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CONSIDERATIONS UPON THE OVERLOADING OF PRESTRESSED BOLTS IN TENSILE FORCED CONNECTIONS

BY

CĂTĂLIN MOGA, MIRCEA SUCIU and CLAUDIA PONDICHI-ALB*

Technical University of Cluj-Napoca,
Faculty of Civil Engineering

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Abstract. The connections made with end plates and bolts are typical of pipe connections subjected to axial stresses (called flanges), of joining girders or beams to other structural members, but also for metal bridge structures, to join together the girders of the flooring. The connections made with end plates and bolts can lead to constructive solutions that are simple and economical if the connection mechanical behaviour is properly modelled. This paper presents several theoretical aspects regarding the overloading of prestressed bolts in tensile stress connection, taking into account the relative stiffness of the component elements in the end plates and bolts. The case of the high strength prestressed bolts (initial stresses) of steel grade 8.8 and 10.9 is analysed. The paper includes a numerical example that highlights the influence of the stiffness of the connection elements, respectively the maximum tensile stresses in the bolts. The comments and recommendations at the end of the paper can be useful for a more appropriate formation of such connections and for getting a proper safety in service of the steel members and elements.

Keywords: connection; girders; end plate and bolts; prestressed bolts; plate-bolt stiffness; Eurocodes; design methodology; calculation analysis; practical recommendations.

*Corresponding author: *e-mail:* Claudia.Alb@infra.utcluj.ro

1. Introduction

Design practice aims at making as simple as possible connections, easy to be made on the building site, with a clear behaviour in the structure and providing service safety when subjected to static and dynamical loads.

The connections with end plates and bolts can be used for steel bridges too, to join together the girders of the deck, so as to have simple and economical constructive solutions, on condition that a proper modelling of the mechanical behaviour of the connections is performed.

This paper analyses the stiffness of the connections made with bolts subjected to tension and evaluates the additional stress of prestressed bolts through the tensile stresses coming from external forces redistribution.

The numerical example presented shows a situation when the bearing capacity of the bolts is exceeded with maximum tensile stresses, a situation that is reached following the overcharging of prestressed bolts, by the redistribution of connection stresses proportionally to the relative stiffness values of its components.

The connection calculation method presented in this paper provides the possibility of making a rapid analysis of the stresses from the connection and of the connection safety, implicitly.

The authors also appreciate that the design recommendations in the final part of this paper can be useful for the design of steel constructions and bridges.

2. Connections with End Plates and Prestressed Bolts

The transmission of the bending moment from a girder type member to the joining element can be performed by means of an end plate, which has to be sized according to the stresses to be applied and which must have a stiffness in agreement with the calculation procedure used for the bolts in the connection.

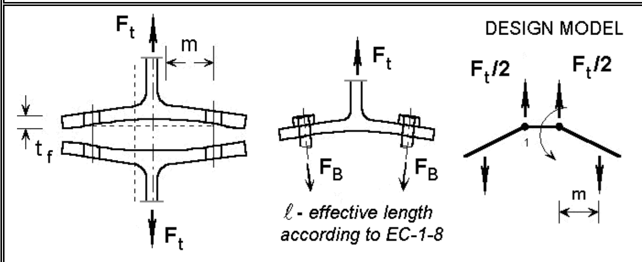
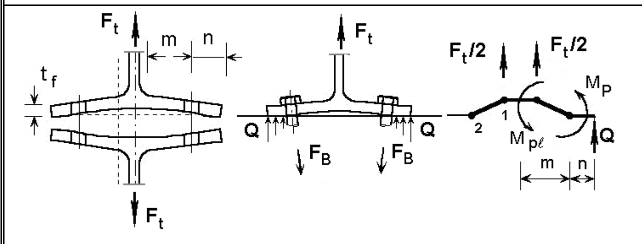
In the case of usual bolts subjected to tensile forces by a force F_t, the calculation model is the one in Table 1 – Case 1; when the bolts present high strength, the calculation model is the one presented in Table 1 - Case 2.

In metal and mixed steel-concrete bridges and constructions, prestressed high strength bolts, namely bolts to which tensile stresses are inserted in the rod after being mounted are currently used.

By a strong tightening of the nut, an important tensile stress is inserted in the bolt rod with a value of about 70%,...,75% from the yielding limit of the material from which the bolt is made, high pressures being exerted in an area around the bolt contact surfaces.

It is for this reason that the joining parts are strongly tightened together so that under the action of a normal stress onto the bolt rod, the relative displacement of the parts is prevented by the friction forces at the contact surfaces.

Table 1
Calculation Model

Case	Connection strength
	$F_B = 0.5 \cdot F_t$ $M_{p\ell} = \frac{1}{4} \cdot \ell \cdot t_f^2 \cdot f_y$ Plate thickness: $t_f = \sqrt{\frac{2\,F_t \cdot m}{\ell \cdot f_y}}$
	$2 \cdot M_{p\ell} = 2 \cdot \frac{1}{4}\, \ell \cdot t_f^2 \cdot f_y$ Plate thickness: $t_f = \sqrt{\frac{F_t \cdot m}{\ell \cdot f_y}}$

The prestressed high strength bolt connection exhibits an elastic behaviour with small deformation values maintained up to high stress values. The behaviour of the connection is not essentially different from the working mode of the parts. Because of this behaviour, it is acceptable to mix together high strength bolts and welding in the same connection.

The actual behaviour of the connection with prestressed bolts shows that when an external elongation force is applied, the stresses in the bolts will change relatively little as the end plates have a relatively high stiffness in comparison with that of the bolts, Fig. 1 (European Steel Design Education Programme; Kullak *et al.*, 2001). The end plates though with high stiffness are not perfectly stiff; their calculation model is presented in Fig. 1 *a* and 1 *b* (European Steel Design Education Programme).

The increase in the elongation force from the connection is compensated by a decrease of the compression stress between the contact plates and to a little extent by the change of the stresses in the bolts, Fig. 1 *c* (Kullak *et al.*, 2001).

When bolts are more elastic in relation with the connection parts, the situation is even more favourable, and longer bolts or (possible spring-type) washers increase bolt elasticity; the plates should consequently be thicker to present a high resistance to bending stiffness.

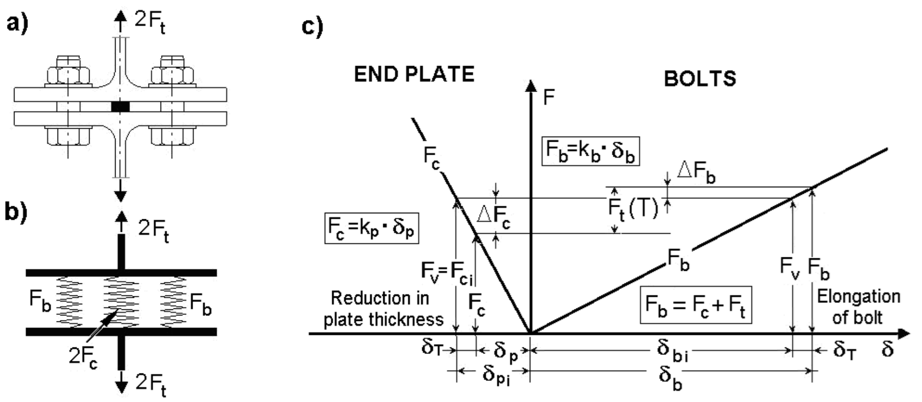


Fig. 1 – Forces in a prestressed fastener.

As seen in Fig 1 *c*, applying an external force F_t leads to a significant change of the compression stress of the end plate, by amount ΔF_c, compared to the increase in the elongation stress in the bolts, $\Delta F_b << \Delta F_c$.

Previously to the separation of the end plates, the stresses in the bolts and plate will be modified as follows:

$$\Delta F_b = k_b \cdot \delta_T \text{ and } \Delta F_c = k_p \cdot \delta_T . \tag{1}$$

It yields:

$$F_t = \Delta F_b + \Delta F_c = (k_b + k_p) \cdot \delta_T ; \quad \delta_T = \frac{F_t}{k_b + k_p} . \tag{2}$$

The *constant of the connection stiffness K* is defined, showing the ratios between the bearing capacities of the connection elements, between the elongated bolts and compressed end plate respectively:

$$K = \frac{k_b}{k_b + k_p} . \tag{3}$$

The stresses in bolts and end plate after applying an external force Ft yield:

$$F_b = F_v + \Delta F_b = F_v + K \cdot F_t \tag{4.a}$$

$$F_c = F_v - \Delta F_c = F_v - (1 - K) \cdot F_t \tag{4.b}$$

When the connection behaves elastically, the end plate separates if $F_c =$ $= 0$, for an external force of magnitude:

$$F_t^{sep.} = \frac{F_v}{1 - K} . \tag{5}$$

If the end plates are very thick (as in the case of flanges), the ratio k_b/k_p has values ranging between 0.05...0.12 and it yields $F_t^{\mathrm{sep.}} = (1.05 \ldots 1.12) F_v$.

In the field of steel constructions, the k_b/k_p values can be higher, as in the numerical example where $k_b/k_p = 0.20...0.28$ and $K_p = 0.17...0.22$.

In the case of stiff plates, after end plates separate, the stress in the bolts will be equal to the external elongation stress F_t.

In everyday design activity, an end plate stiff behaviour is usually considered, which is however not the most appropriate behaviour as the connection can be over charged. The thickness of the end plate determined from the condition of resistance to bending (example Table 1) does not define its degree of stiffness.

In many situations, it is found that the end plates are very thick versus the thickness of the girder soles or versus the pipe flange wall thickness, in the case of flanges.

The paper proposes the use of the diagram in Fig. 2, which reflects the loading stages of a connection subjected to elongation for a relatively known stiffness of the connection components, that is of the end plate and bolts.

The diagram shows the supposition that the end plate is relatively thick and respectively a high stiffness to transversal bending, while bolts are quite near to the web so that the cross deformation of the plate does not occur.

If the end plate has a low stiffness to transverse bending, the prying force is added to the stresses in the bolts (Kullak *et al*., 2001).

The design norms and the technical literature do not offer a relatively simple and practical method for evaluating the stiffness of the connection parts, but it suggests the use of the Shigley method (Budynas *et al.*, 2015) for calculating the relative stiffness of the bolts and end plates, which is used in mechanical engineering.

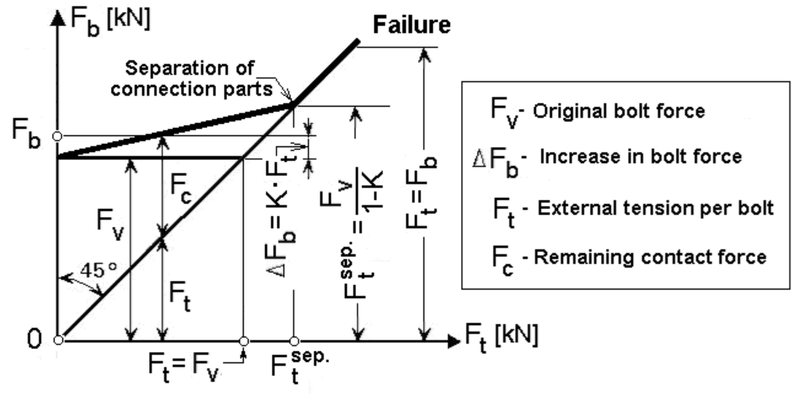


Fig. 2 – Bolt forces function of the applied load in tension type connection.

2.1. The Relative Stiffness of the Connection Elements

The stiffness of a bolt is given by the stiffness of the rest of rod areas, be it with thread or without thread, Fig. 3 *a*, seen as two springs connected in series, (Budynas *et al.*, 2015):

$$\frac{1}{k_b}=\frac{1}{k_1}+\frac{1}{k_2}\quad\Rightarrow k_b=\frac{k_1k_2}{k_1+k_2};\quad k_1=\frac{A_sE}{\ell_1};\ k_2=\frac{A_bE}{\ell_2};$$

where: A_b is the brutto area of the bolt; A_s – the net area of the bolt.

The constant of the bolt stiffness k_b is found:

$$k_b=\frac{A_sA_bE}{A_b\ell_1+A_s\ell_2}\approx\frac{A_bE}{\ell}\,. \tag{6}$$

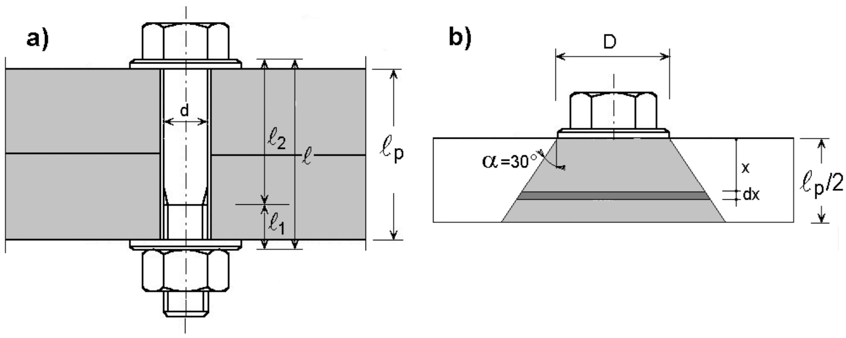


Fig. 3 – Characteristics for calculating stiffness values.

To find the end plate stiffness constant, we start from the deformation of the cone frustum exerted by the pressure resulting from tightening the bolt, Fig. 3 *b*, and considering a pressure distribution under an angle $\alpha = 30°$.

$$d\delta = \frac{F dx}{EA(x)} \Rightarrow \delta = \frac{F}{\pi E} \int_0^{\ell_p/2} \frac{dx}{f(x)};$$

The stiffness of two springs connected in series it is obtained:

$$k_p = \frac{1}{2} \cdot \frac{F}{\delta} = \frac{\pi d E \operatorname{tg}\alpha}{2 \ln\left[f(\operatorname{tg}\alpha; t; d; D) \right]}.$$

The end plate stiffness constant can be written as an exponential; function which helps easily calculate its value (Budynas, *et al.*, 2015):

$$k_p = 0.787 \cdot d \cdot E \cdot \mathrm{e}^{0.628 \frac{d}{\ell_p}}. \tag{7}$$

3. Calculation of Stresses in the Connection and Verifications at SLU

To calculate the connection for the bending moment, the hypothesis of the rotation relative to the compresses sole axis does not fully correspond to the actual behaviour of the connection as the end plate does not behave very stiffly, consequently a more accurate calculation should consider the finding of the neuter axis position along the end plate depth leading to a certain compressed surface, Fig. 4.

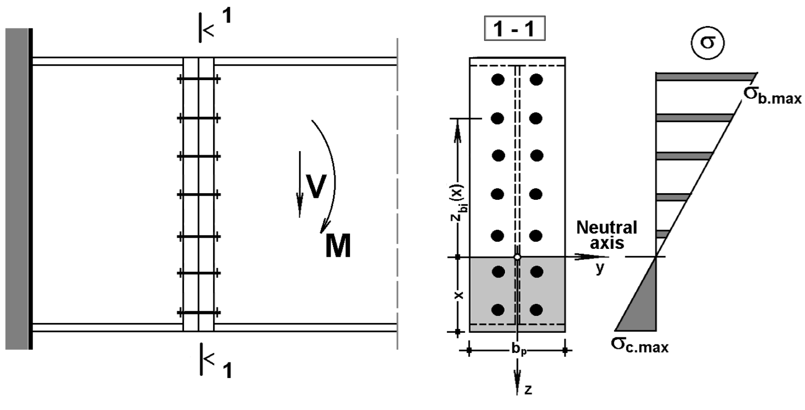


Fig. 4 – End plate connection.

The position of the neuter axis is obtained by equalising the static moment of the compressed surface to the static moment of the elongated bolts:

$$\frac{1}{2} b_p x^2 = 2\sum_{1}^{n_t} A_b z_{bi}(x) \;\; \Rightarrow x . \tag{8}$$

The inertia moment is:

$$I_{b.p} = \frac{b_p x^3}{3} + n_{bt} I_b + 2A_b \sum_{1}^{n_t} z_{bi}^2 . \tag{9}$$

According to EC3-1-8 (SR EN 1993-1-8/2006. Eurocod 3), the connections with elongated bolts are calculated in one of the following manners:

Category D non-prestressed bolts, where bolts of grade 4.6 to 10.9 inclusively are used and where bolts do not require prestressing.

In the joint area between the end plates, the bolts are verified through the interaction relationship between the moment and shearing force, according to EC3-1-8, Table 3.4:

$$\frac{F_{v.Ed}}{F_{v.Rd}} + \frac{F_{t.Ed}}{1.4 \cdot F_{t.Rd}} \le 1 \tag{10}$$

where:

$$F_{V.Ed} = \frac{V_{Ed}}{n_b}; \;\; F_{t.Ed} = \sigma_{b.\max} \cdot A_b;;$$

$$F_{V.Rd} = \frac{\alpha_v \;\, f_{ub} \;\, A_b}{\gamma_{M2}}; \;\; F_{t.Rd} = \frac{0.90 \;\, f_{ub} \;\, A_s}{\gamma_{M2}}$$

Category E prestressed bolts, where bolts of grades 8.8 and 10.9 are used with a controlled tightening, according to the Reference Standards - Group 7.

The calculated resistance to sliding of a bolt of grade 8.8 or 10.9 is found with the relationship:

$$F_{s.Rd} = \frac{k_s \; n \; \mu}{\gamma_{M3}} F_{p.C} , \tag{11}$$

where: k_s is the function of hole type; n – number of friction surfaces; μ – friction coefficient function of friction surface class.

The theoretical prestress force $F_{p.C}$ is found with:

$$F_{p.C} = 0.7\ f_{ub}\ A_s \tag{12}$$

For C category connections, where sliding should not occur in the ultimate state, the calculated resistance to sliding of a bolt is determined with the relationship:

$$F_{s.Rd} = \frac{k_s\, n\, \mu}{\gamma_{M3}}(F_{p.C} - 0.8\, F_{t.Ed}) \tag{13}$$

If in a connection the compressed area contact force counterbalances the tensile force applied to the elongated area, then it is not necessary to reduce the connection resistance to sliding (pct. 3.9.2 (2) from EC3-1-8).

4. Numerical Application

In this numerical application, it is analysed the state of stresses from the connection between a steel girder with and end plate and bolts, given the following calculation data:

The metal girders are made from steel S355M:

f_y = 355 N/mm^2; f_u = 470 N/mm^2.

The bolts to be used are from M 27- grade 10.9, prestressed, with calculation characterists as follows:

f_{yb} = 900 N/mm^2; f_{ub} = 1,000 N/mm^2; A_s 4.59 cm^2; A_b = 6.16 cm^2.

The stresses in the connection, the bending moment and the shearing force are: M_{Ed} = 1,650 kN·m; V_{Ed} = 1,200 kN.

The calculation is performed for the hypothesis that the end plate has a high stiffness to cross bending and the prying force effect is not considered.

The calculation takes the constructive solution of elongated sole and the following hypotheses:

– the elongated plates are flexible (semi-stiff) to rotation;

– the end plates are stiff to transversal bending;

– the bolt state of stress is determined for non-prestressed and prestressed bolts cases.

Case 1: Non-prestressed bolts

The connection constructive scheme and the stress evaluation diagrams are given in Fig. 5.

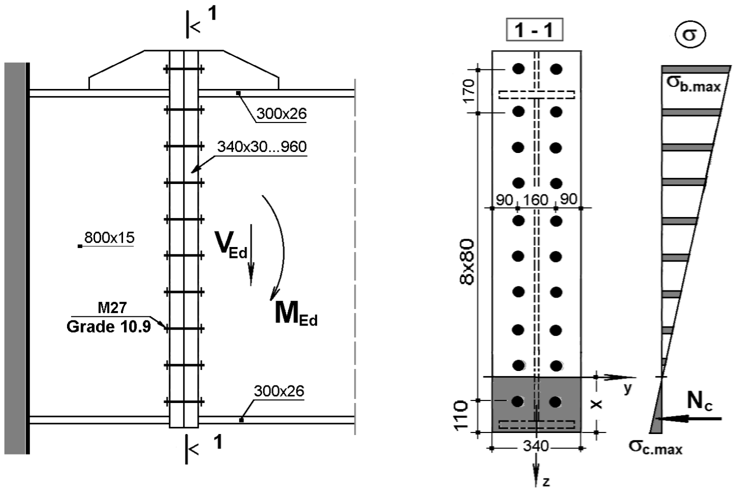


Fig. 5 – Connection with elongated end plates.

The position of the neuter axis is found as $x = z_p = 15.44$ cm.

The inertia moment: $I_{b.p} = \dfrac{b_p x^3}{3} + n_{bt} I_b + 2A_b \sum_{1}^{n_t} z_{bi}^2 = 245{,}269\,\text{cm}^4$.

The maximum unit stresses in the upper bolts:

$$\sigma_{b1} = \frac{M_{Ed}}{I_{b.p}} z_{b1} = \frac{1{,}650 \times 10^4}{24.53 \times 10^4} \times 76.56 = 5150\,\text{daN / cm}^2 .$$

The axial tensile stress in the bolt:

$$N_{b1} = \sigma_{b1} A_b = 5150 \times 6.16 \times 10^{-2} = 317.2\,\text{kN} = F_{t.Ed} < F_{t.Rd} = 330.5\,\text{kN};$$

$$F_{t.Rd} = \frac{0.90\, f_{ub} A_s}{\gamma_{M2}} = \frac{0.90 \times 10{,}000 \times 4.59}{1.25} \times 10^{-2} = 330.5\,\text{kN}.$$

The verification for the mixed stress of tension and shearing in the joint area is made with the interaction relationship:

$$\frac{F_{v.Ed}}{F_{v.Rd}} + \frac{F_{t.Ed}}{1.4 F_{t.Rd}} \le 1; \quad \frac{60}{246.4} + \frac{317.2}{1.4 \times 330.5} = 0.93 < 1,$$

where:

$$F_{V.Ed} = \frac{V_{Ed}}{n_b} = \frac{1{,}200}{20} = 60\,\text{kN}; \quad F_{t.Ed} = N_{b1} = 222.5\ \text{kN};$$

$$F_{V.Rd} = \frac{\alpha_v\, f_{ub}\, A_b}{\gamma_{M2}} = \frac{0.5 \times 10{,}000 \times 6.16}{1.25} \times 10^{-2} = 246.4\,\text{kN}.$$

The bearing force of the bolt when pressing upon the hole is (Table 3.4 in EC 3-1-8):

$$F_{b.Rd} = \frac{k_1 \alpha_b f_u d t}{\gamma_{M2}} = \frac{2.5 \times 0.7 \times 4700 \times 2.8 \cdot 3}{1.25} \times 10^{-2} = 552.7\,\text{kN} > F_{V.Rd} > F_{V.Ed}\,.$$

Case 2. Prestressed bolts

The case of bolts type M27- grade 10.9 prestressed to a stress $F_{p.C}$ is analysed:

$$F_{p.C} = 0.7\, f_{ub}\, A_s = 0.7 \times 1{,}000 \times 459 \times 10^{-3} = 321.3\,\text{kN};\;\; F_t = N_b = 317.2\,\text{kN}.$$

The stiffness constants of theconnection parts are assessed.
The bolt stiffness constant k_b:

$$k_b \approx \frac{A_b E}{\ell} = \frac{6.16 \cdot \text{E}}{6 + 2 \cdot 0.8} = 0.79\text{E}\,\text{daN / cm}.$$

The end plate stiffness constant:

$$k_p = 0.787 d E \text{e}^{0.628\frac{d}{\ell_p}} = 0.787 \times 2.7 \times E\, \text{e}^{0.628\frac{2.7}{6}} = 2.82 E\,\text{daN/cm}.$$

The connection stiffness constant:

$$K = \frac{k_b}{k_b + k_p} = \frac{0.79}{0.79 + 2.82} = 0.22$$

After loading with a force F_t, the stresses in the bolts will be:

$$F_b = F_v + \Delta F_b = F_v + K \cdot F_t = 321.3 + 0.22 \cdot 317.2 = 391\,\text{kN}$$

The plate separation force:

$$F_t^{sep.} = \frac{F_v}{1 - K} = \frac{321.3}{1 - 0.22} = 412\text{ kN} = 1.28 F_v$$

The following aspects are found:

$$F_b = 391\,\text{kN} \begin{cases} > F_{t.Rd} = 330.5\,\text{kN} \\ < F_t^{sep.} = 412\,\text{kN} \end{cases}$$

The forces are centralised in Table 2.

Table 2
Forces in Connection

Design forces	Case 1	Case 2
Maximum tensile force in bolts $N_{b.\max}$, [kN]	317.2	391
$\dfrac{F_{v.Ed}}{F_{v.Rd}}+\dfrac{F_{t.Ed}}{1.4F_{t.Rd}}$	0.93	–

One can conclude that the extreme bolts exceed the theoretical strength to tension before the end plates separate.

The results found are presented graphically in the diagram from Fig. 6.

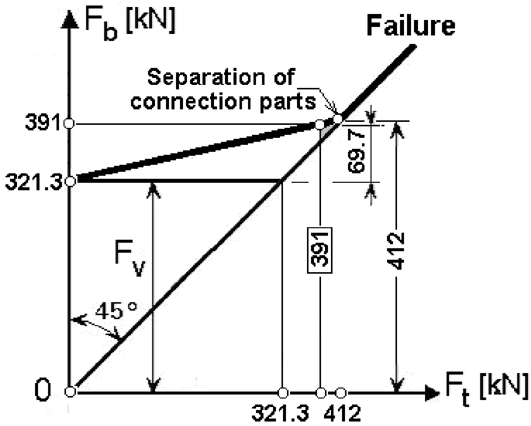


Fig. 6 – Bolt forces in connection.

An analysis of the case when the end plate should be much thicker, for example 50 mm instead of 30 mm.
The bolt stiffness constant k_b:

$$k_b \approx \frac{A_b E}{\ell} = \frac{6.16 \cdot E}{10 + 2 \cdot 0.8} = 0.53E \text{ daN / cm}$$

The plate stiffness constant:

$$k_p = 0.787dEe^{0.628\frac{d}{\ell_p}} = 0.787 \times 2.7 \times Ee^{0.628\frac{2.7}{10}} = 2.52E\,\text{daN/cm}.$$

The connection stiffness constant:

$$K = \frac{k_b}{k_b + k_p} = \frac{0.53}{0.53 + 2.52} = 0.17.$$

After loading with a force F_t, the stresses in the bolts will be:

$$F_b = F_v + \Delta F_b = F_v + KF_t = 321.3 + 0.17 \times 317.2 = 375\,\text{kN}.$$

The plate separation force:

$$F_t^{sep.} = \frac{F_v}{1-K} = \frac{321.3}{1-0.17} = 387\ \text{kN} = 1.2 F_v.$$

The following are found out:

$$F_b = 375\,\text{kN} \begin{cases} > F_{t.Rd} = 330.5\,\text{kN}; \\ < F_t^{\text{sep.}} = 412\,\text{kN}. \end{cases}$$

In this case also, the extreme connection bolts exceed the theoretical tensile resistance, so that it is necessary to change the connection, possibly by increasing the number of bolts.

5. Conclusions and Recommendations

Connections made with end plates and bolts can be used for metal structures as they can lead to simple and economical constructive solutions, on condition that they are properly modelled for their mechanical behaviour.

To use such solutions the height of the girder section should be large enough to enable the placement of a sufficient number of bolts to take over the stresses in the connection.

Prestressing the bolts in the end plate increases the stresses in the bolts so that their bearing capacity to tension can be exceed so that such connections become less recommended.

To provide a perfect contact between the end plates, we recommend an initial tightening to a stress value of 10...20% from the prestressing force $F_{p.C}$.

The connection calculation method presented in this paper provides the possibility of a rapid analysis of the stresses with prestressed bolts subjected to tension and of the implicit connection safety, too.

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CONSIDERAŢII PRIVIND SUPRAÎNCARCAREA ŞURUBURLOR PRETENSIONATE ÎN ÎMBINĂRILE SOLICITATE LA ÎNTINDERE

(Rezumat)

Îmbinările realizate cu plăci de capăt şi şuruburi sunt specifice pentru îmbinările ţevilor solicitate la eforturi axiale (fiind denumite flanşe), pentru realizarea prinderii grinzilor sau riglelor de alte elemente structurale, dar pot fi utilizate şi în cazul structurilor de poduri metalice, pentru îmbinarea grinzilor platelajului.

Îmbinările cu plăci de capăt şi şuruburi pot conduce la soluţii constructive foarte simple şi economice, cu condiţia modelării corespunzătoare a comportării mecanice a acestor îmbinări.

În lucrare se prezintă unele aspecte teoretice privind supraîncărcarea şuruburilor pretensionate în îmbinările solicitate la întindere, cu luarea în considerare a rigidităţii relative ale elementelor componente din îmbinare – şuruburile şi placa de capăt.

Se analizează cazul şuruburilor realizate din oţeluri cu rezistenţă ridicată, grupele 8,8 şi 10,9 pretensionate (cu eforturi iniţiale).

Lucrarea include un exemplu numeric prin care se evidenţiază influenţa rigidităţii elementelor îmbinării asupra eforturilor finale din îmbinare, respectiv eforturile maxime de întindere în şuruburi.

Comentariile şi recomandările prezentate la finalul lucrării pot fi utile pentru alcătuirea cât mai corectă a acestor îmbinări ăi la obţinerea unei siguranţe corespunzătoare în exploatare a elementelor metalice proiectate.