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Analysis of the strengthening of a bolted connection with end-plates under tension load

Jacek Nawrot[1]

ABSTRACT:
In this work, an analysis of a bolted preloaded connection with end-plates under tension load was carried out. Two variants of the connection were analyzed: before strengthening and after strengthening in the form of additional connectors and horizontal ribs between the end plate and the web of the steel section. Analytical calculations based on the mechanical model of the node (component method) and numerical calculations using FEM were carried out, showing a high correlation between the obtained results. For both analyzed connection variants (before and after strengthening), the distribution of stresses in the contact zone and the reactions in individual bolts are presented. It has been shown that the use of a structural solution to strengthen the existing contact increases the load capacity of the connection by approx. 56%. The influence of the end plate stiffening ribs on the distribution of internal forces in the bolts was also determined. It has been shown that the use of ribs leads to a reduction in the reaction in the bolts, but does not change the value of the maximum stresses in the connection.

KEYWORDS:
bolted connections; load-bearing capacity of the joints; strengthening of steel structures

1. Introduction

Bolted connections are one of the oldest types of connection of steel construction elements. They are characterized by ease and speed of execution as well as the lack of specialized equipment needed during assembly (e.g. unlike welded joints), which is why they are quite commonly used, especially in steel bar structures. However, research is still being carried out to improve the existing material and construction solutions [1-3] and to develop more effective computational models [4, 5].

Changing the operating conditions, increasing the loads or progressing corrosion may make it necessary to strengthen a structure, including the existing connections within it. Reinforcement of bolted connections should be preceded by an analysis of the condition of the nodes in the existing structure, modification design and execution documentation [6].

Bolted connections can be strengthened by replacing the existing fasteners with new ones that have a higher load capacity, by expanding the existing connection by increasing the number of fasteners [7] or by using injection bolts [8]. The same type of bolts should be used as in the existing connection, and any additional plates should be made of the same steel grade as the elements of the existing joint.

In this work, an analysis of the strengthening of a bolted connection with end-plates under tension load was carried out. Analytical calculations carried out in accordance with the standard [9] were compared with the results of calculations made using the IdeaStatica program, using the finite element method (FEM).

[1] Czestochowa University of Technology, Faculty of Civil Engineering, ul. Akademicka 3, 42-218 Częstochowa, Poland, e-mail: jacek.nawrot@pcz.pl, orcid id: 0000-0002-9581-1388

2. Goal and scope of work

The goal of the work is to analyze the load capacity of a bolted preloaded connection with end-plates under tension before strengthening and after strengthening. M16 class 10.9 bolts were used in the connection. In the first variant (before strengthening) eight bolts were used (Fig. 1), in the second variant (after strengthening) horizontal ribs welded to the end plate and the I-beam web and additional bolts were used (Fig. 2).

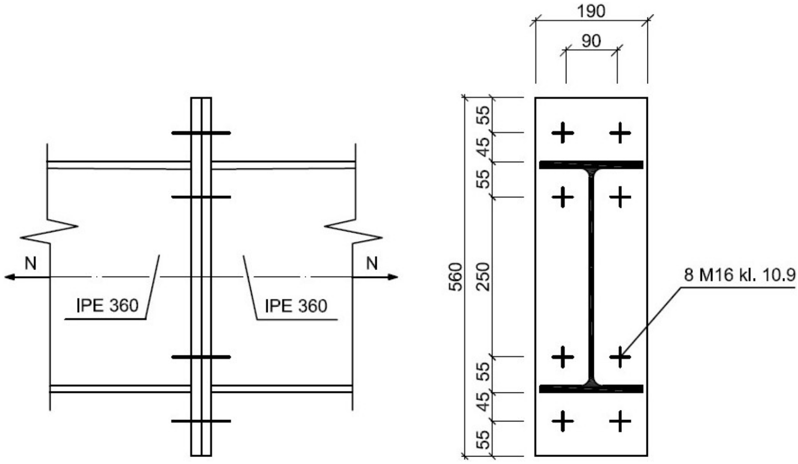

Fig. 1. Connection before strengthening (variant 1)

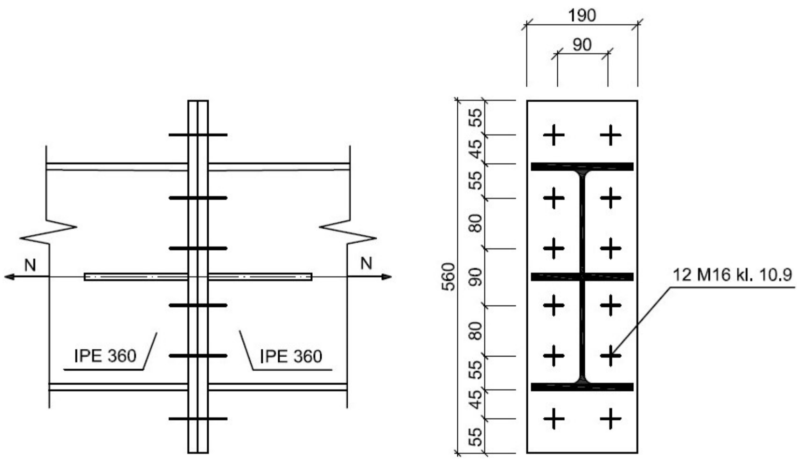

Fig. 2. Connection after strengthening (variant 2)

Parameters of the analyzed connections:
- steel section: IPE 360,
- end plate dimensions: 18x190x560,
- horizontal ribs: 10x80x180, fillet weld 5 mm,
- steel grade: S235,
- fillet welds fixing the end plate: with a web – th. 4 mm, with straps – th. 5 mm,
- connection tensile force: N_{Ed} = 1000 kN.

3. Calculation results

3.1. Analytical calculations

Analytical calculations were made in accordance with the standard [9], using the mechanical model of the joint and using the component method, according to which the load capacity of the connection was determined by the load capacity of the weakest element. For both analyzed variants, the load capacity of the joint was calculated and compared with the value of the force loading the connection. The results of the calculations are presented in Table 1.

Table 1
Results of analytical calculations

Connection variant	Tensile force N [kN]	Load capacity of the joint $N_{t,Rd}$ [kN]	The load capacity condition $N/N_{t,Rd}$ [%]
1	1000.00	732.17	136.58
2	1000.00	1145.04	87.33

The load capacity of the joint before strengthening is insufficient, the capacity condition is exceeded by more than 36%. After strengthening the joint by adding four additional bolts, the load-bearing capacity of the joint increased by over 56% and the load capacity condition is met with a less than 13% margin.

3.2. Numerical calculations

Numerical calculations were performed using the IdeaStatica program based on the finite element method (FEM). The reactions occurring in individual bolts caused by the load acting on the connection were determined and compared with the load capacity of the bolts. The calculation results are presented in Table 2.

Table 2
Results of numerical calculations

Connection variant	Reaction in the most strenuous bolt series $F_{t,Ed}$ [kN]	Bolt load capacity $F_{t,Rd}$ [kN]	The load capacity condition $F_{t,Ed}/F_{t,Rd}$ [%]
1	154.50	113.00	136.73
2	99.30	113.00	87.88

The value of the reaction in the bolt for the first variant is over 36% greater than the bolt load capacity, which proves that the load capacity of the connection has been exceeded. In the second variant (after strengthening), the reaction in the bolt decreases by less than 56%, which ensures that the load capacity condition for the analyzed connection is met.

Maps of stresses that arise in the walls of the joined elements within the contact area were also prepared. The maximum stress value for the first variant was less than 235 MPa and occurred in the end plate around the most stressed bolt. Slightly lower stresses, equal to 217 MPa, occurred at the contact point of the I-beam chords with the end plate (Fig. 3).

After modifying the connection by adding four bolts and applying horizontal ribs between the web and the end plate, the zone of maximum stresses equalled 235 MPa covering not only the area of the end plate near the most stressed bolt (as in the first variant), but also the web at the point of contact with the ribs. The stresses in the I-beam chords at the point of contact with the end plate were significantly reduced to 140.5 MPa (Fig. 4), which should be explained by the change in the load distribution on the individual components of the joint.

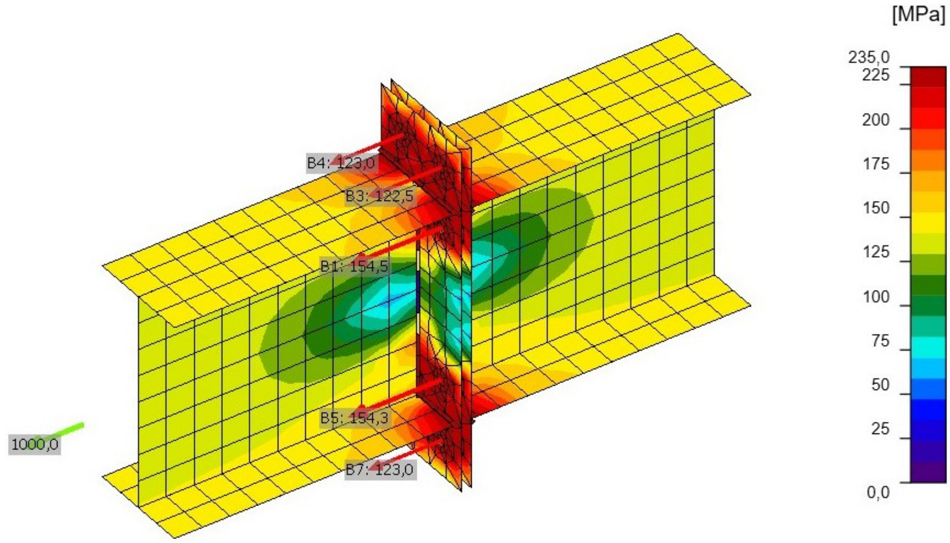

Fig. 3. Reactions in bolts and stress distribution (variant 1)

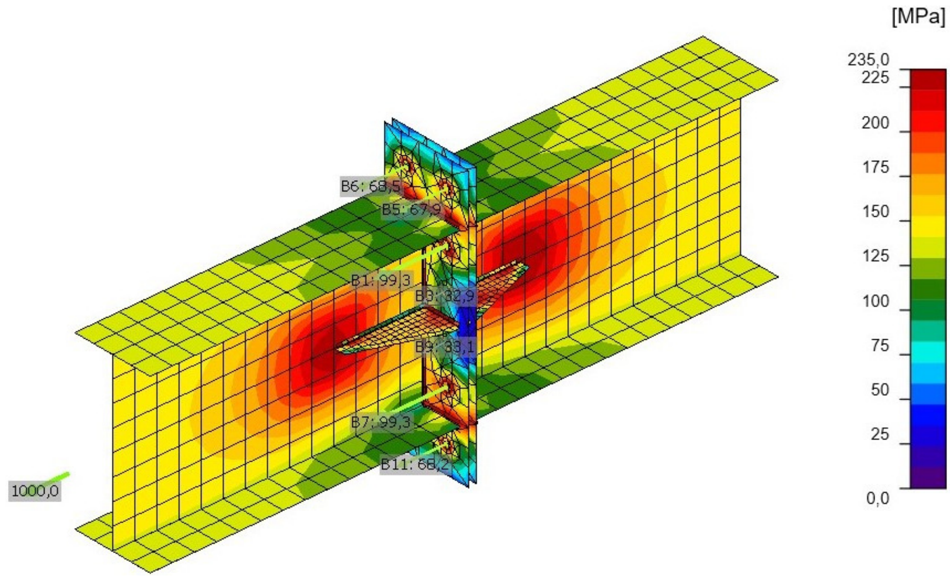

Fig. 4. Reactions in bolts and stress distribution (variant 2)

In order to determine the effect of the applied ribs (between the web and the end plate) on the reaction value in the bolts and on the stress distribution in the joint, an additional analysis was carried out for strengthening by adding only additional bolts (Fig. 5).

The lack of ribs increased the reaction in the bolts: in the outer row by more than 40%, in the first inner row by about 7% and in the second inner row by about 273%. Despite the greater effort of the screws, the load-bearing conditions of the connection were met. The zone of maximum stresses in the web was shifted towards the end plate and their value decreased to 204 MPa, while the stresses at the contact point of the flanges with the end plate increased to 164 MPa. The value and location of the maximum stresses in the end plate did not change – 235 MPa around the most stressed bolt.

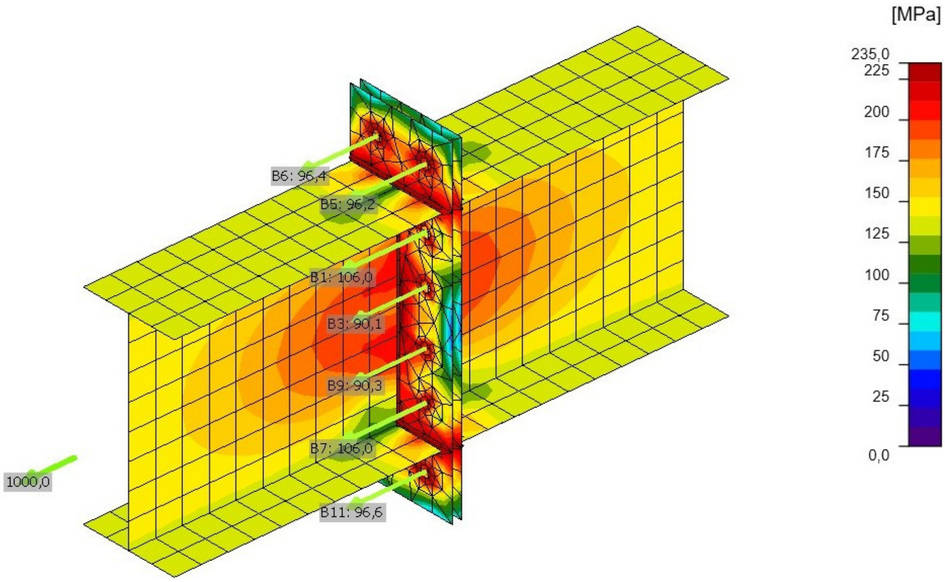

Fig. 5. Reactions in bolts and stress distribution (variant 2 without ribs)

4. Conclusions

The proposed strengthening of the analyzed joint is relatively easy to perform, involves little interference with the existing structure and allows for a significant increase in the load capacity of the connection (in the analyzed example, the load capacity increased by more than 56%).

The results of analytical and numerical calculations show a high degree of agreement (the discrepancy is less than 1%), which proves the accuracy of the analysis. Typically, the difference between these results is greater and ranges from a few to several percent [7]. This is due to the different computational models adopted for each method. For analytical calculations, a mechanical model of the joint is assumed and its load capacity is determined using the component method, where the load capacity of the weakest component of the joint determines the load capacity of the connection [9]. Numerical calculations, based on the finite element method, obtain (with the assumed load) values of stresses and strains in the joint and internal forces in the bolts close to the real ones. Thanks to this, their results are more accurate than the results of analytical calculations based on the component method. Such a high correlation coefficient obtained for the analyzed connection is quite rare.

The use of horizontal ribs between the web and the end plate changes the distribution of internal forces in the connection, which results in a reduction in the reaction in the bolts and a slightly different distribution of stresses in the contact zone. In the analyzed connection, both the variants, with and without ribs, meet the requirements regarding the load capacity of the connection. However, in the general case (for other calculation parameters), due to the greater effort of the bolts, the lack of ribs could result in exceeding the load capacity of the connection.

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Analiza wzmocnienia śrubowego połączenia doczołowego poddanego rozciąganiu

STRESZCZENIE:
Przeprowadzono analizę śrubowego sprężanego połączenia doczołowego poddanego rozciąganiu. Analizowano dwa warianty połączenia: przed wzmocnieniem oraz po wykonaniu wzmocnienia w postaci dodatkowych łączników oraz żeber poziomych między blachą doczołową a środnikiem kształtownika stalowego. Przeprowadzono obliczenia analityczne bazujące na mechanicznym modelu węzła (metoda składnikowa) oraz obliczenia numeryczne wykorzystujące MES, wykazując dużą korelację między otrzymanymi wynikami. Dla obu analizowanych wariantów połączenia (przed i po wzmocnieniu) przedstawiono rozkład naprężeń w strefie styku oraz reakcje w poszczególnych śrubach. Wykazano, że zastosowane rozwiązanie konstrukcyjne wzmocnienia istniejącego styku powoduje wzrost nośności połączenia o ok. 56%. Określono również wpływ żeberek usztywniających blachę czołową na rozkład sił wewnętrznych w śrubach. Wykazano, że zastosowanie żeberek prowadzi do zmniejszenia reakcji w śrubach, nie powoduje natomiast zmiany wartości maksymalnych naprężeń występujących w połączeniu.

SŁOWA KLUCZOWE:
połączenia śrubowe; nośność węzłów; wzmacnianie konstrukcji stalowych