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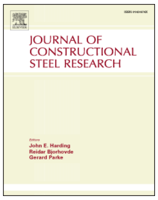

Static strength of high strength steel CHS X-joints under axial compression

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ABSTRACT

This paper presents an investigation on the static strength of high strength steel circular hollow section (CHS) X-joints subjected to axial compression in the braces which failed by chord face plastification. Using validated finite element models, extensive numerical simulations were conducted considering a wide range of geometric parameters and chord preload ratios. The material properties of high strength steel with nominal yield stresses of 700, 900 and 1100 MPa were carefully incorporated in finite element models. The static strengths obtained from numerical analysis in this study and experimental tests in the literature were compared with those calculated from mean strength equations on which the design equations in Eurocode EN 1993-1-8 and the CIDECT design guide are based. The comparison results show that the mean strength equation adopted by the CIDECT design guide is generally more accurate than that of EN 1993-1-8. The mean strength prediction of the CIDECT design guide without using reduction factors of joint strength is relatively accurate for CHS X-joints with nominal steel yield stresses ranging from 650 to 700 MPa. However, the mean strength predictions of EN 1993-1-8 and the CIDECT design guide generally become more unconservative with increasing steel yield stress. The mean strength equations are unconservative for CHS X-joints with nominal steel yield stresses exceeding 700 MPa.

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1. Introduction

High strength steel (HSS) with a nominal yield stress higher than 450 MPa has become readily available due to rapid development of steel production technology. The application of high strength steel can reduce structural self-weight and lower construction costs as well as carbon footprints by using less steel material. Thus, high strength steel is increasingly popular in construction industry as an economical and sustainable construction material.

Steel tubular joints are a critical part of onshore and offshore steel tubular structures. Comprehensive design rules for normal strength steel tubular joints with a nominal steel yield stress not exceeding 355 MPa are available in design codes and guides including Eurocode EN 1993-1-8 [1], the CIDECT design guides [2,3], ISO 14346 [4], IIW recommendations [5] and API RP 2A WSD [6]. However, there is limited design guidance for HSS tubular joints. EN 1993-1-8 [1] stipulates an additional reduction factor of joint strength of 0.9 for steel tubular joints in steel grades greater than S355 and up to S460. EN 1993-1-12 [7] further extends the use of steel grades up to S700 and imposes a reduction factor of 0.8 for steel tubular joints using steel grades greater than S460 and up to S700. Similarly, a reduction factor of 0.9 combined with the limitation on yield stress (f_y) to 0.8 of ultimate stress ($0.8f_u$) for steel tubular joints using steel grades greater than S355 and up to S460 is specified in the CIDECT design guides [2,3]. These restrictions in Eurocode [1,7] and the CIDECT design guides [2,3] for HSS tubular joints are stipulated due to relatively large deformation observed in chord face plastification failure, lower deformation capacity of steel with yield stresses exceeding 355 MPa, and required sufficient joint ductility for failure modes of punching shear and effective width failure [8]. These provisions are based on limited research on HSS tubular joints.

Kurobane [9] conducted experimental investigation on circular hollow section (CHS) gap K-joints made of S460 steel. It is found that the joint strength is 18% lower than that of corresponding S235 joints in relative terms after taking account for the increased yield stress. Liu and Wardenier [10] carried out numerical study on rectangular hollow section (RHS) gap K-joints using S460 steel and found that the reduction of joint strength varies from 10 to 16% compared with corresponding S235 joints. Fleischer et al. [11] conducted finite element analysis on the reduction factor of the static strength of CHS X-joints made of S460 and S690 steel compared with corresponding S355 joints. It is found that the reduction factors are marginally higher than 0.9 for S460 joints and higher than 0.8 for S690 joints. Puthli et al. [12] carried out experimental tests on CHS right angle X-joints using steel grades up to S770 without considering chord axial stress effect. It is found that the test strength generally exceeds the design strength in EN 1993-1-8 [1]

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Nomenclature

d	chord diameter
t	chord wall thickness
l	chord length
A_0	cross section area of chord member
β	brace to chord diameter ratio ($=d_1/d$)
θ	angle between brace and chord members
f_y	yield stress
COV	coefficient of variation
N_{ei}	joint strength calculated from mean strength equations
d_1	brace diameter
t_1	brace wall thickness
l_1	brace length
τ	brace to chord wall thickness ratio (t_1/t)
2γ	chord diameter to wall thickness ratio ($=d/t$)
n	chord preload ratio
E	elastic modulus
r_{si}	strength ratio ($=N_{ei}/N_{fi}$)
N_{fi}	joint strength obtained from finite element analysis and tests

without using the reduction factors. Becque and Wilkinson [13] conducted tests on RHS T- and X-joints made of C450 steel with a nominal yield stress of 450 MPa. It is found that the test strength is higher than the mean strength converted from the design strength in the CIDECT design guide [2]. It is without imposing the reduction factor and limitation on the yield stress for the joints which failed in ductile modes (i.e. chord face plastification and side wall buckling), provided the geometric limits in CIDECT provisions are satisfied. However, the test results justify the introduction of the reduction factor and limitation on yield stress for the joints which failed by fracture, in particular, failure modes of punching shear and effective width failure. Mohan et al. [14–15] carried out numerical investigation on RHS T-, X-, K- and N-joints using C450 steel. The numerical strength is found to be generally higher than the design strength without imposing the reduction factor and limitation on yield stress in the CIDECT design guide [2]. Cheng et al. [16] proposed a design methodology for equal-width RHS X-joints using steel grades up to C450 which failed by chord side wall buckling. Lee et al. [17] conducted experimental tests and numerical analysis on CHS X-joints made of HSA800 steel with measured yield stresses up to 800 MPa without chord preload. It is found that the joint strength exceeds the design strength in EN 1993-1-8 [1] without using the reduction factor. However, research on high strength steel tubular joints with steel yield stresses higher than 700 MPa remains limited.

A numerical study on the static strength of CHS X-joints with nominal steel yield stresses of 700, 900 and 1100 MPa under axial compression was conducted. The numerical study covered a wide range of geometric parameters and chord preload ratios. The static strength obtained from numerical analysis and experimental tests in the literature was compared with that calculated from mean strength equations on which the design equations in EN 1993-1-8 [1] and the CIDECT design guide [3] are based. The suitability of current design rules for high strength steel CHS X-joints which failed by chord face plastification was evaluated.

2. Finite element model

The finite element (FE) software ABAQUS [18] was used to carry out the numerical analysis. Test results of CHS X-joints made of S355, S690 and S770 steel [12] and HSA800 steel [17] subjected to axial compression in the braces were used to validate the FE models. Table 1 shows the parameters of CHS X-joints, namely chord diameter (d), chord wall thickness (t), brace diameter (d_1), brace wall thickness (t_1), the ratio (β) of brace diameter (d_1) to chord diameter (d), and the ratio (2γ) of chord diameter (d) to chord wall thickness (t). The angle (θ) between brace and chord members of specimens is 90°. Other parameters not listed in Table 1 are detailed in Puthli et al. [12] and Lee et al. [17]. It should be noted that the static strength of CHS X-joints is determined by the peak load or the load at a 3% indentation at the chord crown (i.e. indentation limit up to 3%d) in load-indentation curves proposed by Lu et al. [19]. The indentation refers to the distance between the original position of the chord crown and that when loads in the brace are applied. The indentation in this study was taken as the largest indentation value at the crown positions of CHS X-joints. If the indentation at the peak load is smaller than 3%d, then the peak load is considered to be the joint strength. If the indentation at the peak load is larger than 3%d, then the load at the indentation of 3%d is considered to be the joint strength.

Table 1
Specimens used for validating FE models.

Specimen	d (mm)	t (mm)	d_1 (mm)	t_1 (mm)	β	2γ	f_y (MPa)	f_u (MPa)
R32 [12]	324.7	14.8	177.9	8.4	0.55	21.94	734	802
R33 [12]	325.1	19.1	178.1	8.5	0.55	17.02	739	798
R47 [12]	324.8	20.3	178.0	8.5	0.55	16.00	376	575
R69 [12]	159.2	9.2	60.6	5.2	0.38	17.30	858	879
R71 [12]	193.8	10.1	139.7	7.2	0.72	19.19	854	900
R75 [12]	244.7	22.0	194.6	16.0	0.80	11.12	811	863
X90-650-0.75-16 [17]	400.0	25.0	300.0	15.0	0.75	16.00	806	938
X90-650-0.62-26 [17]	650.0	25.0	400.0	25.0	0.62	26.00	798	914

2.1. Material properties

Puthli et al. [12] and Lee et al. [17] only reported the yield stress (f_y) and ultimate stress (f_u) of steel grades S355 (specimen R47), S690 (specimens R32 and R33), S770 (specimens R69, R71 and R75) and HSA 800 (specimens X90-650-0.75-16 and X90-650-0.62-26), as shown in Table 1. However, the stress-strain curves for the steel materials of specimens were not reported [12,17]. Therefore, a simplified bi-linear stress-strain curve for S355, S690 and S770 steel was adopted. The values of elastic modulus (E) and ultimate strain (ε_u) at ultimate stress are 210 GPa and 10%, respectively, in accordance with Fleischer et al. [11] and Puthli et al. [12]. The Poisson's ratio (v) equals to 0.3. The true stress-strain curve was input in FE models after converting the engineering stress-strain curve using the following equations [20]:

$$\varepsilon_T = \ln(1+\varepsilon) \tag{1}$$

$$\sigma_T = \sigma(1+\varepsilon) \tag{2}$$

where ε_T and ε are true and engineering strain, respectively, and σ_T and σ are true and engineering stress, respectively. The same material properties for the chord, brace and weld were adopted [11,12]. The

Table 2
Results of mesh convergence study on specimen R69.

Element type	Mesh size (mm)			N_{FE}/N_{Test}
	Joint zone	Outside joint zone	Weld	
Shell element	15	30	–	1.11
	10	20	–	1.07
	5	10	–	1.04
	3	6	–	1.04
Solid element	12	24	6	1.09
	10	20	5	1.08
	8	16	3	1.05
	6	10	2	1.05

Note: $N_{Test} = 519$ kN.

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