Analysis of Hollow Shape Semi Rigid Joints Made by Use of Thermal Drilling Technology

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Abstract. The results of numerical and empirical analysis of a new type frame T- joints for rectangular hollow sections are presented. The butt T-joints are designed as connected by screws into bushes formed in the wall of rectangular hollow sections bars by use of a thermal drilling technology. Literature in this subject applies only to joints without additional stiffeners or T-joints with concrete filled hollow steel columns. In the paper deals with the 4 proposals of a new butt T-joints for hollow sections including additional stiffeners. Numerical analyses conducted for the designed new types of T-joints proved that the proposed joints stiffeners lead to higher capacity than in case of unstiffened joint. Experimental verification of the joints behaviour confirmed results of the numerical simulation.

1. Introduction

The design, operational and economic benefits of the thin-walled hollow square hollow sections and rectangular hollow sections bars made such type of profiles commonly used in steel structures. One of the main issues in the hollow sections structures is the appropriate construction of the connections. Welded joints of thin-walled sections bars are mainly used as a combination of workshop connections of structural components. Assembly connections generally require bolted connections, usually capable of transferring bending moments. Structural connections with bolts passing through the holes in two opposite walls of the hollow cross section profiles are not recommended due to an extra stress capacity from bending the bolts and due to the possibility of deformation of the hollow cross section walls near the bolts with multiple application of loads. Connections with end-plates go beyond the face of the hollow cross sections and therefore their use is avoided.

At the end of the twentieth century attempts have been made to use in the assembly connections of hollow cross sections with a new technology of forming threaded bolt bushes. The bushes in the hollow cross section walls are formed by thermal drilling (flow drilling) [7] - [9]. It is a new technology (1978) [26] allowing to form threaded bushes in the walls of steel profiles with the thickness of 12.5 mm [7] - [9]. Drilling holes in the hollow cross section wall with the use of a tungsten carbide cone produces the amount of heat sufficient to yield the wall of the steel profile and form a bush (Figure 1) [26]. Then, to make the thread, no-chip plastic forming tools are used, which locally increase the steel strength in the bush by means of cold pressing [7] - [9]. After this process we obtain durable thread allowing to install bolts directly into the threaded bushes in the hollow section wall.
Both, the hole and the thread forming process are carried out on a regular table drill with appropriate pressure force. The tools that form the bush and the thread are reusable as the melting point of steel is approx. $1400^\circ C$, whereas of tungsten carbide approx. $2870^\circ C$.

The ease and cheapness of execution of butt joints with the use of the thermal drilling technology was the reason to start research works on such connections at the end of the twentieth century. The most of researcher’s work concerned the drilling tools [1] - [4], [7] - [9], [23], [26] and thermal drilling technology for a different steel grades [5], [6], [16], [17], [20] - [25]. The small group of works concerned flow drill screw steel bar connections in engineering structures [2], [10] - [14], [18], [27]. They establish the load capacity criterion for the tested joints and for the tested tubular profiles – present the equilibrium paths. These works have also constituted one of the bases for the standard [28]. Studies [2], [10] - [14] showed that capacity of unstiffened tubular section T-joint is low and such joints are not able to transfer bending moments effectively. In the work [11] research based on filling tubular columns with concrete showed significantly increased capacity in compare to unstiffened T-joints.

Figure 1. Single stages of forming a threaded bush in the hollow cross section wall using thermal drilling technology [17]

2. Joints variants description
Numerical and experimental analyses presented in the works [2], [10] – [14] shown that the primary limitation of load bearing capacity of this type T-joints with the bushes made by means of the thermal drilling technology are the plastic wall deformations of the tubular profiles. To fully benefit from the advantages of the joints an attempt has been made to find such stiffener of the joint that would lower the elastic-plastic deformations and allow transferring higher bending moments. For this purpose, the five variants of the „column – beam” connection FEM analysis has been performed (Fig. 2-5):

- variant „1” – without additional elements stiffening the end-plate,
- variant „2” – with stiffening the end-plate with a vertical sheet,
- variant „3” – with flat diaphragm near the tensioned bolts,
- variant „4” – with stiffening of the end-plate and the hollow cross section diaphragm near the tensioned bolts,
- variant „5” – with stiffening of the end-plate and the plate diaphragm near the tensioned bolts.

Based on the guidelines of the standard [14] and experimental data of formed bushes, for the numerical analyses, the following values have been assumed for further analysis:

- column and beam with the system length of $600 mm$ made of the $SHS 100x100x4$ profile made of $S355JR$ structural steel,
- endplate $100x180x8 mm$ made of $S355JR$ steel,
- stiffening elements made of $8 mm$ plate and $Ø 20x3$ pipe cross sections made of $S355JR$ structural steel,
- $4xM-12/25-8.8$ bolts in normal size holes. Vertical spac. 140 mm, horizontal spac. $50 mm$,
- total depth of the threaded wall and the bush equals three times the thickness of the wall,
- the wall thickness of the bush was estimated $3.0 mm$ at the hollow cross section internal wall face and $2.0 mm$ in the end of the bush. Total bush length: $10.0 mm$. 


Figure 2. Variant „1” of the „column - beam” connection in cross section

Figure 3. Variant „2” of the „column - beam” connection in cross section

Figure 4. Variant „3” of the „column - beam” connection in cross section
Figure 5. Variant „4″ of the „column - beam” connection in cross section

Figure 6. Variant „5″ of the „column - beam” connection in cross section

3. FEM Analysis
In the FEM calculation models the following settings have been applied:
- friction between the structural elements of the joint with the tangential friction coefficient \( \mu = 0.15 \) taken into consideration,
- endplate – column wall gap allowed,
- material model of steel: ideally plastic steel material with Young Modulus 210 GPa,
- variable load increment step from 0.001 to 0.01 of the target value \( M_{Rd,e} \) was applied,
- Abaqus 2016 software was used.

Figure 7. Sample mesh for Variant „3″ of the connection
Based on preliminary calculations carried out in accordance with the standard [29] it was found that the weakest elements of the joints, proposed above in Figure 4, connecting the SHS 100x100x4 profiles of S355JR steel, will be the hollow cross section walls near the threaded bushes. Therefore, near the holes in the bar walls, the finite elements mesh density was increased (Figure 8).

Figure 8. The beginning of SHS 100x100x4 steel wall yielding near tensioned bolts under moment loading– joint variant „3”

The objective of the FEA analysis, performed using the ABAQUS software, was to determine the equilibrium paths of the joint rotation angle $\theta$ and the bending moment $M$ acting in the joint, conducted for each variant of the joints. The bending moment $M$ was expressed in a non-dimensional form of $M/M_{Rd,el}$, where $M=M_{lim}$ is the moment at which the hollow cross section wall steel yielding occurs near the threaded holes (Figure 8). The rotation angle $\theta$ of the joint were determined in radians in accordance with the standard [30] by reading the horizontal displacement value of the extreme upper and lower elements of the joint for individual values $M/M_{Rd,el}$. The equilibrium paths for joints variants „1” - „5”, obtained from the FEM calculations, are presented in Figure 9. The joint equilibrium path is described by equation (1).

$$\theta = f \left( \frac{M}{M_{Rd,el}} \right) \quad (1)$$

It was assumed, that the maximum bending moment $M_{lim}$, corresponding to the end of the linear-elastic range of the joint is the maximum joint capacity. Such assumption excludes the occurrence of permanent deformations of the all thin-walled structural elements. The equilibrium paths (i.e. rotation characteristics) for the 5 analysed structural joint variants, in the entire elastic (linear and nonlinear) range and for the load range $M/M_{Rd,el} = 0-1$, are presented in Figure 9. The rotation characteristics for the 5 variants of analysed connections in the linear-elastic range are presented in Figure 10.
Figure 9. Rotation characteristics of joint’s variants „1” – „5” in the entire elastic range

Figure 10. Rotation characteristics of joint’s variants „1” – „5” limited to the linear elastic range

For the needs of the static analysis of the racking system structure in accordance with the standard [14] also the stiffness of connections in the elastic range has been determined in order to carry out the stability analysis and determine the distribution of internal forces in a multi-storey and multi-bay frame of an industrial steel rack. The angle of the joint elastic rotation $\theta_{el}$ is presented in the form of relation (2) and the data read from FEM models for the analysed joint variants are given in the Table 1.

$$\theta_{spr} = ak_\varphi$$

(2)

Table 1. Data to determine stiffness of the joint variants in the linear elastic range

| Variant | $a$ [kNm/rad] | $k_\varphi$ [kNm/rad] |
|---------|--------------|-------------------------|
| „1“    | 34.8308      | 557                     |
| „2“    | 46.8187      | 749                     |
| „3“    | 53.4967      | 856                     |
| „4“    | 84.7866      | 1357                    |
| „5“    | 88.8197      | 1421                    |
In the Table 2 there are presented numerically determined relative load capacity $M/M_{Rd,el}$, measured by the beginning of yielding the material in the area of tensioned bolts as presented in the Figure 7 and accompanying gap between the endplate and column face.

| Joint variant | Relative joint capacity $M/M_{Rd,el}$ | Endplate opening [mm] |
|---------------|--------------------------------------|-----------------------|
| „1”           | 0.09                                 | 0.15                  |
| „2”           | 0.11                                 | 0.15                  |
| „3”           | 0.16                                 | 0.17                  |
| „4”           | 0.20                                 | 0.12                  |
| „5”           | 0.20                                 | 0.12                  |

4. Experimental verification

Experimental verification of the calculation model for joint variant „1” was conducted. Experiment purpose was to prove the convergence of Abaqus simulation model to reality. Procedure was planned according to specification of [33], however the number of trials was limited to 1 as research is at the pilot phase. Results of the experiment are presented in the Figure 11 and 12.

Despite pre-loading of the joint up to 10% of the anticipated load bearing capacity, in the initial period of loading there was a significant unmarked slippage of the joint. For this reason, an adjustment has been made which skips the initial range within which the alleged slippage of the joint occurred. The chart with the adjustment is presented in Figure 13. After taking into account the adjustment, the curves are clearly getting closer to one another and run on a similar trajectory. A successfully conducted pilot study carried out on a single joint model has confirmed the effectiveness of the chosen method of FEM simulation.
Figure 12. Comparison of the equilibrium path of the joint obtained based on experimental studies and the numerical solution – without adjustment (initial joint slip)

Figure 13. Comparison of the equilibrium path of the joint obtained based on experimental studies and the numerical solution – including offset

5. Conclusions
Based on the obtained results of numerical calculations and experiment it was proven that joint rotation characteristics can be significantly modified by adding stiffening elements. Modifications of joints elasticity can be used further for example to properly design steel racking systems or other unbraced structures made of hollow shapes in terms of sway stability.

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