Design Method for End-Plate Bolted Connections

Birdean Calin Ioan¹, Cernescu Anghel¹, Faur Nicolae¹

¹University of Timisoara, Faculty of Mechanics, Polyethnic Bd. Mihai Viteazu 1, 300222, Timisoara, Romania

calin.birdean@student.upt.ro

Abstract. The design of buildings envelopes is more elaborate than it has ever been. Starting from the design method of nodal space frames made of one layer of structure and covered in glass, this paper presents a new type of end-plate beam to beam connection. Specific to this is the fact that both end-plates are welded inside of the tubes, having a minimum gap between them of 2 mm. This will reduce considerably the in-surface and welding-induced end plates tolerances which appear at classical end-plate connections. Through the pre-tensioning of the bolts, a continuous contact surface is assured along the cross-sections of the hollow profiles. Several tests were run with the software Gas Win in order to establish the maximum capacity of the connection. This condition is achieved when the neutral axis goes out of the cross-section and the entire cross-section is compressed. Installation hand-holes were also considered. In order to get a better understanding about the force flow, an FEM analysis was run using the Abaqus software. A comparison between the results followed.

1. Introduction

The shapes of the buildings respectively of the structures are getting more and more complex. The latest software allow the architects to transpose their visions into reality with high accuracy. From flowing shapes (the so called free-form structures) to organic shapes everything seems to be in perfect harmony with the nature and the surrounding environment. The architectural exposed steel systems represent in our days the architectural trade mark of a building being a high-end product, constructed using mostly custom made parts. These visions are bringing in front of the engineers the toughest design challenges in order to create sustainable systems made of steel and glass. One of them is represented by the design of the steel connections. Their shapes and dimensions have to follow the overall design intention and they have to provide a higher accuracy (tighter tolerances in case of interface between trades), ease of fabrication and constructability. Due to the complexity of the structures geometries, the layout of the connections represent a key point in the design phase.

Significant improvements have been made to the beam-column end-plate connections by increasing the bolts contribution in the stability and strengths of the steel connections, [1]. In an experimental study on the behaviour of the eccentric end plate (EEP) connections, compared with partial-depth end plate (PDEP) connections, it was observed that the EEP connection offers higher stiffness and strength than the PDEP connections. However, being a semi-rigid connection, the EEP introduce a torsion moment on the primary beam that limits its use, [2]. Kollipara et al., [3], derived design equations for the yield and ultimate moment strength of a beam-beam splice connection of hollow tubes. Their analysis revealed that for a better serviceability condition, the connection should be design as intermediate type. The failure of this type of connection occurs due to failure of the end plate.
In case of regular end-plate bolted connections (beam to beam), due to several factors, the contact surface between the two end-plates cannot be considered continuous and uniform. One of the factors are the fabrication tolerances of the plates. The irregularities in the surface of the plate can be eliminated only by machining, process that it is not sustainable and economical at all. Another problem are the deformations induced by welding (end-plate to the beam). These can be corrected only up to a specific level. The grinding of the welds between the end plates and the beams is another factor that influences the class and quality of the architecturally exposed steel structure. It is a highly time-consuming process, very expensive and could weaken the connection. Using the design method of the space frames, Figure 1, an example of end-plate bolted connection is evaluated.

Figure 1. Node connection of space frame, [4]

An endplate bolted connections, which also is limited to the element’s perimeter, was experimentally studied by Both et al. [5]. The results show that the connection can transfer the bending moment with good rigidity. The distance between the bolts has an important role in the response of the connections, especially on the rigidity and ductility of bolted connection, as shown in [6]. The numerical simulations can be performed with simple 2D or 3D elements, but the detailed responses are obtained from 3-dimensional analysis [7] as intended also for the present paper.

A strength analysis of the interior end-plate beam-beam connection of the hollow tubes was performed in this paper, considering both analytical formulations and numerical simulations. The strength capacity of this connection type depends on the pre-tensioning of the end-plate clamping bolts, over which a bending moment overlaps.

2. Design method of Space Frames
S. Stephan and C. Stutzki proposed a general design method for single or multi-bolt connections of beams with arbitrary thin-walled cross sections, suitable for application in computer programs [8]. The design method is based on the classical strain iteration algorithm for cross sections. In this method, the ultimate capacity of bolted connections will be obtained using an iterative numerical determination of the elastic-plastic stress distribution in the connection elements. The numerical method is derived in two steps – the numerical determination of the stress distribution in the connection for a given combination of internal forces and – the determination of the ultimate capacity of the connection.

3. Design method of End-plate bolted connection
Starting from a typical end-plate beam to beam bolted connection with pre-stressed bolts where the end plates are outsides of the hollow section beams, Figure 2, a new location of the end-plates inside of the tubes with a minimum of 2 mm gap between them is proposed, Figure 3. In this manner the contact surface between the two beams is represented only by the cross-section of the tubes, surface which can be considered uniform due to the negligible tolerances that occur during the cutting process.
Figure 2. Typical end-plate bolted connection with the plates welded outside of the beams

Figure 3. End-plate bolted connection with the plates welded inside of the beams

Two hollow beams RHS260 x 180 x 10 from S355 steel (RHS - Rectangular Hollow Section), connected by 4 x M24 pre-stressed bolts grad 10.9, are proposed for investigation, Figure 4. On the exterior, at the end of the beams, a small chamfer of 1.5x1.5mm is prepared in order to be sealed and painted on site so that the connection will become completely invisible from outside. The compression stresses along the cross-section are obtained by pre-stressing the bolts. As a result, the opening section is avoided and the beams remain in contact (the seal is not supposed to crack).

The pre-stress force applied to the bolts is $P_V = 95\text{kN}$, the bolts having a distance of 180mm on the vertical and 70mm on the horizontal between them. Installation hand-holes are also considered: 150x120 mm. The thickness of the weld was $a_w=7\text{mm}$. 

Figure 4. Proposed connection for calculation
Using the computer software Gas_Win developed by K. Knebel according to the design method of space frame proposed by S. Stephan and C. Stutzki a series of trials (try and error) were performed, Figure 5. Starting with a bending load $M_y=80\,\text{kHzm}$, the value of the bending moment was lowered in order to get a result were the neutral axis is outside of the cross-section of the tubes so that the entire contact surface is in compression. The maximum value at which this condition was met is $M_y=63\,\text{kHzm}$, Figure 6.

---

| Bolt pretensioning | Bending moment | Position of the Neutral Axis | Observations |
|--------------------|----------------|-----------------------------|--------------|
|                    | 80 KNm         |                             | The neutral axis is located within the cross-section. The part above it finds itself in compression, while the one below is in tension. |
|                    | 80%            |                             | The neutral axis is located outside of the cross-section at its lower limit. The entire cross-section finds itself in compression. |

---

Figure 5. Neutral axis locations - within and outside of the cross-section

Several tests were run lowering the value of the load in order to get a result were the neutral axis is outside of the cross-section of the tubes so that the entire contact surface is in compression. The maximum value at which this condition was met is $M_y=63\,\text{kHzm}$, Figure 6.

---

Figure 6. Neutral axis outside of the cross-section. Entire contact surface under compression
The required end-plate thickness is 21.2mm which is rounded up to \( t = 25 \text{mm} \), Figure 7. The maximum utilization of the cross-section at the location of the hand-holes was 31\%, Figure 8.

4. Finite Element Analysis

The numerical simulation of the end plate connection with the end plate inside the hollow section can reveal a detailed response for the stress distribution. For this purpose, the connection presented in Figure 9 consisting on a pair of rectangular hollow sections RHS260x180x10 having a length of 500 mm with an end plate of 25 mm inside the RHS, was modeled in the general-purpose finite element software Abaqus [9].
The opening for the bolt tightening access in the RHS profile is defined only on one side of the steel section as presented in Figure 10a) having a width of 120 mm and a length of 150 mm. The endplate was defined with the dimensions of the inner perimeter of the RHS having chamfered corners. The surfaces that will be in contact to the washer of the bolt assembly were defined at this stage, Figure 10b). The M24 bolt assembly, Figure 10c), consisted of the bolt, nut and washers, all in on part. The shank of the bolt was defined with the net area of a M24 bolt, \( d_{\text{shank}} = 21.2 \) mm.

The material was defined with elastic-plastic behaviour in the numerical analysis. Young modulus is considered similar for all parts, 210 GPa, and a Poisson ratio of 0.3. The plastic stress-strain curve for structural steel (RHS and plate) and bolt material is presented in Figure 11. A bilinear behaviour is considered for both materials having the yield and ultimate limits considered with the nominal values. For structural steel, the yield limit and the tensile strength is 355 MPa and 510 MPa, respectively. For the bolt material, the yield limit and the tensile strength is 900 MPa and 1000 MPa, respectively.

![Figure 9. Connection assembly model](image)

![Figure 10. The parts of the connection: a) RHS, b) end plate, c) bolts](image)

![Figure 11. Plastic stress-strain curve of material](image)
The contact property was defined for **tangential** and **normal** behaviour. The tangential behaviour was defined with a *Penalty* formulation having a friction coefficient of 0.2 while the normal behaviour was defined with a *Hard Contact* and the *separation after contact* was allowed.

These interactions were defined for the contact between the end plates and the bolts; respective the contact between the RHS sections and between the two endplates, Figure 12.

![Contact interactions](image12)

**Figure 12.** Contact interactions

Each endplate was considered to be tied on the entire contact surface to the RHS profile, Figure 13. Another constraint was considered for the support and loading conditions. Each end was defined as a rigid body having a reference point defined in the centroid of the cross-section.

![Tie constraints](image13)

**Figure 13.** Tie constraints

For the analysis with a preload of the bolts, two steps were necessary. In the first step the preload was defined as a *Bolt load* type equivalent to 70% of the proof load of a M24 10.9 bolt, 177 kN. The second step was dedicated to the concentrated moment application such that the opening is either tensioned or compressed, Figure 14. The other end of the model was considered fully fixed in the *Reference point* defined as a reference to the *rigid body* constraint at the end cross section.

![Bolt preload and concentrated moment](image14)

**Figure 14.** a) bolt preload, b) concentrated moment

An initial mesh size of 10mm was chosen for the area close to the connection and the size was gradually increased toward the ends of the model, Figure 15.
5. Results and discussions
In order to assess the quality of the results a comparison of the FEM analysis with the analytical model was performed. The moment leading to the extreme position of the neutral axis (analytical model) was compared to the moment which leads to approximately zero stress in the extreme fibre of the RHS (in the finite element program). In Figure 16, the red areas represent the stress close to zero value corresponding to a moment of 65 kNm, similar to the value obtained in the analytical manner.

![Figure 16. Stresses map in the tensioned area at the detachment of the parts](image)

It has to be mentioned that for the analytical solution the stresses are considered to be uniform along the height of the cross-section (the elastic neutral axis is horizontal), in the numerical model, before the fully detachment of the two connected assemblies, the stresses have a non-uniform distribution of the stresses as presented in Figure 17. The grey area represent the positive stresses in the longitudinal direction.

![Figure 17. Stresses map in the tensioned area before the detachment of the parts](image)
Further on, the qualitative results of the numerical analysis highlights the response of the connection and the failure mode.

Compared to a common connection where the bolts join a pack of plates in contact, the current connections has a 4 mm gap between the connected plates. It is observed that due to non-uniform rigidity of the support conditions the bolts are subjected to bending even from the preloading of the bolts, and in the final stage the stress difference between the extreme sides of the shank cross-section is approximately 790 MPa, Figure 18.

![Stress distribution in the bolts](image1)

**Figure 18.** Stress distribution in the bolts

The deformed shape for the positive moment (compressed opening) and negative moment, (tensioned opening) are presented in Figure 19 and Figure 20, respectively. Although local buckling is normal for the first case, it is observed that, due to the slightly bended end plate and the spatial distribution of stresses, a distortion in the tensioned flanges develops but of minor significance. In both cases the failure occurs due to fracture of the bolts.

![Failure mode for the compressed opening](image2)

**Figure 19.** Faillure mode for the compressed opening

![Failure mode for the tensioned opening](image3)

**Figure 20.** Failure mode for the tensioned opening
The quantitative results are further expressed function of the failure criteria considered for the analytical method, i.e. the detachment of the extreme tensioned fibre or, in other words, the tensile stresses in the extreme fibre.

Although the maximum force in the two cases are similar, it is obvious that the compression in the flange with the hole hand leads to a detachment between the two parts of the connection at an earlier stage (approx. 60 kNm) while for the tensioned opening the detachment appears later (75 kNm), Figure 21.

![Figure 21. Moment vs relative displacement between the connected elements in the tensioned fiber](image)

Also, an important parameter in establishing the deformed shape of the structure is the rigidity of the connection. Figure 22 presents a comparison between the 1000 mm RHS profile and the same length with the connection and the hand hole. The rigidity of the connection is smaller, and this should be considered in the analysis of the structure in order to obtain the real displacements of the nodes.

![Figure 22. Moment response of the RHS profile](image)

Compared to a simple RHS bar, the connection can provide a relatively similar rigidity only for the first 50kNm, until the two parts start to lose contact.

6. Conclusions

It has been noted that the location of the neutral axis governs the capacity of this type of connection. Even if the bolts and the end-plates would be able to take more load, once the connection starts to open, the contact surface does not run any more over the entire cross-section.

The installation hand-holes with this dimensions and locations do not play a key role in establishing the maximum capacity of this end-plate beam to beam connection.
The obtained results look feasible which means that the basic design theory of the space frame could be applied also on this type of connections.

Nevertheless, a further investigation is recommended: a laboratory test run on a minimum of 3 mock-ups having the same cross-section and bolts layout.

References
[1] M.A. Shaheen, A.S.J. Foster, L.S. Cunningham, “A novel devices to improve robustness of end plate beam-column connections”, Structures, 28: 2415-2423, 2020.
[2] D.A. Hawxwell, K.D. Tsavdaridis, “Beam-to-beam eccentric end plate connections – Experimental comparison to fin plate and partial-depth end plate connections”, Structures, 19: 411-423, 2019.
[3] V.R. Kollipara, T.D. Gunneswara Rao, “Theoretical approach to the moment capacities of beam-beam splice connection for SHTS”, Journal of Constructional Steel Research, 160: 332-339, 2019.
[4] Schmeer K. Geschraubte Knotenanschlüsse für Tragstrukturen von Freiformflächen mit Stahlhohlprofilen. 2010
[5] I. Both, D.L. Nunes, A. Ivan, and D. Vučićević, “The Response of In-Line Connection of RHS Sections Subjected to Bending and Shear,” 18th edition - Modern Technologies For The 3rd Millennium, Oradea, Romania, April 2019, pp-ce.
[6] I.Both, I. Marginean, C. Neagu, F. Dinu, D. Dubina, and R. Zaharia, “Experimental research on t-stubs under elevated temperatures”, Applications of Structural Fire Engineering-Series, 2017, DOI: https://doi.org/10.14311/asfe.2015.023
[7] I. Marginean, I. Both, A. Dogariu, and R. Zaharia, “Advanced Calculation Models in Thermo-Mechanical Analysis”, Modern Technologies For The 3rd Millennium,pp. 191-196, 2017,WOS:000413420300034
[8] Stephan S. & Stutzki, C. (Stahlbau 2004), A General Method for the Design of Bolted Connections for Space Frames
[9] Dassault Systemes, “Abaqus 6.14 Documentation”, Providence, RI, 2014