EFFECT OF BOLTS OVERLOADING IN FLANGE-TYPE JOINTS

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ABSTRACT:

The joints of bars composed of flanges and high-strength bolts are currently used in steel structures as simple and economical construction solutions. This paper presents some theoretical aspects regarding the behavior and calculation of joints with flanges and partially pre-tensioned bolts. The overloading of the pretensioned high-strength bolts produced by the tensile effort resulting from the external actions is usually neglected in the technical materials and in the design norms for constructions, as long this tensioning effort does not exceed the pretensioning force of the high-strength bolts. The overloading effort of the bolts can be evaluated theoretically by estimating the relative stiffness of the flanges and bolts and confirmed through experimental tests and computer simulations. This paper also theoretically and computationally analyzes a joint for a tensioned bar made up of pre-stressed high-strength bolts and end flanges.

1. INTRODUCTION

Joints made up with flanges (end plates) and fastened with bolts are particularly specific to pipe joints, but can also be used in steel structures as bars subjected to axial load, being simple and economical constructive solution.

This paper theoretically analyzes a joint for a tensioned pipe bar made-up with prestressed high-strength bolts, with end flanges and compares the results to those obtained from a computer model.

The issue of overloading the pre-tensioned high-strength bolts due to external tensile forces is neglected in technical materials and design standards, including EN 1993-1-8/2005. Eurocode 3: Design of Steel Structures, as long as the tension does not exceed the pre-tensioning force in the bolts. The overloading effort of the bolts can be evaluated theoretically by estimating the relative stiffness of the flanges and bolts and confirmed through experimental tests and computer simulations. Figure 1 shows a flange joint connected by bolts.

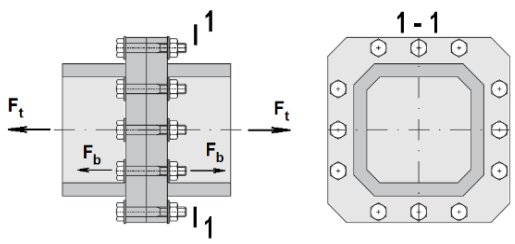


Figure 1. Flange type join

In the case of non-preloaded bolts, when there is no compressive force on the contact surfaces, the applied external tensile force F_t on the joint will be transferred to the bolts through forces F_b. Consequently, any change in the tensile force F_t will result in a corresponding change in the forces of the bolts, causing a relative displacement of the end plates (flanges) at the same time.

2. BEHAVIOUR OF JOINTS WITH FLANGES AND PRESTRESSED HIGH-STRENGTH BOLTS

2.1 Forces in a tensioned joint with flanges

By strongly tightening the nut, a significant tensile force is introduced into the bolt rod, which can reach up to 70-75% of the yield strength of the bolt material. This results in high pressure being exerted on the contact surfaces around the bolts.

In the case of pre-tension with force F_v, during the initial phase, this force is in equilibrium with the compressive force that arises at the contact surface, F_c. The two flanges will work as a monolithic element as long as the external force F_t has a lower value the pre-tension force F_v.

Therefore, if there is no applied external force (F_t=0), the result will be $F_b = F_c = F_v$. A more accurate analysis reveals that when an external force is applied, there will be a slight change of the forces in the bolts, as shown in Figure 2 (Kullak, 2001).

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It can be observed that an increase in the tensile force of the joint is counterbalanced by a substantial decrease of the compressive force between the contact plates, and to a minor degree by the change of the forces in the bolts.

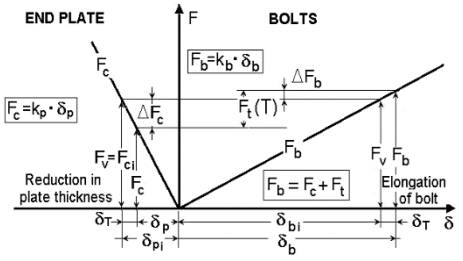


Figure 2. Forces in the joint before to flanges separation

The application of an external force F_t causes a significant change of the compressive force in the end plate, with the value ΔF_c, compared to the relatively small increase of the tension effort in the screws, ΔF_b, $\Delta F_b << \Delta F_c$.

Prior to the separation of the end plates, the result will be:

$$\Delta F_b = k_b \cdot \delta_T \text{ and } \Delta F_c = k_p \cdot \delta_T \Rightarrow$$
$$F_t = \Delta F_b + \Delta F_c = (k_b + k_p) \cdot \delta_T; \quad \delta_T = \frac{F_t}{k_b + k_p},$$

where: k_b is the relative rigidity of the bolts
k_p is the relative rigidity of the end plate

For proper behavior of the joint, it is recommended that the pre-tensioning effort in the bolts to be greater than the tensile force from external actions. Additionally, the location of the contact area between the components should be considered, as shown in Figure 3 (ESDEP).

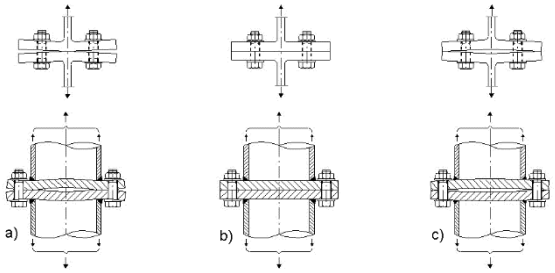


Figure 3. Contact area between joint parts

The relationship between the forces developed in the joint is illustrated by the force triangle, as shown in Figure 4, (ESDEP and Kullak, 2001).

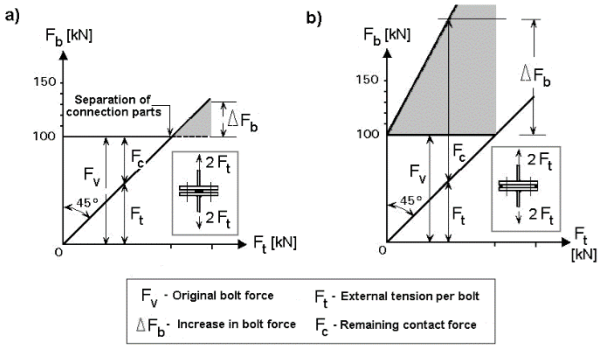


Figure 4. Effect of contact pressure zone location on the efforts in the bolts

In Figure 4.a, the contact is limited to the central area of the joint, leading to no increase of the bolt force until relative displacement of the parts occurs. In Figure 4.b, the contact is developed in the marginal areas of the joint and in this case, any stretching force will increase the bending of the plate, and also increase both F_c and the effort in the screw with the value ΔF_b.

2.2 Design parameters

The relative rigidity of the joint K and the overloading factor of the bolts are defined by the equation:

$$K = \frac{k_b}{k_b + k_p} \tag{1}$$

By cumulating the initial pre-tensioning force with the effect of overloading the bolts due to the tensile effort produced by the external loadings, the real stretching forces in the bolts of the joint are obtained:

$$F_b = F_v + \Delta F_b = F_v + K \cdot F_t = F_v + \frac{k_b}{k_b + k_p} F_t \tag{2}$$

The compression force on the end plates (flanges) will be:

$$F_c = F_v - \Delta F_c = F_v - (1 - K) \cdot F_t \tag{3}$$

The separation of the end plates occurs when $F_c = 0$, and the external force is:

$$F_t^{sep.} = F_v \left(1 + \frac{k_b}{k_p}\right) = \frac{F_v}{1 - K} \tag{4}$$

The diagram in Figure 5 shows the loading sequence of a pre-tensioned screw joint, given the known relative rigidity of the components, such as the plates and bolts.

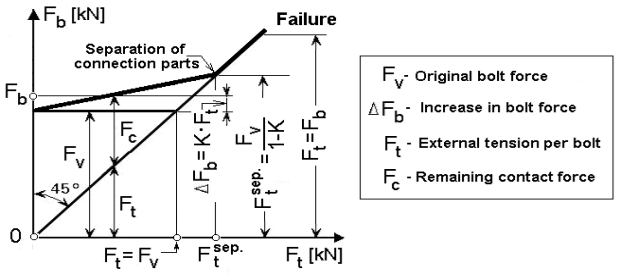


Figure 5. Evolution of the bolt forces

2.3 Relative stiffness of the joint elements

2.3.1 Relative stiffness of the bolts: The rigidity of a screw is determined by the stiffness of both the threaded and non-threaded sections of the rod, as shown in Figure 6. These sections are considered to be two springs connected in series (Budynas, 2015):

$$k_b = \frac{A_s A_b E}{A_b \ell_1 + A_s \ell_2} \approx \frac{A_b E}{\ell} \quad (5)$$

Where: A_b - the gross area of the screw
A_s – the area of the threaded part of the screw

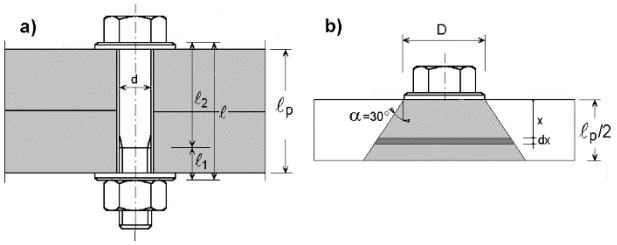


Figure 6. Characteristics to evaluate bolt stiffness

2.3.2 Relative stiffness of the flanges: Considering a pressure distribution at an angle$\alpha = 30^o$, the rigidity constant of the flange can be expressed in exponential form (Budynas, 2015):

$$k_p = 0.787 \cdot d \cdot E \cdot e^{0.628\frac{d}{\ell_p}} \quad (6)$$

2.4 Effect of prying action

The phenomenon of "prying action" involves the creation of lateral lever forces named as *prying forces* due to transverse deformation of the flexible end plate in the connection, as shown in Figure 7.a (Kullak, 2001). These prying forces result in an increase of stress on the bolts, which is added to the previous stress, as depicted in Figure 7.b

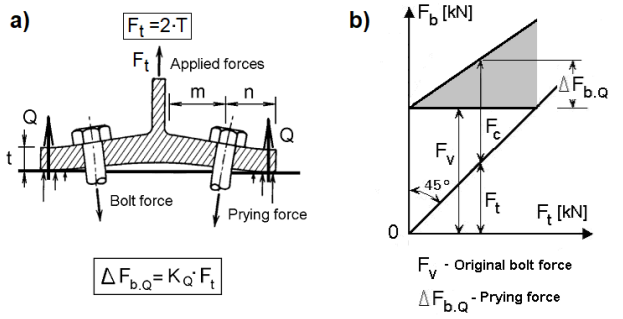


Figure 7. Prying action: a) Development of prying forces; b) Diagram of forces in the joint

In this situation, any tensile force will amplify plate bending and will also increase both, F_c and the force in the bolt with the amount of $\Delta F_{b.Q}$.

The prying force is directly proportional to the outer tensioning force and can be put in the general form:

$$\Delta F_{b.Q} = Q = K_Q \cdot F_t \quad (7)$$

For rectangular flanges, some semi-empirical relationships (Kullak, 2001) can be used to quickly evaluate the marginal prying forces:

$$K_Q = 0.5 \cdot \left(\frac{3m}{8n} - \frac{t^3}{20}\right)_{U.S.units} = 0.5 \cdot \left(\frac{3m}{8n} - \frac{t^3}{328}\right)_{S.I.units} \quad (8)$$

For circular end plates, the prying action can be calculated using advanced computer programs.

When the bolts have a high rigidity (large diameter and short length), the two effects, i.e., overloading the bolts due to the redistribution of the stretching force between the bolts and the plate and the prying forces accumulate.

Cumulating the effect of overloading the bolts due to the tensile effort produced by the outer loadings and the prying force effect, the tension forces in the bolts will be:

$$F_b = F_v + \Delta F_b + \Delta F_{b.Q} = F_v + (K + K_Q) \cdot F_t \quad (9)$$

The force transmission is dependent on the connection's elastic behavior and, in general, the contact mode in the bolt area is important.

In the papers (Choudhury, 2008, Guțiu, 2021, Leonardo da Vinci Project, 2003, Novoselac, 2014 and Urse, 2018), the behavior of flange-type joints connected by preloaded high strength bolts is also discussed, including the fatigue and dynamic response of these types of joints.

3 WORKING EXEMPLE

The forces in a joint with high-strength bolts and flanges are analyzed. It uses 8 M20 bolts, group 10.9, with the following design characteristics:

$F_{yb} = 900 N/mm^2$; $f_{ub} = 1000 N/mm^2$;
$A_s = 2.45 cm^2$; $A_b = 3.14 cm^2$;
The bolts are pretensioned at an effort: $F_v = 120 kN$;
The design tension force in the joint is: $N_{t.Ed}^{tot} = 800$ kN;
The end plates (flanges) thickness $t_p = 40$ mm.

The constructive solution of the joint is shown in Figure 8 (Chindriș, 2022).

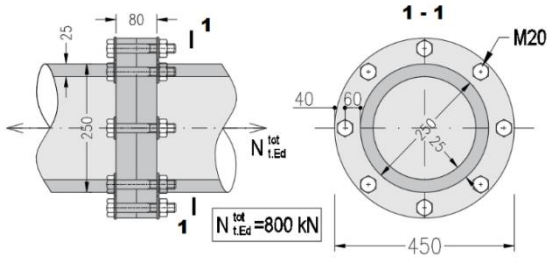


Figure 8. Joint with flanges and high-strength preloaded bolts

Simplified calculation, accepted by design rules

In a simplified calculation, for tension efforts produced by external actions less than the preloading effort, i.e.,$F_{t.Ed}^b = 100kN \leq F_v = 120kN$, the effort in screws will equal the pre-tensioning effort, $F_b = F_v = 120kN$.

Design in accordance to the methodology of factor K

The situation where the M20 bolts - group 10.9 of the joint are pre-tensioned to the effort $F_v = 120\ kN \approx 0.70 \cdot F_{p.C}$ is analyzed, where (EN 1993-1-8/2005):

$$F_{p.C} = 0.7\ f_{ub}\ A_s = 0.7 \cdot 1000 \cdot 245 \cdot 10^{-3} = 171.5\ kN$$

The tensile force of the screw is (EN 1993-1-8/2005):

$$F_{t.Rd} = \frac{0.90\ f_{ub} \cdot\ A_s}{\gamma_{M2}} = \frac{0.90 \cdot 10000 \cdot 2.45}{1.25} 10^{-2} = 176.4\ kN$$

Given the efforts:

$$F_v = 120\ kN \text{ and } F_t = \frac{N_{tED}^{tot}}{n_b} = \frac{800}{8} = 100\ kN.$$

The relative rigidity constants of the joint parts are evaluated:

Bolt relative rigidity constant:

$$k_b \approx \frac{A_b E}{\ell} = \frac{3.14 \cdot E}{8+2 \cdot 0.8} = 0.33E\ daN/cm.$$

End plate relative rigidity constant:

$$k_p = 0.787 \cdot 2.0 \cdot E \cdot e^{0.628\frac{2}{8}} = 1.84 \cdot E\ daN/cm$$

Joint relative rigidity (bolts overloading factor):

$$K = \frac{k_b}{k_b + k_p} = \frac{0.33}{0.33 + 1.84} = 0.15$$

It results the efforts in the bolts after loading with the effort Ft will be:

$$F_b = F_v + \Delta F_b = F_v + K \cdot F_t = 120 + 0.15 \cdot 100 = 135\ kN$$

The plate separation force:

$$F_t^{sep.} = \frac{F_v}{1 - K} = \frac{120}{1 - 0.15} = 141\ kN = 1.18 F_v$$

The following shall be noted:

$$F_b = 135\ kN \begin{cases} < F_{t.Rd} = 176\ kN \\ < F_t^{sep.} = 141\ kN \end{cases}$$

The obtained results are graphically transposed in the diagram of Figure 9.

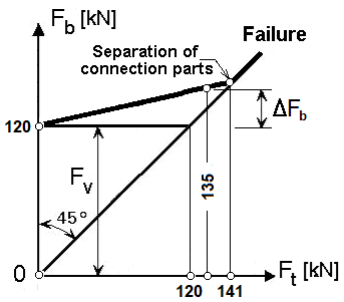


Figure 9. Bolt forces in connection

In conclusion, it can be assessed that the joint analysed in this scope meets the conditions of resistance because:

- overloading the bolts from the external actions, $\Delta F_b = K \cdot F_t = 0.15 \cdot 100 = 15kN$, does not change the value of the effort in the bolts to lead to the separation of the end plates;
- tensile efforts from the bolts, increased by the overload effort, do not exceed the design tension strength of the screws;
- the effort of stretching in the bolts at which the separation of the end plates occurs is lower than the tensile strength resistance of the screw.

In the papers (Guțiu, 2016, Guțiu, 2019 and Moga, 2019a) theoretically and working examples and also some design applications regarding the connections of flanges type are presented.

The calculation of the connections using end plates and bolts subjected to tension force, bending moment and shear force is presented in papers (Moga, 2019b and Guțiu, 2022).

4. FINITE ELEMENT ANALYSIS RESULTS

The joint presented in Figure 8 was modelled in Abaqus using 8 nodes linear brick type elements, with reduced integration and an hourglass control, C3D8R type elements. The flange mesh is presented in Figure 10 and the mesh of the joint is presented in Figure 11.

In order to simulate the effect of the applied load on the pretensioned bolts, 3 steps were defined. In the initial step the boundary conditions are applied (the assembly is fixed at one end), then a pretensioning of the bolts is defined, the pretensioning load in each of the 8 bolts has a value of 120 kN and at the final step the 800 kN load is applied at the free end.

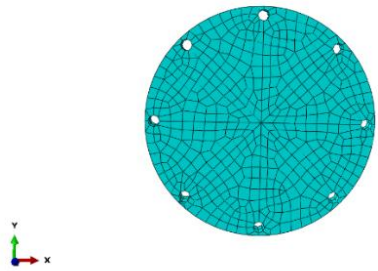


Figure 10. Flange mesh with C3D8R elements

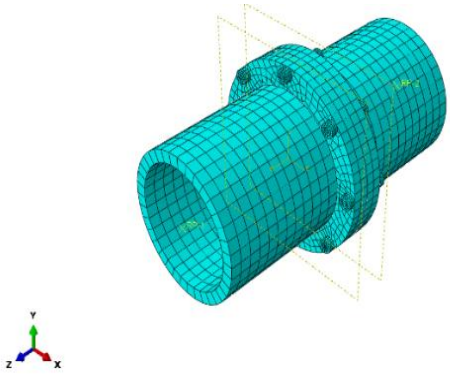


Figure 11. Joint mesh with C3D8R elements

The stress distribution in the joint is presented in Figure 12. By analyzing the results, it is found that the average stress force in

the bolt has a value of 151 kN, that means an overloading of the bolt from external actions with 31 kN, double than the analytically computed value of 15kN.

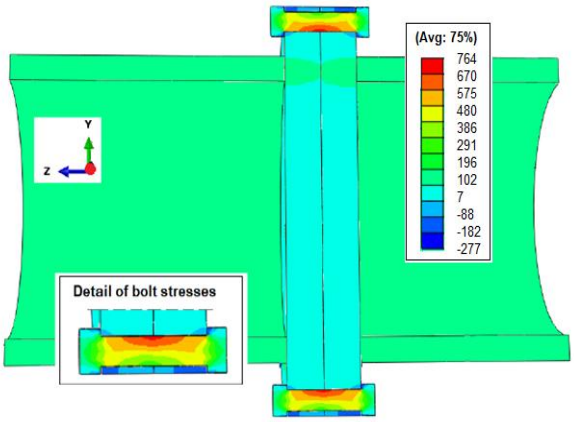


Figure 12. Stress distribution in the bolts

The reason for this difference is that in the analytical example, the effect of the prying force was not considered because the theoretical value is only established for T-shaped profiles.

5. CONCLUSIONS, COMMENTS AND DESIGN RECOMMENDATIONS

Joints with flanges and bolts are a simple and economical solution for steel structures.

To ensure proper contact between the flanges, it is recommended to initially tighten the bolts at 60% to 80% of the pre-tensioning force $F_{p.C}$.

Overloading of the pre-tensioned high-strength bolts caused by external tensile forces is usually ignored in technical materials, as long as this tensile force does not exceed the pre-tensioning force of the bolts.

The overloading effort of the bolts can be evaluated by theoretical estimation of the relative stiffness of the flanges and the bolts, confirmed by experimental tests and computer simulations.

In the case of pretensioning the bolts, which are tensioned from the external loads, they are additionally overloaded with 10...20% of the pretensioning effort, respectively with 15...25% of the tensile force resulting from the external actions.

The tensile stress produced by the external actions overlaps the initial pre-tensioning effort, and the safety of the joint may become critical.

When dealing with flexible flanges, the phenomenon of "prying action" should be taken into account, which is the development of lateral lever forces (prying forces) due to transverse deformation of the end plates.

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