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A numerical analysis of the influence of the prestressing force of bolts in a end-plate joint on the deflection of a steel I-beam

Przemysław Palacz[1]

ABSTRACT:
Bolted end-plate joints are most commonly used in steel framed structures because they allow quick and easy assembly on the construction site. Bending moments usually occur in prestressed end-plate joints, which means that the bolt connectors may be loaded with additional forces resulting from the summation of the forces from the external load with the forces of initial prestressing of the bolts, which may even lead to the breakage of the bolts. In prestressed end-plate joints, it is important to select the appropriate bolt tightening torque so that the initial prestressing force of the bolts is sufficient to ensure adequate stiffness of the connection while ensuring safe operation. The article presents an analysis of the influence of the prestressing force of bolts in a end-plate joint on the deflection of a steel I-beam and the stress distribution. A finite element numerical analysis was performed for a standard end-plate joint with different bolt pre-stressing forces depending on the use of the bolt yield strength. The results showed that the connection does not behave linearly depending on the value of the selected bolt pre-stressing force, but the greater the force, the stiffer the connection.

KEYWORDS:
steel structure; end-plate joints; bolted connections; connection capacity; FEM analysis

1. Introduction

In steel structures, connections are extremely important elements because they transfer internal forces in the structure elements to the individual load-bearing elements. Properly selected and designed mounting contacts ensure safe operation of the facility [1, 2]. There are many types of connections in steel structures: welded, bolted, riveted, welded and even glued. Among them, we distinguish bolt connections that enable easy and quick assembly of prefabricated structural elements on the construction site [3]. The most frequently used bolted connection is the end-plate connection, which is characterized by ease of production and high stiffness [4]. End-plate joints are often used in frame structures to connect elements made of H or I-type sections [5].

Many researchers have undertaken the analysis of end-plate joints in their work. In end-plate joints subject to cyclical loads, a prestressed connection, i.e. category E, should be used. In this type of connections, an appropriate flat contact surface of the end plates is required, because any deformations may cause a significant increase in forces in the bolts under the influence of external load. In this case, the forces of initial prestressing of the bolts add up to the forces from external loads, which may consequently lead to the breakage of the bolts [6]. In most cases, deformations of end plates have an unfavorable effect on the load-bearing capacity of end-plate joints, as the authors presented in their studies [6-11].

Experimental and numerical studies show that the fatigue strength of joints is influenced by many factors, including the pre-stressing force of bolts [12]. The load-bearing capacity of

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[1] Czestochowa University of Technology, Faculty of Civil Engineering, ul. Akademicka 3, 42-218 Częstochowa, Poland, e-mail: przemyslaw.palacz@pcz.pl, orcid id: 0000-0002-2040-3494

connections is also influenced by the condition of the connection and weather conditions, as the authors demonstrated in their works [13-15]. The authors in [13] presented experimental tests of the load-bearing capacity of bolted connections subjected to corrosion. They performed corrosion tests and then examined the properties of these connections at various degrees of corrosion and ultimately found that the corrosion environment had a significant impact on the preload of the bolts. In turn, the authors [14, 15] in their works examined the impact of corrosion on the properties of friction joints and showed that the fatigue life can be significantly reduced by corrosion. Attention should also be paid to the operation of connections at elevated temperatures, which reduces the load-bearing capacity of bolted connections [16], which has been shown by many authors in their works [17-19]. The authors of [18] presented fire tests of end-plate joints with end plates of different thickness and showed that the thickness of the end plate significantly increases the stiffness of the connection at ambient temperature, while fire resistance was not significantly improved when a thicker end plate was used.

This article presents a numerical analysis of the influence of the prestressing force of bolts in a end-plate joint on the beam deflection and stress distribution. Numerical calculations using the finite element method were performed for various values of pre-stressing forces and the impact of the force on the stiffness of the connection was assessed.

2. Goal and scope of the work

The aim of the work was the numerical analysis of a simply supported I-beam with a end-plate joint. The aim of the analysis was to examine the relationship between the initial prestressing force in the bolts and the resulting deflections in the beam. A simply supported beam diagram was adopted for the analysis, which is shown in Figure 1. In the middle of the beam span, a end-plate connection with bolts extended outside the cross-section in the tension zone was modeled, which is shown in Figure 2.

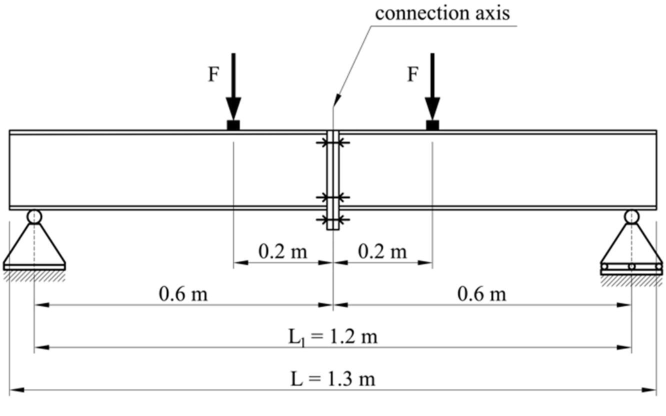

Fig. 1. Static diagram of the analyzed beam

The FEM numerical analysis was carried out for a beam made of a 1.3 m long IPE 160 rolled I-section. The steel grade of the beam cross-section and end plate was S235 steel. The supports in the beam were assumed to be articulated, fixed on one side and frictionless on the other. The beam was loaded with two concentrated forces F of 65 kN applied at a distance of 0.2 m on both sides from the connection axis (Fig. 1). The force value was assumed as the maximum allowable for the beam using up to 90% of the load-bearing limit state of the beam cross-section.

Based on analytical calculations, the maximum internal forces in the beam were calculated and are presented in Table 1. Then, the load-bearing limit state of the adopted beam profile was checked based on PN-EN 1993-1-1 [19]. The bending and shear resistance of the steel I-beam cross-section was calculated using formulas (1) and (2) for a class 1 cross-section, where: $M_{c,Rd}$ – bending resistance, W_{pl} – bending strength index, $V_{c,Rd}$ – shear resistance, A_v – cross-sectional area under shear, f_y – value of the steel yield point, γ_{M0} – partial factor.

$$M_{c,Rd} = M_{pl,Rd} = \frac{W_{pl} \cdot f_y}{\gamma_{M0}} \tag{1}$$

$$V_{pl,Rd} = \frac{A_v \cdot (f_y/\sqrt{3})}{\gamma_{M0}} \tag{2}$$

The allowable beam deflection was calculated using formula (3) based on the standard [19], where: f_{lim} – the maximum allowable deflection for a beam, L_1 – span for a simply supported beam.

$$f_{lim} = \frac{L_1}{250} \tag{3}$$

The load-bearing limit state conditions of the cross-section and the permissible deflection for the assumed beam are presented in Table 1.

Table 1
Maximum internal forces in the beam, cross-section load capacity and ultimate limit state conditions and permissible beam deflection

Maximum bending moment in the beam [kN m]	26.00
Bending resistance of the cross-section [kN m]	29.09
Maximum shear force in the beam [kN]	65.00
Shear resistance of the cross-section [kN]	108.54
Ultimate limit state [%]	89.38
Allowable deflection for a beam [mm]	4.80

To analyze the influence of the pre-stressing force of the bolts on the beam deflections, a end-plate joint with a full end plate was selected. The thickness of the end plate as well as the diameter and class of the bolt were selected and dimensioned in accordance with PN-EN 1993-1-8 [20]. The construction diagram of the selected end-plate joint is shown in Figure 2. Then, the connection was analyzed using the finite element method. The evaluation of the connection performance was compared for various pre-tensioning forces of the bolts in the connection.

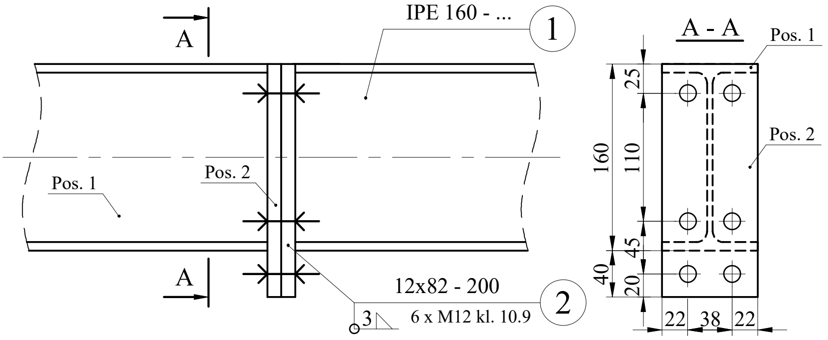

Fig. 2. Construction diagram of the analyzed end-plate joint

3. Numerical model and results

The numerical model of the beam with the connection was modeled in the Ansys Research environment, declaring the geometry, boundary conditions and loads identical to those in the analytical calculations. The numerical model of the analyzed beam with a connection is shown in Figure 3.

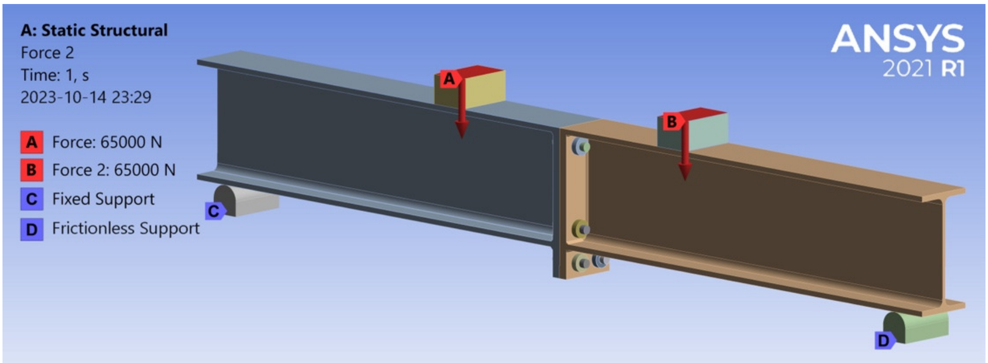

Fig. 3. Numerical model of the analyzed beam with a end-plate connection with declared boundary conditions and load

The steel beam and the end-plate elements, including the bolts, were modeled as 3D finite elements with an adaptive mesh size, but not larger than 0.005 m. The material values of the model elements adopted on the basis of the standards [19, 20] are presented in Table 2. The value of the friction coefficient between elements in the model was assumed to be μ = 0.2.

Table 2
Material properties adopted in the numerical model based on eurocode [19, 20]

Name of property	Value of property	
	Beam, end plate	Bolts, nuts
Density ρ [kg/m^3]	7850	7850
Poisson's ratio v	0.3	0.3
Modulus of elasticity E [GPa]	210	210
Yield strength f_y [MPa]	235	900
Highest tensile strength f_u [MPa]	360	1000

The bolts in the connection were modeled according to the VDI 2230:2014 standard [21]. The values of the pre-stressing forces of the bolts were adopted on the basis of the tightening torque and pre-load calculator [22] in accordance with the standard [21] for class 10.9 bolts, assuming the friction value between the nut and the bolt μ = 0.12. The values of the tightening torque and pre-stressing force of the bolts were determined using the yield strength of the bolts in the range from 40 to 95%, with an increment of 5%. The range from 40% of the yield strength of the bolts was analyzed because with lower pre-stressing forces of the bolts, the beam deflections were significantly beyond the permissible deflection range and the system was unstable. Then, numerical calculations were performed for the given range of bolt pre-stressing forces and the stress distribution in the connection and the maximum deflection in the beam were analyzed. The calculations were performed in two time steps, in the first step the preload of the bolts was applied, and in the second step the external load was applied. The values of the tightening torque together with the pre-stressing forces of the bolts and the corresponding beam deflection are presented in Table 3. The beam deflection was read in the connection axis. The distribution of stresses in the connection for selected values of the pre-stressing forces of the bolts is shown in Figure 5, while the distribution of stresses in the most heavily loaded bolts is shown in Figure 6.

Table 3
The values of the tightening torque along with the pre-stressing forces of the bolts and the corresponding beam deflection read in the numerical analysis

No.	Using the yield strength of bolt [%]	Bolt pre-tension force [kN]	Bolt tightening torque [Nm]	Deflection of beam with end-plate joint [mm]
1.	40	28.17	55.24	72.59
2.	45	31.68	62.15	50.37
3.	50	35.20	69.05	27.93
4.	55	38.71	75.96	8.72
5.	60	42.23	82.86	4.30
6.	65	45.74	89.77	3.92
7.	70	49.26	96.67	3.58
8.	75	52.77	103.58	3.28
9.	80	56.29	110.48	3.12
10.	85	59.80	117.39	3.06
11.	90	63.32	124.29	3.03
12.	95	66.83	131.20	3.01

Analyzing the beam displacements depending on the assumed pre-stressing force of the bolts, it can be seen that the greater the pre-stressing force of the bolts, the smaller the beam deflection and, consequently, the greater the stiffness of the connection, which is the expected result. The tested beam showed permissible deflections (less than 4.80 mm) from 3.01 to 4.30 mm in the pre-stressing range of the bolts from 66.83 to 42.23 kN, respectively, while with a lower pre-stressing force of the bolts in the range from 38.71 to 28.17 kN, the beam deflections range from 8.72 to 72.59 mm respectively, which significantly exceed the range of permissible deflections above 4.80 mm. Based on data from Table 3, a graph of the degree of utilization of the bolts yield strength (on the vertical axis) in relation to the maximum beam deflection (on the horizontal axis) was made. The graph is shown in Figure 4.

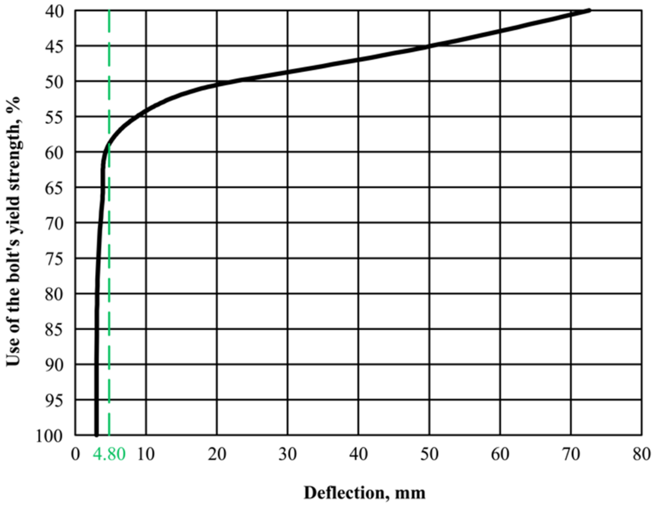

Fig. 4. Chart of the use of bolt yield strength for maximum beam deflections

Analyzing the graph, it can be seen that the increase in beam deflections in relation to the bolt pre-stressing forces is not linear over the entire range and a significant increase in beam deflections occurs below 60% use of the bolt yield strength. A bolt prestress value ranging from 70 to 95% of the bolt yield strength most effectively ensures sufficient joint stiffness while ensuring deflection below the maximum allowable for the analyzed beam. Therefore, it will be most advantageous to use the bolt tightening torque in the range of 70 to 80% use of the bolt yield strength, because the stiffness of the connection is ensured and the bolts will work with a greater margin in the bolt load.

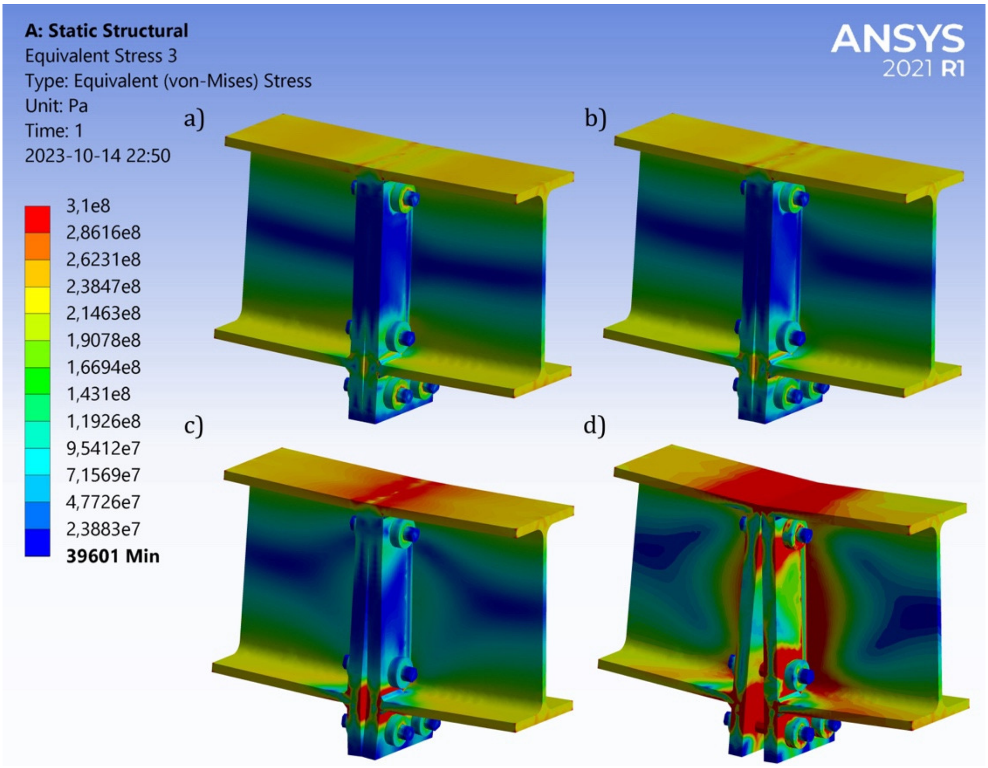

Fig. 5. Stress distribution in the analyzed end-plate joint for selected values of bolt pre-stressing forces using the bolt yield strength: a) 90%; b) 75%; c) 60%; d) 45%. The deformations are shown on a double scale

By analyzing the distribution of stresses in the connection (Fig. 5), it is possible to assess the efficiency of the connection due to the distribution of internal forces in the connected beams. In connections in which the initial prestressing force is 66.83 and 52.77 kN, using the bolt yield strength of 90 and 75%, respectively (Fig. 5a and 5b), it can be seen that the stresses are evenly transmitted between the connected beams through the end plate. Increased stresses occur in the upper and lower chords of the beam and, respectively, in the end plates in the places where the chords join, but these stresses do not exceed the permissible stresses for the adopted steel grade and are below 235 MPa. Analyzing the deformations, one can notice the opening of the end plates in the tension zone, which proves the correctness of the numerical model, but assuming the actual scale of deformations, these deformations are unnoticeable. In turn, in connections in which the initial prestressing force is 42.23 and 31.68 kN, using the bolt yield strength of 60 and 45%, respectively (Fig. 5c and 5d), it can be seen that the stresses are unfavorably transferred from the beams to the end plates and occur increased stresses at the point of contact between the sheets in the tension zone and amount to approximately 300 MPa, and in the extreme variant (Fig. 5d), increased stresses in the end plate appear in a significant part of the sheet in the vicinity of the bolts, and the stresses significantly exceed the stresses permissible for the selected steel grade and are above 300 MPa. Analyzing the deformations, one can notice a significant opening of the end plates in the tension zone. The distribution of stresses in the most loaded bolts is shown in Figure 6. The most loaded bolts are the bolts that extend beyond the cross-section in the tension zone.

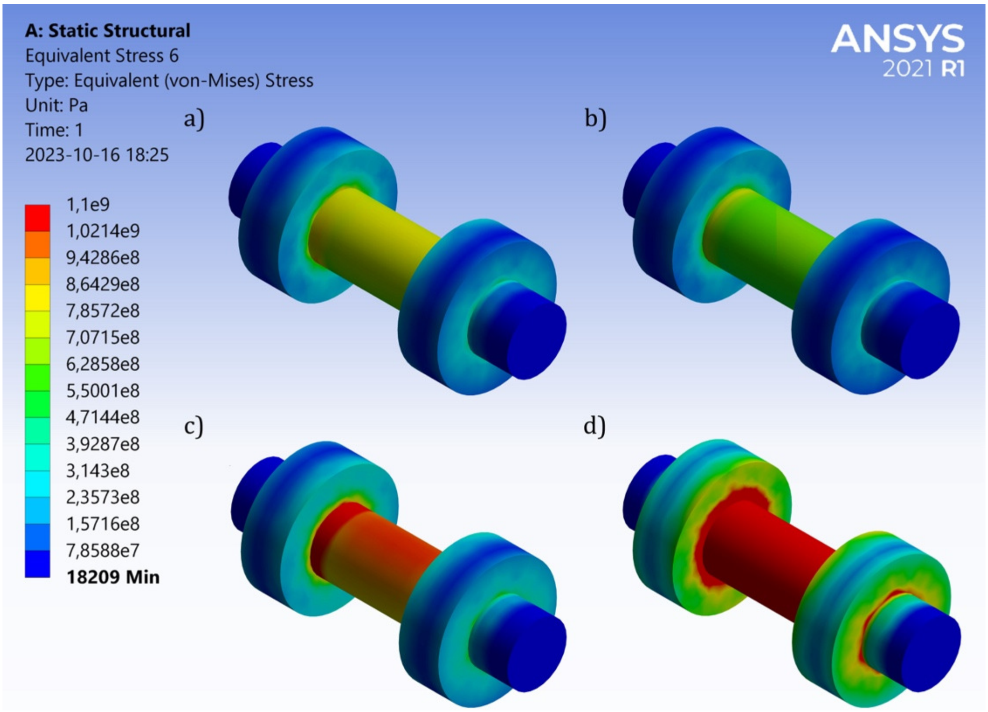

Fig. 6. Distribution of stresses in the most heavily loaded bolts (extended beyond the cross-section in the tension zone) in the analyzed end-plate joint for selected values of bolt pre-stressing forces using the bolt's yield strength: a) 90%; b) 75%; c) 60%; d) 45%

Analyzing the distribution of stresses in the bolts (Fig. 5), it can be seen that in the case of bolts with a pre-stressing force within the use of the bolt yield strength of 90 and 75% (Fig. 6a and 6b), the stresses correspond to the selected pre-stressing force, which proves the correctness of the model execution. However, in bolts with a pre-stressing force in the range of the bolt yield strength of 60 and 45% (Fig. 6c and 6d), an increase in stress can be seen despite lower pre-stressing forces, and even exceeding the permissible stresses for the adopted bolts. In this case, the bolts in the connection do not work effectively, and the bending moment in the beam due to the external load increases the resultant force in the bolts, which in extreme cases may lead to their breakage.

4. Conclusions

As a result of the numerical analysis, the influence of the selection of the prestressing force of the bolts in the end-plate joint on the deflection of the steel I-beam and the stress distribution was assessed. The numerical analysis showed that the connection does not behave linearly depending on the value of the pre-stressing force of the bolts, but the greater the force, the stiffer the connection is and the stresses are distributed more evenly between the connected beams.

Selecting the appropriate pre-stressing force for bolts in end-plate joints is extremely important, because a properly bolted connection can ensure adequate stiffness and operational safety. However, it should be remembered that such bolts cannot be tightened too tightly, because that the forces from the external load may add up and lead to the bolts breakage. The performed numerical analysis showed that when the pre-stressing forces are selected in the range of 70 to 80% of the use of the bolts yield strength, the connection works as effectively as with the maximum permissible pre-stressing force, while maintaining 20 to 30% of the bolts' load-bearing capacity. Therefore, appropriate selection of the pre-stressing force of the bolts can ensure greater tolerance to the resulting manufacturing errors, while ensuring sufficient stiffness of the connection.

Summing up the results of the FEM numerical analysis showed the influence of the selected pre-stressing force of the bolts in the end-plate joint on the joint stiffness and stress distribution. The subject of further work will be a comparative analysis based on experimental research.

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Numeryczna analiza wpływu siły wstępnego sprężenia śrub w połączeniu doczołowym na ugięcie stalowej belki dwuteowej

STRESZCZENIE:

Śrubowe połączenia doczołowe są najczęściej stosowane w konstrukcjach stalowych ramowych, ponieważ umożliwiają szybki i łatwy montaż na miejscu budowy. W stykach sprężonych połączeń doczołowych zazwyczaj występują momenty zginające, przez co łączniki śrubowe mogą być obciążone dodatkowymi siłami wynikającymi z sumowania się sił od obciążenia zewnętrznego z siłami wstępnego sprężenia śrub, co nawet może prowadzić do zerwania śrub. W sprężonych połączeniach doczołowych ważne jest dobranie odpowiedniego momentu dokręcenia śrub, tak aby siła wstępnego sprężenia śrub była wystarczająca do zapewnienia odpowiedniej sztywności połączenia, przy jednoczesnym zapewnieniu bezpiecznej eksploatacji. W artykule przedstawiono analizę wpływu siły wstępnego sprężenia śrub w połączeniu doczołowym na ugięcie stalowej belki dwuteowej oraz rozkład naprężeń. Przeprowadzono analizę numeryczną metodą elementów skończonych dla standardowego połączenia doczołowego z różnymi siłami wstępnego sprężenia śrub w zależności od wykorzystania granicy plastyczności śrub. Wyniki wykazały, że połączenie w zależności od wartości dobranej siły wstępnego sprężenia śrub nie zachowuje się liniowo, natomiast im większa siła, tym połączenie jest sztywniejsze.

SŁOWA KLUCZOWE:
konstrukcja stalowa; połączenie doczołowe; połączenia skręcane; nośność połączeń; analiza MES