal of Civil Engineering. 1976. 3 (2). Pp. 280–291. DOI: 10.1139/l76-034
37. Krolo, P., Grandić, D., Bulić, M. The Guidelines for Modelling the Preloading Bolts in the Structural Connection Using Finite Element Methods. Journal of Computational Engineering. 2016. 2016. Pp. 1–8. DOI: 10.1155/2016/4724312

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