# STATIC ANALYSIS OF A SIMPLE END-PLATE CONNECTION WITH HIGH TENSILE BOLTS AT DIFFERENT TIGHTENING TORQUE USING FEM SOFTWARE

SELEJDAK Jacek, KULIŃSKI Krzysztof, MAJOR Maciej

*Częstochowa University of Technology, Faculty of Civil Engineering, Częstochowa, Poland, EU*
*jselejdak@bud.pcz.czest.pl, kkulinski@bud.pcz.czest.pl, mmajor@bud.pcz.czest.pl*

## Abstract

In this paper the finite element method approach is presented in order to determine the effective stress redistribution and deformation in the bolted beam end-plate connection assembled with high tensile bolts. Connection is represented via HEA profile with both end-plates, bolted to the I-shape short cantilevers welded to the supporting columns. It has been assumed that the building would be foreseen as a warehouse and the beam would be located in the ceiling, thus live load with value of 5.5 kN/m$^2$ has been adopted. Analyzed beam, end-plates and beam rib elements have been assumed to be made of S235JR steel grade. Three different bolt grades i.e. 8.8, 10.9 and 12.9 and four different multipliers of maximum acceptable tightening torque i.e. 1.00, 0.75, 0.50, 0.25 are taken into considerations. For each bolt grade the minimum number of bolts and end-plate thickness required for safe connection work have been determined on the basis of polish national standards. Through the analysis it can be observed that the higher tightening torque, the smaller T-stub deformation, whereas Misses stress under the bolts heads and nuts are significantly increased. Stated boundary problem is solved with the utilization of SolidWorks software.

**Keywords:** High tensile bolts, end-plate connection, tightening torque, static analysis, FEM

## 1. INTRODUCTION

Nowadays, steel is the most commonly used material for newly erected structures due to its properties and predictable behaviour under applied loads. In order to reach significant span dimensions or to assembly two consecutive steel elements, connections via bolts/pins or welding are mainly practiced. If only possible welds should be done at the production process in order to obtain its better quality, whereas bolted/pinned joints can be easily assembled in situ. Depending on transferred load values, its direction and the direction of connected elements a large number of connection types may be listed.

In the late 70's extensively various aspects of bolted tee-hanger and end-plate connections were investigated by Krishnamurthy [1]. Author presented an economical and safe design procedure of end-plate connections which was combined of classical theory mathematical model and modification factors reflecting the actual connection work, which was furtherly validated with experimental tests giving satisfactory results. In the subsequent years' due to the rapid technological and industrial development interest in the steel structures connections significantly increased. Behaviour of four-bolt extended end-plate connection subjected to monotonic and cyclic lateral loading was discussed in [2]. In the study the effect of both material and various connection geometric properties were investigated. Through the numerical analysis it was shown that the geometry of connected beams and material properties has only a small influence on the connection behaviour. Experimental and theoretical analysis of the moment-rotation behaviour of stiffened extended end-plate connections was performed by Yongjiu et al. [3]. A new theoretical model for stiffened and extended steel beam-column and end-plate connections was proposed. Via the experimental tests it was proved that with proposed analytical model moment-rotation, moment-shear rotation and moment-gap rotation can be precisely evaluated. Various aspects of different stiffened and end-plate connections were discussed in [4-6]. Modern methods concerning the use of Shape Memory Alloys in steel structures connections subjected to seismic loads in order to mitigate the damage in structural members was presented in [7]. It should be noted that recently, experimental tests are frequently postponed after the end of numerical analysis based on finite element method due to significant time and cost reduction of performed tests. Moreover, not only small scale problems can be solved with FEM, as an example advertising board tower was investigated in [8].

In this paper the influence of high tensile bolts utilization in the beam to beam end-plate connection on stress distribution and connection deformation is discussed. It is assumed that the connection is represented via HEA steel profiles, bolted to the I-shape short cantilevers welded to the supporting columns. For the analysis purposes three different bolt grades i.e. 8.8, 10.9 and 12.9 and four different multipliers (i.e. 1.00, 0.75, 0.50, 0.25) of maximum acceptable tightening torque were taken into considerations. For each bolts grade with constant Ø16 diameter, the number of bolts and end-plate thickness were formerly determined on the basis of polish national standards and validated with Autodesk Robot Structural Analysis. The main aim of this work is the estimation of how, the number of bolts, their grade and tightening torque affect the stress distribution, connection gap distance and overall beam vertical displacement in specified end-plate connection under evenly and unevenly distributed live load onto the ceiling floor. In order to solve stated boundary problem SolidWorks software fully based on finite element method was chosen.

## 2. NUMERICAL MODEL ASSUMPTIONS

For the numerical analysis purposes beam composed of three segments, interconnected with high tensile bolts is chosen. It is preliminarily assumed that the building is foreseen for a warehouse, construction must have been easily assembled without the necessity of welding, ceiling slab is supported directly on the top surface of a beam and end-plate cannot be extended outside the contour of a beam cross section. Adopted ceiling slab layers with specified loads, supported on discussed beam are presented in **Table 1**.

**Table 1** Ceiling slab layers supported on discussed beam

| Nr | Layer | Thickness | Mass/Density | Characteristic load | Coeff. | Factored load |
|---|---|---|---|---|---|---|
| | | [ m ] | [ kN/m$^3$ ] | [ kN/m$^2$ ] | [ - ] | [ kN/m$^2$ ] |
| 1 | Epoxy resin | 0.0015 | 14.50 | 0.022 | 1.35 | 0.029 |
| 2 | Concrete | 0.05 | 21.00 | 1.050 | 1.35 | 1.418 |
| 3 | Insulation (Mineral wool) | 0.12 | 1.40 | 0.168 | 1.35 | 0.227 |
| 4 | Reinforced concrete C20/25 | 0.08 | 25.00 | 2.000 | 1.35 | 2.700 |
| 5 | Live load | - | - | 5.50 | 1.50 | 8.25 |
| | Total load | - | - | 8.740 | - | 12.624 |

Presented in **Table 1** mass/density loads are adopted on the basis of PN-EN 1991-1-1:2004. Referring to the total load values presented in **Table 1** and knowing that the assumed horizontal and vertical axial spacing between columns is equal 5.50m, HEA360 profile made of S235JR steel grade is determined as the beam cross section in accordance with PN-EN 1993-1-1:2006 and [9]. The first and last segment of the beam is welded to the host supporting column and have a length of 0.50m, whereas middle beam member have 4.00m. Due to the column relatively high bending stiffness and fact that short cantilever beams are welded symmetrically to the flanges of host column, the effect of column deformation is neglected in the further analysis. Analyzed scheme of three segmental beam bolted with 12.9 grade hex bolts is presented in **Figure 1**.

For the analysis purposes three different high tensile bolt grades are taken into considerations i.e. 8.8, 10.9 and 12.9. It is assumed that utilized bolts for each analyzed connection have exactly the same diameter equal Ø16 mm. On the basis of manufacturer information [10], maximum tightening torques corresponding to the adopted bolts grades are: 193, 279 and 333 Nm, respectively. In case of 8.8 and 10.9 bolts grade minimum end-plate thickness was determined as 20 mm, whereas for the 12.9 grade 22 mm should be provided. Minimum number of fasteners for each considered bolt grade, which meet the ultimate limit state was determined on the basis of PN-EN 1993-1-8:2006. For the 8.8 bolt grade minimum eight high tensile bolts are obtained. Connectors are arranged in two columns with four rows, where space from the top and side end-plate edge to the first bolt center remains same as shown in Detail "A" in **Figure 1**. Spaces between bolts in the vertical plane are equal 80mm, whereas in the horizontal plane 220 mm. In case of the 10.9 and 12.9 hex bolt grade, minimum six bolts are required i.e. two columns with three rows (see **Figure 1**). Assumptions concerning connection dimensions and number of high tensile bolts for each fastener grade were additionally validated with Autodesk Robot Structural Analysis showing good agreement. Moreover, in the performed analysis two different types of live load distribution are investigated - evenly distributed and distributed only on one side in regard to the longitudinal beam axis resulting in additional beam torsion.

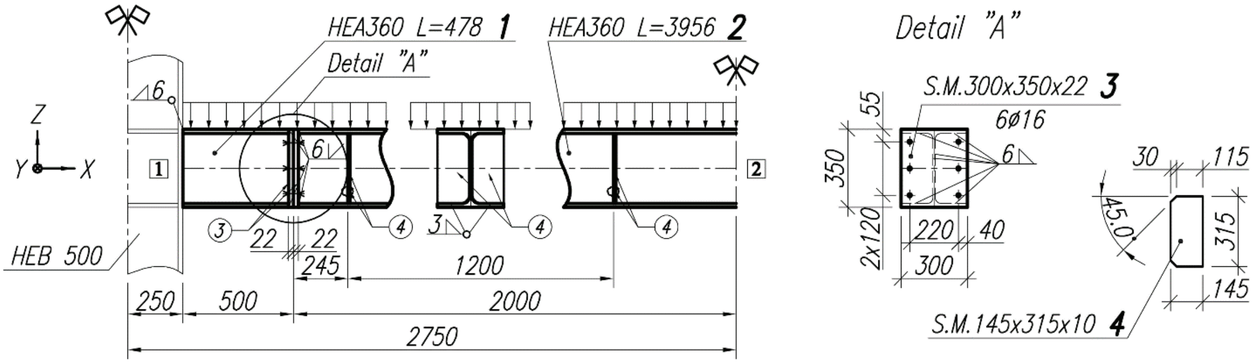

**Figure 1** Analyzed scheme of beam to beam end-plate connection, bolted with Ø16 12.9 grade hex bolts

In the numerical analysis only half of the discussed beam was examined due to the analyzed scheme symmetry. Following boundary conditions are assumed: fixed X,Y,Z-axis displacement and rotations on YZ oriented face of cantilever beam (point A in square box shown in **Figure 1**), symmetry boundary condition on YZ oriented face of middle span beam (point B in **Figure 1**). Assumed slab layers were simplified to the simple steel plate with exactly the same bending stiffness. According to that plate with following dimensions have been modelled: 5.50 m along Y-axis, 2.50 m along X-axis and 44.5mm thickness along Z-axis direction, respectively. Bottom plate surface is supported on the top surface of HEA beams and plate X-axis symmetry coincide with HEA profile longitudinal axis. Between mentioned elements contact without penetration is used. On plate external faces oriented in XZ plane, Y-axis displacement is fixed, whereas on face oriented in YZ plane close to the point A from **Figure 1**, X-axis displacement is fixed and near point B, symmetry condition is applied. Weight of plate is neglected. Presented in **Table 1** loads are applied to the top plate surface as pressure.

For the end-plate connections bolts with two washers are assumed, one under the bolt head and another under the nut. Flat washers with external diameter Ø30 mm, internal diameter Ø18 mm and thickness 3 mm are introduced. Hex bolts are represented with SolidWorks bolt elements with specified alloy steel and tightening torque properties corresponding to the appropriate bolt grade. In the SolidWorks software for S235JR steel grade elements the homogeneous, elastic and isotropic material has been chosen with Young's moduli E = 210 GPa, Poisson's ration v = 0.28 and mass equal 7800 kg/m3, respectively. Due to the fact that in this paper the subject of interest is end-plate connection, deformations and stress of steel plate were not discussed. Discretization of all numerical models have been performed with the use of 3D-Solid 9-node tetrahedron finite elements. Fine mesh with element size around ~ 3mm is used for washers and the area under and near the washers elements, where the stress results are read-out. For the rest part of the model adaptive mesh from 3 up to 100mm is used.

## 3. RESULTS AND DISCUSSION

In this chapter obtained results concerning maximum Misses stress in end-plate connection, end-plate connection gap distance and overall beam maximum Z-axis displacement in the middle span are discussed. Mentioned maximum Misses stress value was read-out from the circle shape area, with the range of 50mm measured from the center of each bored hole under high tensile bolt. Gap distance was measured between two points, which were located on the crossing of end-plates top edges with HEA symmetry XZ-plane. Obtained results are presented in **Table 2**.

**Table 2** Obtained results of maximum Misses stress, connection gap distance and Z-axis displacement in analyzed scheme subjected to the dead load and evenly distributed live load

| Number of bolts (Bolt grade) | End-plate thickness | Tightening torque | Misses Stress | Connection gap distance | Overall Z-axis displacement |
|---|---|---|---|---|---|
| | [mm] | [Nm] | [ MPa ] | [ mm ] | [ mm ] |
| 6x (12.9) | 22 | max = 333 | 345.9 | 0.552 | 1.813 |
| | | 0.75·max = 250 | 301.0 | 0.556 | 1.814 |
| | | 0.50·max = 167 | 256.4 | 0.559 | 1.814 |
| | | 0.25·Max = 83 | 211.8 | 0.563 | 1.815 |
| 6x (10.9) | 20 | max = 279 | 388.3 | 0.517 | 1.759 |
| | | 0.75·max = 209 | 336.5 | 0.521 | 1.759 |
| | | 0.50·max = 140 | 289.5 | 0.524 | 1.760 |
| | | 0.25·max = 70 | 249.3 | 0.527 | 1.760 |
| 8x (8.8) | 20 | max = 193 | 307.5 | 0.514 | 1.673 |
| | | 0.75·max = 145 | 275.1 | 0.516 | 1.673 |
| | | 0.50·max = 97 | 243.3 | 0.518 | 1.673 |
| | | 0.25·max = 48 | 211.7 | 0.521 | 1.673 |

On the basis of presented results in **Table 2**, one can state that the higher number of bolts in end-plate connection, the lower Misses stress is obtained near the bolts located in the corners. It is worth noting that with higher tightening torque for any bolt grade, higher values of Misses stress are obtained consecutively. For any bolt grade almost linear relationship between tightening torque and obtained maximum value of Misses stress can be observed. Percentage stress increase for any high tensile bolt grade between two consecutive tightening torques stands around 15%. Higher values of Misess stress for the 10.9 bolts grade in comparison to 12.9 grade bolts is connected with the end-plate thickness. For 10.9 grade bolts end-plate with 20mm thickness was determined, whereas for 12.9 grade bolts 22mm, respectively. Misses stress redistribution in the discussed end-plate connection with 12.9 grade bolts and applied tightening torque equal 333 Nm with scale limited to the S235JR grade steel yield point is presented in **Figure 2**.

Connection gap distance depends not only on number of fasteners, but also on thickness of end-plate and tightening torque. With the highest number of high tensile bolts, the gap distance is the smallest - compare grade 8.8 bolts with maximum tightening torque to 10.9 and 12.9 grade bolts. In this particular case, where eight high tensile bolts are used, end-plates adjoin to each other with the largest area.

With introduced in bolts pretension force, end-plate in micro scale starts to deform i.e. local area near the connection stick to the area on the opposed end-plate, whereas other plate area starts to deform in opposite direction. According to above larger gap for 12.9 grade bolts in regard to the 10.9 grade bolts was obtained due to the higher tightening torque.

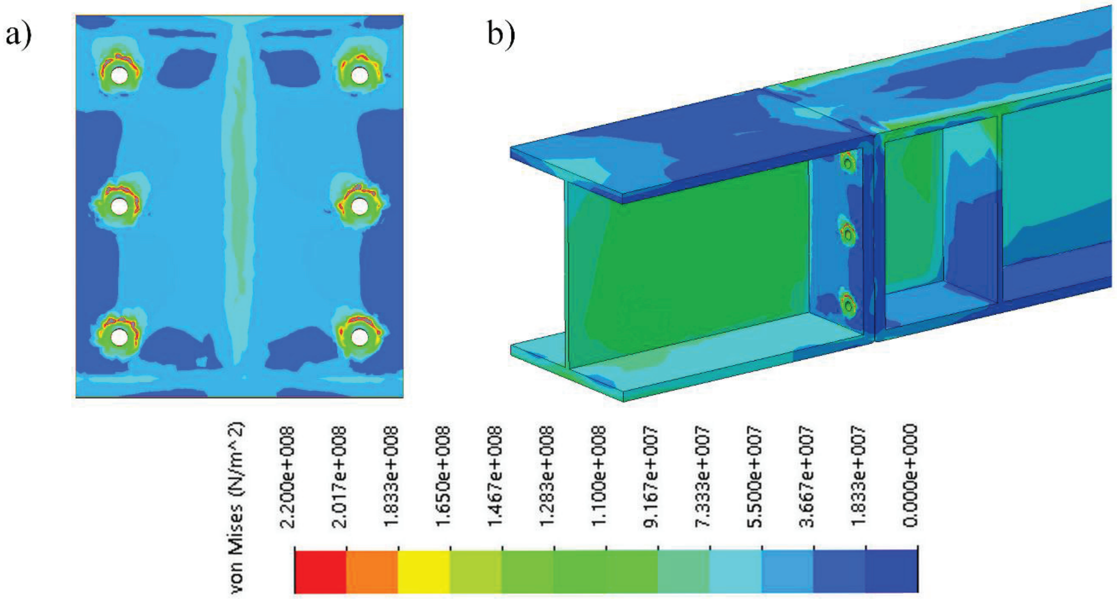

**Figure 2** Misses stress redistribution band plot for the beam to beam connection with 12.9 grade bolts at 333 Nm tightening torque, a) end-plate, b) overall isometric view of beam to beam connection

Changes in overall beam Z-axis displacement are strictly connected with the connection gap distance. According to that the lowest displacement was obtained for the connection with eight 8.8 grade bolts. In case where the number of bolts is exactly the same (compare grade 12.9 bolts in regard to 10.9 bolts from **Table 2**) at any tightening torque the difference between Z-axis displacement remains almost the same i.e. ~0.055 mm. It is worth noting that for the same considered bolt grades difference in the gap distance stands around ~0.034 mm. Hence higher displacements were observed for the beam with 12.9 grade bolts.

The influence of uneven distributed live load in the discussed construction on Misses stress redistribution due to previously observed almost linear relationship between bolt tightening torque and obtained stress results was examined only for maximum torque for each bolt grade. Percentage incensement of Misses stress near the corner bolts is presented in **Figure 3**.

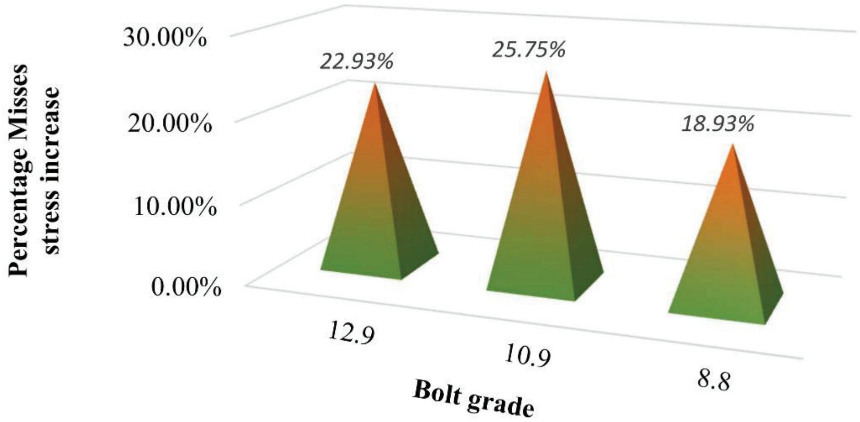

**Figure 3** Percentage maximum Misses stress increase in the end-plate connection under the bolt washer for a beam subjected to the uneven live load distribution

Considering results presented in **Figure 3** one can state that the highest percentage increase was obtained in the beam connected with 10.9 grade bolts where obtained stress value was equal 488.3 MPa. Comparing connection with 12.9 grade bolts in regard to the connection with 10.9 grade bolts, thicker end-plate sheet metal allows reduce percentage stress increase in a small manner. With greater number of applied bolts in the connection with same considered dimensions the influence of uneven load distribution can be significantly minimized - corner bolts have to transfer smaller resultant force.

Despite the fact that obtained stress results under the bolts washers in the beam to beam end-plate connection exceeded the S235JR grade steel yield point, the plastic work of material covered only a very small local region. Hence, on the basis of PN-EN 1993-1-8 such significant thickness of end-plate is determined in order to eliminate the risk of connection failure due to material plastic work near the bolts.

## 4. CONCLUSION

In this paper the influence of applied load to the construction and high tensile bolts prestressing in the beam to beam end-plate connection on obtained Misses stress results was discussed. For the assumed constant diameter of each individual bolt equal Ø16 mm and three considered bolt grades i.e. 8.8, 10.9 and 12.9, minimum number of bolts and end-plate thickness in considered connection were determined. Through the numerical analysis was shown, that even 2 mm thicker end-plate can significantly decrease the Misses stress redistribution near the fasteners for evenly distributed load. Considerable stress decrease in the connection with exactly the same dimensions can also be obtained with greater number of high tensile bolts introduced. In consequence smaller value of resultant force have to be transferred, especially via corner bolts. In the beam subjected to the uneven load distribution Misses stress in the end-plate near the corner bolts increased approximately by 20-25%, depending on the number of high tensile bolts utilized and the thickness of end-plate. However, in this paper specified type of beam to beam end-plate connection with high tensile bolts was discussed, other steel structures connection geometries should also be studied.

## REFERENCES

[1] KRISHNAMURTHY, N. Fresh look at bolted end-plate behavior and design. *Engineering Journal*, 1978, vol. 15, no. 2, pp. 39-49.

[2] MASHALY, E., EL-HEWEITY, M. Behavior of four-bolt extended end-plate connection subjected to lateral loading, Alexandria Engineering Journal, 2011, vol. 50, no. 1, pp. 79-90.

[3] YONGJIU, S., GANG, S., YUANQING, W. Experimental and theoretical analysis of the moment-rotation behavior of stiffened extended end-plate connections. *Journal of Constructional Steel research*, 2007, vol. 63, no. 9, pp. 1279-1293.

[4] GHASSEMIEH, M., NASSERI, M. Evaluation of stiffened end-plate moment connection through optimized artificial neural network. *Journal of Software Engineering and Applications*, 2012, vol. 5, no. 3, pp. 156-167.

[5] COUCHAUX, M., HIJAJ, M., RYAN, I., BUREAU A. Effect of contact on the elastic behaviour of tensile bolted connections. *Journal of Constructional Steel Research*, 2017, vol. 133, pp. 459-474.

[6] WANG, M., WANG, P. Strategies to increase the robustness of endplate beam-column connections in fire. *Journal of Constructional Steel Research*, 2013, vol. 80, pp. 109-120.

[7] FARMANI, M. A., GHASSEMIEH, M. Shape memory alloy-based moment connections with superior self-centering properties. *Smart Materials and Structures*, 2016, vol. 25, no. 7, pp. 1-17.

[8] MAJOR, M., KULIŃSKI, K. Comparative numerical analysis of advertising board tower using ADINA and Autodesk Robot Structural Analysis. *Transactions of the VSB - Technical University of Ostrava*. Civil Engineering Series, 2015, vol. 15, no. 2, pp. 1-10.

[9] BORKOWSKI, S., ULEWICZ, R., SELEJDAK, J. *Materials for economists*. Warszawa: Wydawnictwa Naukowo - Techniczne, 2005. 225 p. (in Polish)

[10] http://www.nbcgroup.co.uk/slewingRings.aspx?PageID=72 (date accessed: 4th March 2017)