Engineering Structures 172 (2018) 523–537

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Moment-rotation behavior of welded tubular high strength steel T joint

Jarmo Havula[a], Marsel Garifullin[b,*], Markku Heinisuo[b], Kristo Mela[b], Sami Pajunen[b]

[a] *Häme University of Applied Sciences, Hämeenlinna, Finland*
[b] *Tampere University of Technology, Tampere, Finland*

ARTICLE INFO

Keywords:
High strength steel
Welded tubular T joint
In-plane moment-load
Moment resistance
Rotational stiffness
Ductility
Reduction coefficient

ABSTRACT

Based on recent studies, high strength steels (HSS) can be efficiently used in civil engineering, reducing the consumption of material and CO_2 emissions. The present Eurocode contains the reduction coefficients (0.8 and 0.9 depending on the steel grade) for high strength steel joints. These reduction factors lead to the excessive consumption of material, making the usage of HSS for construction not as economically viable as it might be. The scope of this paper is to present experimental results dealing with the welded in-plane moment-loaded HSS joints. Twenty tests on square hollow section T joints were performed to observe their moment-rotation relationship, studying the following parameters: (1) bending resistance, (2) rotational stiffness, (3) ductility. The results show that the reduction factors are needed only for butt-welded joints, as well as for joints with small fillet welds and made of steel grades higher than S500. The required ductility was achieved by all specimens, even when using welds smaller than full-strength fillet welds. In addition, it was shown experimentally that fillet welds considerably increase the resistance and stiffness of joints.

1. Introduction

The application field for high strength steel (HSS) joints covers a wide range of structures, including bridges, lattice masts, towers and buildings with large openings. Hollow section joints subject to bending moment are found in beam-to-column connections or as a simple joint configuration in Vierendeel girders. The beam-to-column T joint is comprised of a brace member connected at an angle of 90° to a chord member.

The developments in manufacturing processes and material technologies increased the strength of available steels worldwide [1]. Generally, the steel grade $f_y \leq 355$ MPa is considered as regular steel, although basic Eurocodes EN 1993-1-1 to EN 1993-1-11 consider steel grades up to $f_y \leq 460$ MPa, where f_y is the yield strength. Following EN 1993-1-12:2007 [2], high strength steel is defined as 460 MPa < $f_y \leq 700$ MPa. To make the usage of HSS in construction as viable as possible, more precise and accurate calculation methods should be developed for HSS structures. Attention should be paid particularly to the resistance and rotational stiffness of joints. The increase of joint resistance clearly reduces material consumption, while the increase of stiffness affects the load distribution in the structure and reduces the buckling length of members, contributing to the reduction of costs.

Currently, EN 1993-1-8:2005 [3] and EN 1993-1-12:2007 [2] contain additional rules for HSS joints. Following these rules, clause 7.1.1(4) of EN 1993-1-8:2005 requires using the factor 0.9 for the static design resistances of end-products with a nominal yield strength higher than 355 N/mm^2. This rule must be fulfilled for the design equations in Section 7; however, it does not concern the design of welds. In addition, clause 2.8 of EN 1993-1-12:2007 specifies the reduction factor 0.8 for steel grades greater than S460 up to S700. The identical requirements can be found in the latest CIDECT Design Guide No. 3 [4]. In the design of HSS joints, these factors considerably reduce the design resistance of joints, making their design very conservative.

Currently, there is no clear evidence regarding the origin of these reduction factors. It should be noted that the rules for HSS have been developed based on a very limited number of experiments with variable types of joints, especially when considering full-scale HSS joints. The lack of experimental data could have led to the necessity to reduce the design resistance of HSS joints, leading to the introduction of these factors. According to [5] and CIDECT Design Guide No. 3 [4], the need for the reduction factors can be explained by the relatively larger deformations that take place in joints with nominal yield strengths of approximately 450–460 MPa, when the plastification of the connecting tubular face occurs. A broad discussion on this issue can be found in [6]. Based on about 100 tests on HSS joints, it proposes no reduction for a steel grade S500, but implies the reduction factor 0.9 for the a grade S700 when the connected brace is loaded with an axial load.

At the same time, the reduction can be also caused by the softening of the heat affected zone (HAZ) [7–9]. According to [8], the effect of weld-induced heat on the mechanical properties of steel tubes results in

* Corresponding author.
E-mail address: marsel.garifullin@tut.fi (M. Garifullin).

https://doi.org/10.1016/j.engstruct.2018.06.029
Received 6 July 2017; Received in revised form 12 March 2018; Accepted 6 June 2018
0141-0296/

an overall reduction around of 8% in HSS. Dunđer et al. [10] present the $t_{8/5}$ cooling time–hardness relationship for TStE 420 steel HAZ softening, clearly indicating the importance of HAZ and weld-heat input when considering the resistance of HSS welded joints. However, both EN 1993-1-8:2005 and EN 1993-1-12:2007 require no reductions in HAZ. Only the Finnish National Annex for EN 1993-1-12:2007 [11] contains a rule to reduce the yield strength, with the factors 1.0 for S500, 0.85 for S700 and linear interpolation in between. However, this reduction does not concern the design equations for hollow section joints in Section 7 of EN 1993-1-8:2005. In any case, this issue remains open and requires more research for moment-loaded joints.

Another problem of HSS joints is the high price of welding when full-strength welds are used. According to [12], full-strength fillet welds result in extremely large throat thickness, namely 1.48 t_1 for S420, 1.61 t_1 for S500 and 1.65 t_1 mm for S700, where t_1 is the wall thickness of the connected tube. Such large welds increase the number of welding runs and thus, taking into account the high costs of welding, make the welding process extremely expensive for HSS joints. According to [6], the full-strength fillet-weld throat thicknesses can be reduced to 1.0 t_1 for S500, 1.2 t_1 for S700 and 1.4 t_1 for S960, provided that they can resist the loads.

Subsequent to the above discussion, the scope of this paper is to present the experimental results of welded moment-loaded HSS joints. Twenty tests on square hollow section T joints were performed to:

- observe the moment-rotation relationship in the whole range of loading: initial stiffness, hardening stiffness, plastic and ultimate moment resistances and ductility;
- determine the need for the reduction coefficients and propose smaller ones, if possible;
- evaluate the ductility of joints and justify the use of welds that are smaller than full-strength ones.

The paper considers only joints with the brace-to-chord width ratio $\beta = b_1/b_0 \leq 0.85$, i.e., when chord face bending governs the deformation of the specimen. Joints with fillet and butt welds are considered. Fig. 1 presents the typical moment-rotation relationship for a hollow section joint with $\beta \leq 0.85$. In the figure, $M_{pl,\mathrm{exp}}$ and $M_{u,\mathrm{exp}}$ denote plastic and ultimate moment resistances, respectively; $S_{j,ini}$ and $S_{j,h}$ denote initial and hardening rotational stiffness, respectively; φ_u denotes rotation corresponding to ultimate resistance. According to [13], for this type of joints plastic moment resistance $M_{pl,\mathrm{exp}}$ is determined as the intersection of the two tangent lines corresponding to initial and hardening stiffness.

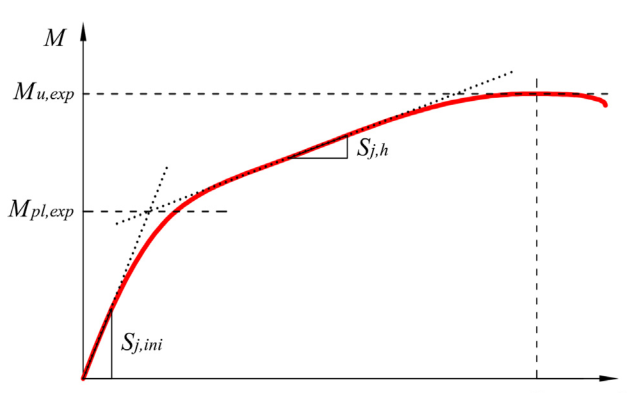

Fig. 1. Typical M-φ relationship for hollow section T joint with $\beta \leq 0.85$.

2. Literature review

2.1. Moment resistance

The first equations for the strength of moment-loaded hollow section joints can be found in [14–17]. A comprehensive research on tubular joints was conducted by Wardenier [18], who first proposed the design formulae based on the classical yield line theory. Currently, these rules are used in many design standards, such as EN 1993-1-8:2005 [3], ISO 14346:2013 [19], and CIDECT Design Guide No. 3 [4]. Some newer experimental tests are presented in [20,21]. Tabuchi et al. [22] presented experimental results for in-plane moment-loaded rectangular hollow section (RHS) T joints and examined their local failures. Szlendak [23] and Packer [24] developed design procedures for RHS connections under the moment loading. Intensive research for uniplanar and multiplanar RHS joints was conducted by Yu [25]. The deformation limit of RHS joints was investigated by Lu et al. [26] and Zhao [27]. The comparison of conventional and bird-beak RHS joints under in-plane bending moment has been conducted in [28]. Cyclic tests on welded RHS connections were performed in [29]. Fatigue tests on hollow section joints made of HSS can be found in [30]. However, most of the presented tests have been conducted for regular steels; no experiments can be found for HSS tubular joints under static moment loading.

2.2. Rotational stiffness

In addition to moment resistance, rotational stiffness is an important quantity in the design of joints, needed particularly in a global analysis model based on beam elements. In addition, initial rotational stiffness has a great effect when cost optimal solutions are sought, both in sway frames [31–35] and non-sway frames [36]. Moreover, rotational stiffness was shown to have an influence on the buckling lengths of truss members [37–39]. Grotmann and Sedlacek [13] employed the component method to propose theoretical equations for the initial rotational stiffness of RHS T joints. Later, these equations were validated against experimental results in [40].

2.3. Ductility

The ductility requirements are not as straightforward as those for moment resistance and initial stiffness, being dependent on the case. EN 1993-1-8:2005 and EN 1993-1-12:2007 provide the requirements for the basic steel material using the ultimate strain ε_u. Annex C of EN 1993-1-5:2006 [41] recommends a value of 5% for the principal strain at the ultimate limit state. To evaluate the ductility of members, the factor R, the ratio of plastic and elastic rotation, is used, being dependent on the layout of the frame and the loading conditions [42,43]. A continuous beam with $R = 3$, the most unfavorable system, is accepted in EN 1993-1-1:2005 [44] as the minimum requirement for the members belonging to the cross-section class 1, allowing the global plastic design of the frame.

Rotation capacity has been studied by Beg et al. [45], who limited the rotation capacity of the entire joint by limiting the relevant principal strains of distinct components to 10–20%. EN 1998-1:2004 [46] proposes a general limit of 0.035 rad for joint rotation to fulfil the requirements for the seismic design. This rule is aimed to allow joints form a sufficient plastic hinge to carry cyclic loads without a brittle fracture in the connection [47].

For tubular joints, the ultimate deformation limit was proposed by Lu et al. [26] to define the strength of joints that do not exhibit a pronounced peak load. Later it was discussed in [27,48]. Following this rule, the local displacement of the chord is limited to 3% of the width of the chord b_0. Applying this rule to moment-loaded joints, the rotation of the joint φ is limited to $\varphi_{lim,3\%} = 0.03b_0/(h_1/2)$, where h_1 is the height of the brace. This limit is based on the observation that hollow section