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Numerical analysis of beams with modified end-plate joints

Analiza numeryczna belek ze zmodyfikowanymi połączeniami doczołowymi

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Abstract. Bolted end-plate joints are an indispensable element of any steel structure. They enable quick and easy assembly of structural elements on the construction site. In end-plate joints irregularities may occur during the welding of the end plate to the beam, which may prevent proper prestressing of the bolts and, as a result, may lead to uneven distribution of forces in the bolts. The article includes an analysis of modified bolted end-plate joints with two-part end-plates in comparison to commonly used full end-plate, end-plate joints. An analytical and numerical analysis of beams with connections was carried out for two beam attachment schemes: simply supported and cantilevered. The parameters tested were stress distribution in the connections, maximum beam deflections and rotational stiffness of the connections. The results have shown that the proposed modified end-plate joints are characterized by high load transfer efficiency and greater rotational stiffness compared to standard end-plate joint solutions.

Keywords: modified end-plate connections; bolted connections; connection capacity; steel I-beam connections; FEM analysis.

Streszczenie. Skręcane połączenia doczołowe są nieodzownym elementem każdej konstrukcji stalowej. Umożliwiają szybki i łatwy montaż elementów konstrukcji na budowie. W połączeniach doczołowych mogą wystąpić nierówności podczas spawania blachy czołowej do belki, co może uniemożliwić prawidłowe sprężenie śrub, a w efekcie doprowadzić do nierównomiernego rozkładu w nich sił. Artykuł obejmuje analizę zmodyfikowanych skręcanych połączeń doczołowych stalowych belek dwuteowych z dwuczęściowymi blachami czołowymi w porównaniu z powszechnie stosowanymi połączeniami doczołowymi z pełnymi blachami czołowymi. Przeprowadzono obliczenia analityczne oraz analizę numeryczną belek z połączeniami w przypadku dwóch schematów zamocowania belki: swobodnie podpartej oraz wspornikowej. Badanymi parametrami były: rozkład naprężeń w połączeniach, maksymalne ugięcie belek oraz sztywność obrotowa połączeń. Wyniki wykazały, że zaproponowane zmodyfikowane połączenia doczołowe charakteryzują się dużą efektywnością przenoszenia obciążeń oraz większą sztywnością obrotową w porównaniu ze standardowymi rozwiązaniami połączeń doczołowych.

Słowa kluczowe: zmodyfikowane połączenia doczołowe; połączenia skręcane; nośność połączeń; połączenia stalowych belek dwuteowych; analiza MES.

Steel structures have been very popular for years due to their lightness and ease and speed of assembly [1]. Important elements in steel structures are connections that enable easy assembly of the structure on the construction site. Connections in steel structures play a very important function because they transfer internal forces in the structure to the load-bearing elements, and damage to the connection may even lead to the destruction of the entire structure [2]. Correctly designed assembly contacts determine the appropriate transfer of internal forces, ensuring safe operation [3]. Many types of connections are available: welded, boltet, riveted and glued. Among them, bolt connections have many advantages, e.g. ease of assembly and disassembly or repair and replacement of damaged elements [4]. One type of bolted connections are end-plate joints, which are characterized by simplicity of execution and the possibility of obtaining appropriate load-bearing capacity and stiffness, especially in welded or hot-rolled I-sections [5].

Commonly used end-plate joints use solid end plates through which bolts pass (Fig. 3). In the case of connections in which the bolt joint is loaded cyclically, a prestressed connection, i.e. category E, should be used. In such connections, a suitably flat contact surface of the end plates is required, because any deformations occurring during the process of welding the plate to the beam may prevent proper prestressing of the bolts. Moreover, in end-plate joint with geometric imperfections of the end plates under the influence of external load, there may be a significant increase in the forces in the bolt connectors in relation to the initial prestressing forces. In this case, the pre-stressing forces of the bolts add up to the forces from external loads, which may even lead to bolt breakage [6]. In most cases, deformations of end plates significantly reduce the load-bearing capacity of prestressed end-plate joints, which, among others, the authors demonstrated in their works [6 – 11].

For many years, scientists have been trying to come up with solutions that will be able to eliminate the unfavorable effects of deformations occurring in the end plates of end-plate joints. Among other things, spacers between the front sheets or filling the gaps between the sheets with polymer have been proposed, but these are not fully effective methods, and even in some cases, the use

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of spacers may have the opposite effect than intended [8]. In turn, the authors in their works [5, 12] presented a new concept of making end-plate joints, in which they replaced the full end plates with T-stubs, created by welding the plates to the beam flanges. The authors discussed and presented the preliminary results of the numerical analysis and showed that this solution is a good alternative to joints with solid end plates.

The analyzed end-plate joints are classified as flexible connections, which in tilt bar structures reduce their critical load-bearing capacity and limit load-bearing capacity. The properties of flexible end-plate joints influence, among others, cross-sectional forces, critical load capacity, limit load capacity and structure displacements. The rotational stiffness of the connection is influenced primarily by the geometry of all components of the joint, including bolts and adjacent elements of the chords and beam web [13]. The authors in [14] presented experience from analyzes of flexible connections and showed that all such connections are deformable and their mechanical properties show significant differences, especially in terms of rotational stiffness and load-bearing capacity. Variations in the rotational stiffness of joints are influenced by, among others, geometric imperfections of end plates. Due to the flexibility of the connection, the load carried by the connected structural element affects the load-bearing capacity and stability of the structure. The compliance characteristics of a node can be assessed from the relationship between the bending moment in the connection and its angle of rotation, i.e. using the M-ϕ curve [14].

This article presents an analysis of modified end-plate joints of I-beams using end plates consisting of two parts. The proposed solutions were compared in terms of stress distribution and estimated rotational stiffness to standard solutions of end-plate joints with a full end plate.

The aim and scope of work

The aim of the work is to perform a numerical analysis of modified bolted end-plate joints of steel I-beams, which were compared to commonly used end-plate joints in steel structures. The aim of the analysis of modified end-plate joints is to check the proposed solutions in terms of work efficiency and application in structures. The diagrams of the analyzed end-plate joints are shown in Fig. 1. The modified end-plate joints analyzed are intended to eliminate solid end plates and thus avoid deviations occurring during the welding process. Two single-span beam fastening schemes were adopted for the analysis, as shown in Fig. 2. Standard end-plate joints (Fig. 1a and 1c) and modified end-plate joints (Fig. 1b and 1d) were modeled in the middle of the beam span.

The analysis was carried out for 1.3 m long beams made of IPE 160 rolled I-sections made of S235 steel. The simply supported beam was loaded with two concentrated forces F1 of 65 kN applied at a distance of 0.4 m from each of the supports (Fig. 2a). The cantilever beam was loaded with one concentrated force F2 of 21.67 kN at a distance of 1.2 m from the restraint (Fig. 2b). The force values were assumed to be maximum for the adopted schemes, using up to 90% of the load-bearing limit state of the beam cross-section.

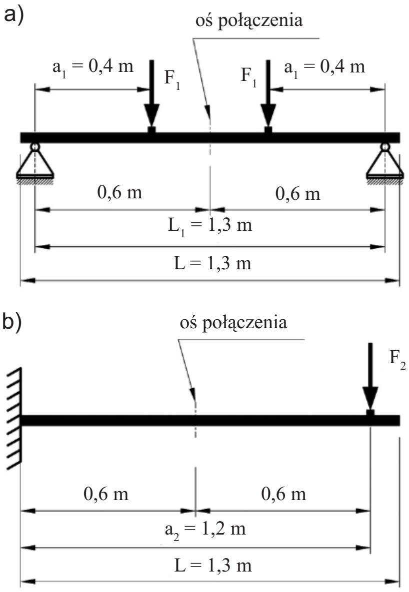

Fig. 2. Static diagrams of beam attachment: a) simply supported beam; b) cantilevered
Rys. 2. Schematy statyczne zamocowania belki: a) belka swobodnie podparta; b) wspornik

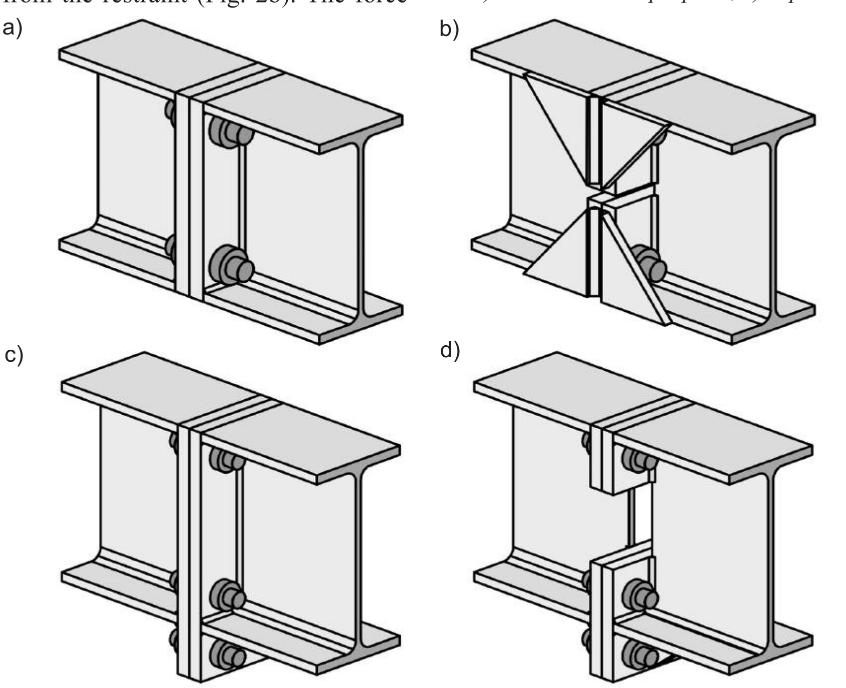

Fig. 1. Analyzed end-plate joints of steel I-beams: a) end-plate joint with bolts inside the cross-section; b) end-plate joint connection with a two-part end-plate with additional side plates and with bolts inside the cross-section; c) end-plate joint with bolts extended beyond the cross-section in the tension zone; d) end-plate joint with a two-part end-plate and bolts protruding beyond the section in the tension zone
Rys. 1. Analizowane połączenia doczołowe stalowych belek dwuteowych: a) połączenie doczołowe ze śrubami wewnątrz przekroju; b) połączenie doczołowe z dwuczęściową blachą czołową z dodatkowymi blachami bocznymi oraz ze śrubami wewnątrz przekroju; c) połączenie doczołowe ze śrubami wysuniętymi poza przekrój w strefie rozciąganej; d) połączenie doczołowe z dwuczęściową blachą czołową oraz z wysuniętymi śrubami poza przekrój w strefie rozciąganej

Based on analytical calculations, internal forces were calculated for the adopted beam fastening schemes. Then, the load-bearing and serviceability limit state conditions of the adopted beam profile were checked (Table 1) based on PN-EN 1993-1-1 [15]. Due to the adopted boundary conditions in the simply supported beam and in order to determine the actual deflections for the stiffness calculations of flexible connections, the maximum deflections for the adopted schemes were read for a continuous beam without a connection in the Ansys program. Diagrams of internal forces and deflections for the adopted beam fastening schemes are shown in Fig. 3.

The bending and shear load-bearing capacity of the steel beam cross-section was calculated in accordance with the standard [15] using formulas (1) and (2), where: $M_{c,Rd}$ – bending load-bearing capacity, W_{pl} – bending strength index, $V_{c,Rd}$ – shear load-bearing capacity, A_v – shear cross-sectional area, f_y – value of the steel yield strength, γ_{M0} – partial factor.

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

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

The permissible deflection of the beams was calculated using formula (3) based on the standard [15], where: f_{lim} – permissible maximum deflection for the cantilever/beam, L – span for the simply supported beam (for a cantilever beam, multiplied by 2).

$$f_{lim} = L/250 \quad (3)$$

For the purpose of comparative analysis, two commonly used types of end-plate joints with solid end plates were selected (Fig. 4). The thickness of the end plates and the bolts in the connections were selected and dimensioned in accordance with PN-EN 1993-1-8 [16]. The connections were then modified so that the end plate consisted of two parts. The modified end-plate joints are shown in Fig. 5. Then, all analyzed connections were subjected to numerical analysis using the finite element method using the Ansys Research program. The evaluation of the joint performance was compared with each other in relation to the distribution of displacement stresses and rotational stiffness.

Table 1. Conditions of the ultimate and serviceability limit state for the analyzed static schemes of beams

Tabela 1. Warunki stanu granicznego nośności i użytkowalności analizowanych schematów belek

Parametrs	Static diagram of the beam	
	simply supported	cantilever
Bending resistance of the cross-section [kNm]	29,09	
Shear resistance of the cross-section [kN]	108,54	
ULS [%]	89,38	89,38
Permissible deflection [mm]	4,80	9,60
SLS [%]	36,77	92,03

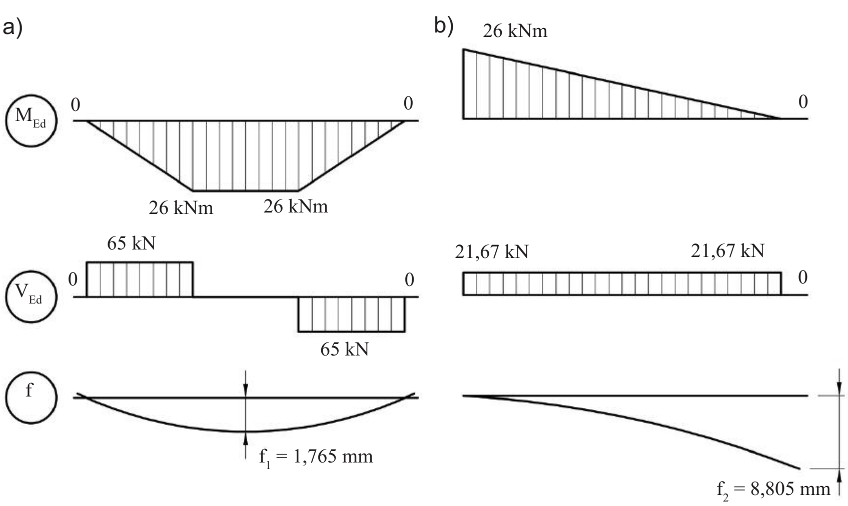

Fig. 3. Diagrams of bending moments – M_{Ed}, shear forces – V_{Ed} and deflections – f for the analyzed beam schemes: a) simply supported beam; b) cantilevered

Rys. 3. Wykresy momentów zginających – M_{Ed}, sił tnących – V_{Ed} oraz ugięcia – f w przypadku analizowanych schematów belek: a) belka swobodnie podparta; b) wspornik

Numerical model

Numerical models of all analyzed joints were created in the Ansys Research program by declaring geometry, boundary conditions and loads identical to the analytical calculations. In order to maintain the symmetry of the system in a simply supported beam, non-sliding supports were adopted on both sides of the beam to determine the rotational stiffness of the connections. In both cases, it was assumed that the beams were protected against buckling. Numerical models for one of the analyzed connections are presented in Fig. 6 and 7.

3D finite elements with an adaptive mesh size, but not larger than 0.005 m, were used for the steel beam and connection elements. The bolts in the connections were modeled in accordance with the VDI 2230: 2014 standard, modeling them from three elements: two nuts and a bolt shank [17]. The values of the initial bolt tension were selected based on the tightening torque and pre-tension calculator [18] in accordance with the VDI 2230:2014 standard for class 10.9 bolts, assuming the nut/bolt friction value μ = 0.12. The tightening torque and preload for the bolts were determined with 50% use of the bolt's yield strength. The values of the adopted tightening torque and preload of the numerical bolts are presented in Table 2. The value of the friction coefficient between the elements in the model was assumed to be μ = 0.2. The material values of the elements were adopted in accordance with the standards [15, 16] and are presented in Table 3. Numerical calculations were performed in two time steps, where in the first step the preload of the bolts was set, and in the second step external loads were set.

Discussion of the results of the numerical analysis

When analyzing the results, stress distribution and maximum displacements were taken into account. The distribution of normal longitudinal stresses for one of the modified end-

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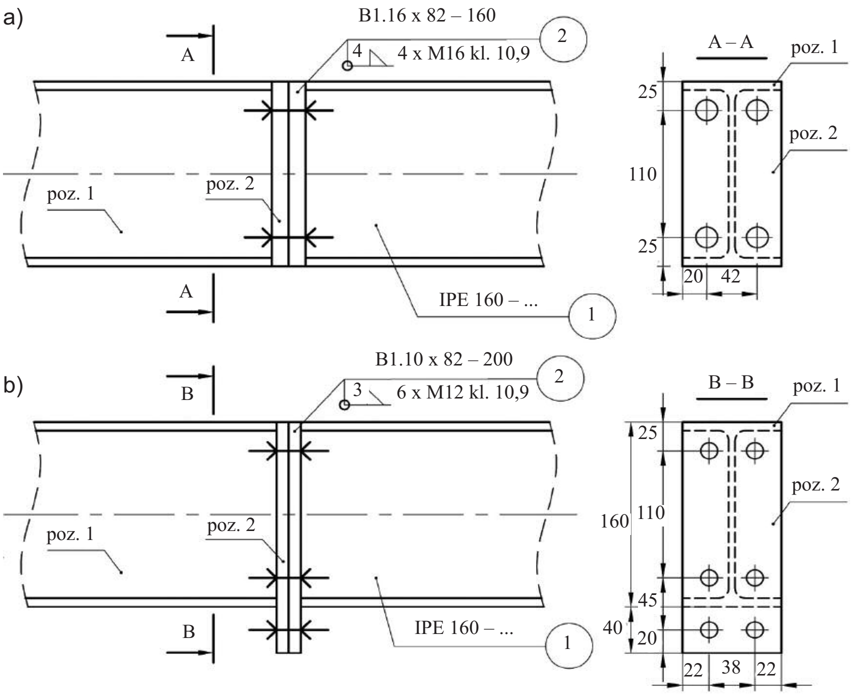


Fig. 4. Schemes of commonly used bolted end connections of steel I-beams: a) end-plate joint with bolts inside the cross-section; b) end-plate joint with bolts extended beyond the cross-section in the tension zone

Rys. 4. Schematy konstrukcyjne powszechnie stosowanych skręcanych połączeń doczołowych stalowych belek dwuteowych: a) połączenie doczołowe ze śrubami wewnątrz przekroju; b) połączenie doczołowe z wysuniętymi śrubami poza przekrój w strefie rozciąganej

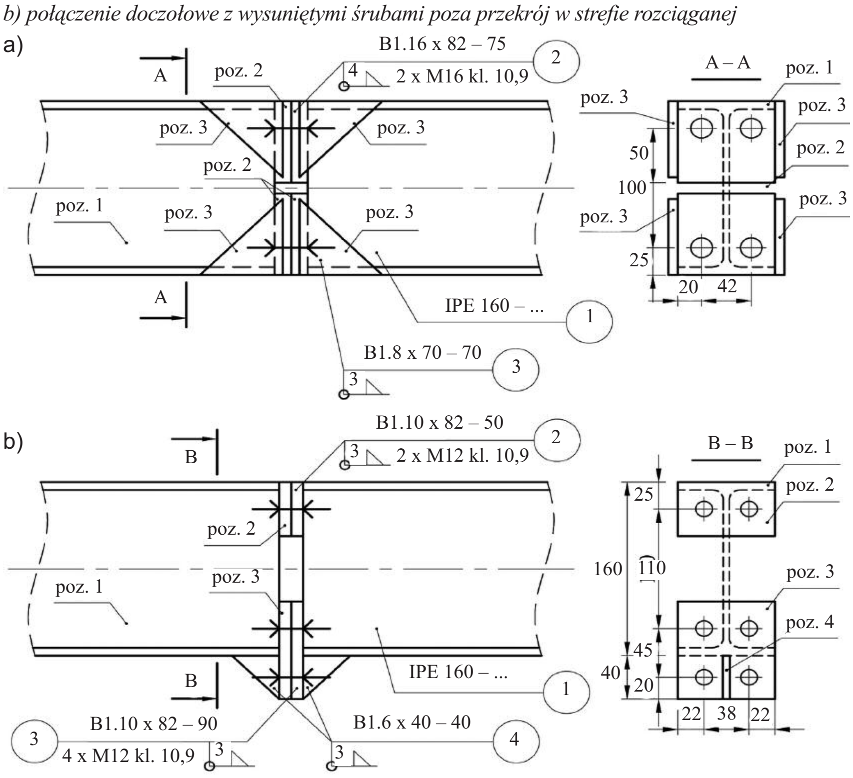


Fig. 5. Schemes of the developed modified end-plate joints: a) end-plate joint with a two-part end-plate with additional side plates and with bolts inside the section; b) end-plate joint with a two-part end-plate and bolts protruding beyond the section in the tension zone

Rys. 5. Schematy opracowanych zmodyfikowanych połączeń doczołowych: a) połączenie doczołowe z dwuczęściową blachą czołową z dodatkowymi blachami bocznymi oraz ze śrubami wewnątrz przekroju; b) połączenie doczołowe z dwuczęściową blachą czołową oraz z wysuniętymi śrubami poza przekrój w strefie rozciąganej

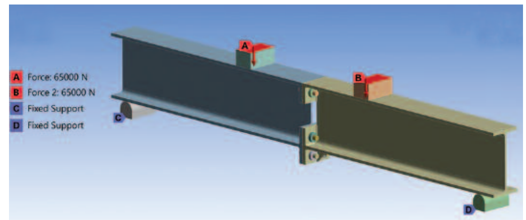


Fig. 6. Numerical model of one of the analyzed variants of a simply supported beam with marked forces and supports

Rys. 6. Model numeryczny jednego z analizowanych wariantów belki swobodnie podpartej z zaznaczonymi siłami oraz podporami

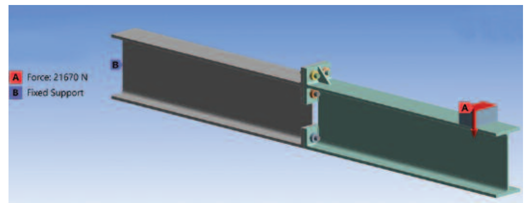


Fig. 7. Numerical model of one of the analyzed variants of the cantilever beam with marked force and restraint

Rys. 7. Model numeryczny jednego z analizowanych wariantów belki wspornikowej z zaznaczoną siłą oraz utwierdzeniem

Table 2. Values of the assumed maximum bolt tightening torque and maximum preload bolt modeled in numerical models

Tabela 2. Wartości przyjętego maksymalnego momentu dokręcenia śrub oraz maksymalnego obciążenia wstępnego śrub zamodelowane w modelach numerycznych

Bolt diameter	Bolt class	Yield strength of the bolt [MPa]	Bolt tightening torque [Nm]	Preload [kN]
M12	10,9	900	69,05	35,18
M16	10,9	900	168,03	66,07

Table 3. Material properties adopted in numerical models based on standards [15, 16]

Tabela 3. Właściwości materiałów przyjęte w modelach numerycznych na podstawie norm [15, 16]

Material property	Material value	
	beam, joints elements	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

-plate joints is shown in Fig. 8, while the maximum deflections read are presented in Table 4.

The distribution of longitudinal stresses in the simply supported beam (Fig. 8a) indicates that in the steel beam mainly compressive stresses prevail in the upper section band in the middle of the beam span at the section of the highest bending moment, while the stresses do not exceed 235 MPa. It can

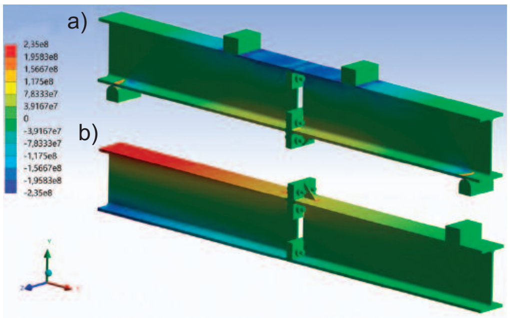


Fig. 8. Longitudinal normal stress distribution for the analyzed model of a beam with end-plate joint with a two--part end-plate and bolts protruding beyond the cross-section in the tension zone: a) simply supported beam; b) cantilevered beam

Rys. 8. Rozkład naprężeń normalnych podłużnych analizowanego modelu belki z połączeniem doczołowym z dwuczęściową blachą czołową oraz z wysuniętymi śrubami poza przekrój w strefie rozciąganej: a) belka swobodnie podparta; b) belka wspornikowa

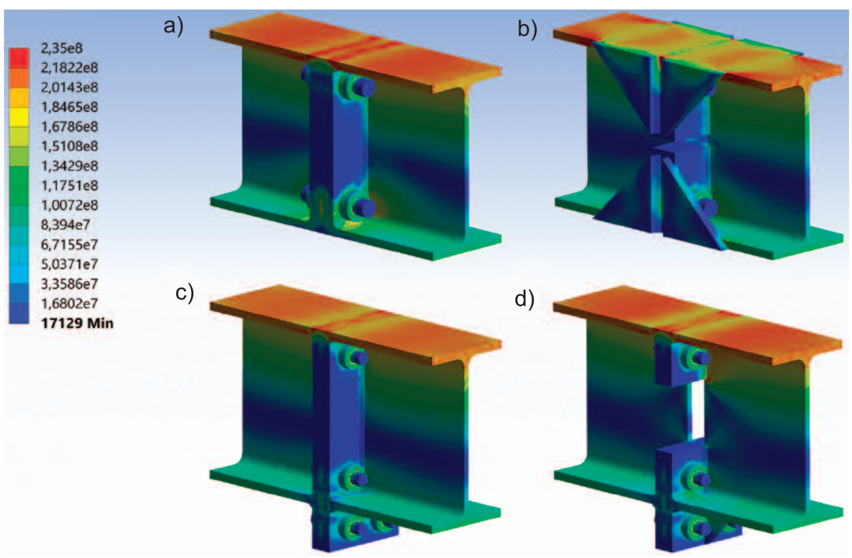
Table. 4. Maximum deflection in a simply supported and cantilevered beam for the analyzed schemes of beam end-plate joint, shown in the same way as in Figure 9

Tabela 4. Maksymalne ugięcie w belce swobodnie podpartej oraz wspornikowej w przypadku analizowanych schematów doczołowych połączeń belek, pokazanych jak na rysunku 9

Analyzed connection model	Deflections for a simply supported beam [mm]	Deflections for a cantilever beam[mm]
a.	1,888	9,361
b.	1,852	9,177
c.	1,834	9,121
d.	1,832	9,096

be seen that the smallest stresses occur below the neutral axis of the cross-section. Additionally, there are constant stresses in the section of the maximum bending moment, which correlates with the bending moment diagram in Fig. 3a. The distribution of stresses in the cantilever beam (Fig. 8b) indicates that in the steel beam the tensile stresses predominate in the upper section strip at the restraint, i.e. in the place of the highest bending moment according to the diagram (Fig. 3b). The stresses in the cantilever beam also do not exceed 235 MPa, which proves compliance with the analytical calculations of the cross-section's load-bearing capacity and the correctness of the selection of the cross-section to the corresponding static scheme and loads. A summary of the reduced stress distribution for all analyzed end-plate joints is shown in Fig. 9. The stress distribution is presented for a more unfavorable scheme, i.e. for a simply supported beam, because the maximum bending moment occurs in the connection axis.

By analyzing the distribution of stresses in the connections (Fig. 9), it is possible to assess the efficiency of the connections due to the distribution of internal forces in the connected beams. In a commonly used end-plate joint with bolts inside the cross-sectional outline (Fig. 9a), increased compressive stresses are visible in the upper band, but the total stresses do not exceed the permissible stresses for the adopted steel grade. In a modified end-plate joint with a front plate consisting of two parts and bolts located inside the cross-section outline and additional side plates (Fig. 9b), the stresses are distributed evenly on the side plates, which means that lower stresses are visible on the section of side plates in the upper chord compared to for tension without side plates. In a end-plate joint with bolts extended outside the cross-section in the lower chord (Fig. 9c), the stresses are distributed evenly in the end plate and the loads are transferred more effectively by the connectors than in a connection with bolts inside the cross-section, despite the thinner end plate and smaller diameter of the bolts. Bolts extended beyond the cross-section are further away from the neutral axis, thus transferring smaller forces resulting from the bending moment. In turn, in a modified end-plate joint with bolts extended beyond the cross-section (Fig. 9d) and a divided end plate, the stresses are distributed as effectively as in the connection with a full end plate. Increased stresses occur at the lower point of contact between the upper end plate and the web, but they do not exceed 235 MPa. Thanks to the use of



Rys. 9. Rozkład naprężeń zredukowanych w analizowanych połączeniach dla belki swobodnie podpartej [Pa]: a) połączenie doczołowe ze śrubami wewnątrz przekroju; b) połączenie doczołowe z dwuczęściową blachą czołową z dodatkowymi blachami bocznymi oraz ze śrubami wewnątrz przekroju; c) połączenie doczołowe ze śrubami wysuniętymi poza przekrój w strefie rozciąganej; d) połączenie doczołowe z dwuczęściową blachą czołową oraz z wysuniętymi śrubami poza przekrój w strefie rozciąganej

Fig. 9. Stress reduced distribution in the analyzed connections for a simply supported beam [Pa]: a) end-plate joint with bolts inside the cross-section; b) end-plate joint connection with a two-part end-plate with additional side plates and with bolts inside the cross-section; c) end-plate joint with bolts extended beyond the cross-section in the tension zone; d) end-plate joint with a two-part end-plate and bolts protruding beyond the section in the tension zone

a triangular stiffening plate of the lower end plate with the beam flange, the stresses are evenly transferred from the end plate to the flange, which additionally stiffens the connection. The stress distribution in the additional triangular plate is visible in Fig. 8b.

Despite increased stresses in some places of the connections, the total stresses do not exceed 235 MPa, therefore the analyzed connections allow for effective connection of beams within the yield strength of steel. Increased stresses in bolts and nuts result from the stress range shown in Fig. 9 to 235 MPa, while the yield strength of the bolts is 900 MPa. The distribution of stresses in the bolts themselves is shown in Fig. 10. As can be seen in Fig. 9, the stresses in the bolts and nuts do not exceed 900 MPa, which proves that the pre-stressing force of the bolts was correctly selected and that the analytical calculations of the bolt load-bearing capacity were correct.

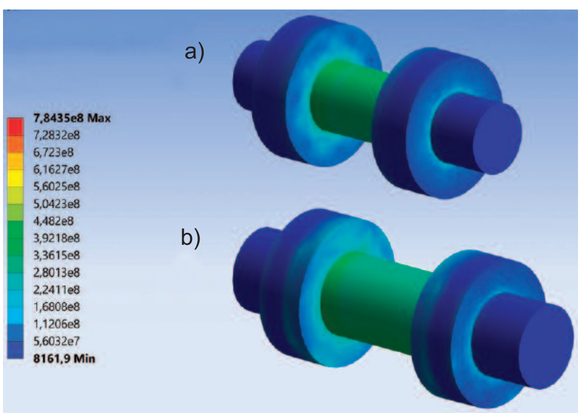


Fig. 10. Stress distribution in numerical models of bolts [Pa]: a) M12 bolt; b) M16 bolt

Rys. 10. Rozkład naprężeń w modelach numerycznych śrub [Pa]: a) śruba M12; b) śruba M16

The largest displacements for a simply supported beam were read at the connection axis, while for a cantilever beam at the end of the cantilever. The displacements of beams with connections can only be determined using a numerical model, because the standard [16] does not specify a method for calculating the displacements of beams with connections. A summary of the maximum displacements for the analyzed connections is presented in Table 4.

Analyzing the maximum deflections of the simply supported beam with the analyzed connections, it was shown that in terms of the smallest deflections, the best connections are those with bolts extended beyond the cross-section in the tension zone (Fig. 9c and Fig. 9d). These connections provide deflections of 1.834 mm and 1.832 mm, respectively. The use of an additional stiffening triangular plate (item 4 in Fig. 5b) resulted in a slight reduction in deflection, and as a result, despite the use of a two-piece end plate, the deflection is smaller. Slightly greater deflections are provided by connections with bolts inside the beam cross-section (Fig. 9a and Fig. 9b) with deflections of 1.888 mm and 1.852 mm, respectively. A modified end-plate joint with a two-piece end plate and side plates provides less deflection than a connection with a full end plate. For all connection variants, the deflections do not exceed the serviceability limit state with the condition being below 39%, which indicates the effectiveness of their work in terms of vertical displacements in simply supported I-beams.

Analyzing the maximum deflections of the cantilever beam, it can be seen that, similarly to the deflections of a simply supported beam, connections with bolts extended beyond the cross-section in the tension zone (Fig. 9c and Fig. 9d) provide the smallest deflections, amounting to 9.121 mm and 9.096 mm, respectively. However, connections with bolts inside the beam cross-section (Fig. 9a and Fig. 9b) ensure deflections of 9.361 mm and 9.177 mm, respectively. As you can see, the modified end-plate joints, thanks to the use of additional sheets, ensure smaller deflections, despite the use of two-piece end plates. For all connection variants, the deflections do not exceed the serviceability limit state with the condition being below 98%, which indicates their effectiveness in terms of vertical displacements in I-beams installed as a cantilever.

Moreover, based on the determined displacements for beams without connections and for beams with connections, the difference in displacements was calculated, from which the angles of rotation in the connections resulting from the work of the connections themselves were then determined using trigonometric relationships. The calculated stiffness values of rotary connections are presented in Table 5.

Table. 5. Rotational stiffness of the analyzed end-plate joint, shown in Fig. 9

Tabela. 5. Sztywność obrotowa analizowanych połączeń doczołowych, pokazanych na rysunku 9

Analyzed connection model	Rotational stiffness of the connection [kNm/rad]
a.	63415
b.	89655
c.	113043
d.	116418

Analyzing the calculated rotational stiffnesses of the connections, it can be seen that the stiffest connections are the connections with bolts extended beyond the cross-section in the tension zone, characterized by a rotational stiffness of 113043 kNm/rad for the standard connection with a full end plate (Fig. 9c) and 116418 kNm/rad for the connection modified with a divided end plate and an additional triangular plate (Fig. 9d). Comparing the connections with bolts inside the beam cross-section (Fig. 9a and 9b), which provide rotational stiffness of 63415 kNm/rad and 89655 kNm/rad, respectively, it can be seen that the modified connection thanks to side plates is characterized by higher rotational stiffness despite the use of a two-piece end plate. The analysis of rotational stiffness was carried out for bending moments in the connection from 0 to 30 kNm, and the graphs of the relationship between the bending moment in the connection and its rotation angle (M-ϕ curves) are presented in Fig. 11. Curve a. is the rotational stiffness for a standard end-plate joint with bolts inside the cross-section, curve b. for a end-plate joint with a two-piece end plate with additional side plates and with bolts inside the cross-section, curve c. for a standard end-plate with bolts extended outside the cross-section in the tension zone, and curve d. for a end-plate with a two-piece end plate and with the bolts

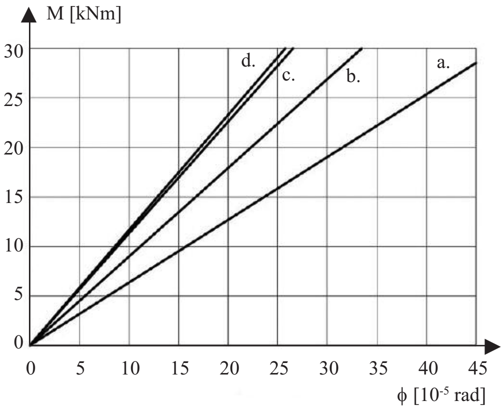


Fig. 11. Rotational stiffness of the analyzed end-plate joints (description in text)
Rys. 11. Sztywność obrotowa analizowanych połączeń doczołowych (opis w tekście)

extended beyond the cross-section in the tension zone. A completely rigid node is characterized by its ordinate axis 0-M, while a perfectly articulated node is characterized by the 0-ϕ axis, so the closer the M-ϕ curve is to the 0-M axis, the greater the rotational stiffness of the connection. As can be seen in Fig. 11, the rotation angle of the connections calculated numerically increases in a straight line depending on the increasing bending moment, while experimental studies show that the characteristics of most joints are curvilinear throughout the entire range of tests [14]. Taking into account the assessment of the susceptibility of the connections, as a result of the numerical analysis, the connections can be compared with each other and assessed in terms of rotational stiffness.

Conclusions

As a result of the numerical analysis, the effectiveness of bolted end-plate joints was assessed in terms of the obtained stress distribution and rotational stiffness. In standard prestressed end-plate joints with solid end plates, a suitably flat contact surface of the end plates is required because unevenness created during the welding of the plate to the beam may prevent proper tensioning of the bolts. In deformed contacts, uneven distribution of forces in the bolts may occur, which may even result in their breakage. The proposed modified end-plate joints made of end plates consisting of two parts will largely eliminate deviations occurring during the welding process. Modified connections (Fig. 5) through the use of reinforcing plates showed better stress distribution and lower deflections and higher rotational stiffness compared to commonly used end-plate joints with solid end plates (Fig. 4). Among the analyzed end-plate joints, the connection with bolts extended beyond the cross-section in the tension zone was the best because it was characterized by the highest rotational stiffness. Bearing in mind that in many cases, elements protruding beyond the cross-section may make their use in the structure impossible, an alternative method of connecting beams may be the proposed end-plate joint with bolts inside the cross-section with side plates (Fig. 5a), which is also characterized by high rotational stiffness and low deflections and uniform stress distribution. Moreover, the order of the obtained displacement results in the FEM analysis is related to the rotational stiffness of the connections, which affects the load-bearing capacity and stability of the structural system.

Summarizing the obtained results of the numerical analysis, the modified bolted end-plate joints with two-piece end plates proposed in the article may be an interesting alternative for use in beam connections in steel structures. Moreover, the analysis showed that the proposed connections can work more effectively than traditionally used end-plate joints, and the current development of technology for making prefabricated steel elements allows their use. In a further stage of the research, the authors will pay attention to the efficiency of the developed connections of steel I-beams as a result of dynamic loads.

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