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Tests of steel and composite CHS X-joints with curved chord under axial compression

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ABSTRACT

This paper presents an experimental investigation on empty and concrete-filled circular hollow section (CHS) X-joints with curved chord under axial compression. A total of 16 specimens was fabricated by hot-rolled bending the chord members into curvature with three different radii to apply axial compression force to the brace members, in which 6 specimens were tested with empty curved chord, 6 specimens were tested with concrete filled in the curved chord only, and 4 traditional empty and concrete-filled CHS X-joints with straight chord were also tested for comparison. The effects of curvature radius of chord member and concrete filled in the chord member on the joint strength and behavior were evaluated. It is shown from the comparison that the ultimate strengths of the CHS X-joints with curved chord are generally larger than those of the traditional CHS X-joints with straight chord. In addition, the ultimate strengths of the concrete-filled CHS X-joints are larger than those of the empty CHS X-joints, and the enhancement of the ultimate strengths of the traditional CHS X-joints with straight chord is much more pronounced than that of the CHS X-joints with curved chord.

1. Introduction

Circular hollow section (CHS) is the most widely used section in onshore and offshore structures due to its aesthetic appearance, uniform flexural rigidity, high fatigue and corrosion resistance. Typical applications of CHS joints, which are fabricated by welding brace members to the continuous chord members, include reticulated shell structures, long-span roof systems and marine petroleum platforms. Connection reinforcement is normally used when a tubular joint has an inadequate resistance and its primary hollow section members cannot be changed. One of the commonly used methods of strengthening is to fill the hollow section with concrete or grout, which is particularly appealing for architecturally exposed steelwork. It is worth noting that the curved chords with certain curvature radius are being used increasingly for architectural and structural purposes in recent years. Up to the authors' knowledge, however, there is no design rule for CHS joints with curved chord, let alone concrete-filled CHS joints with curved chord.

Numerous studies have been performed on traditional CHS joints. An experimental investigation was conducted by Wang et al. [1] on seismic behavior of thick-walled CHS X-joints subjected to cyclic out-of-plane bending. It was found that CHS X-joints with large brace to chord diameter ratio (β) have better joint ductility and energy dissipation capacity than CHS X-joints with small β ratio under cyclic out-of-plane bending. A systematic finite element analysis was performed by Qian et al. [2] on the static strength of thick-walled CHS X-joints under brace moment loadings. The critical load path for CHS X-joints under in-plane bending was observed to be around the crown position of chord wall. Whereas, the critical load path for CHS X-joints under out-of-plane bending was found to be around the saddle position of chord wall. A yield line model was developed by Soh et al. [3] to predict the ultimate strength of axially loaded CHS X-joints. It was demonstrated that joint strength was determined by the plastic moment resistance of yield lines and the membrane action in the yield zone of the chord surface. A new approach in the definition of joint strength was proposed by Choo et al. [4] for thick-walled CHS X-joints subjected to brace axial loadings. Good agreements were achieved between the joint strengths predicted by the proposed approach and the design recommendations given in the ISO standard [5] and CIDECT code [6] for CHS X-joints with chord radius to thickness ratio $\gamma > 7$. In the meanwhile, an extensive parametric study was carried out by Choo et al. [7] to evaluate the effect of chord stresses on the static strength of CHS X-joints. A

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Nomenclature

d_0	chord diameter	P_{uf}	ultimate strength of concrete-filled CHS X-joint
d_1	brace diameter	P_{us}	ultimate strength of CHS X-joint with straight chord
E	elastic modulus	Q_u	influence function for geometric parameters β and γ
f_{cu}	concrete cube strength	R	Curvature radius
f_u	ultimate tensile stress of steel	t	thickness of thinner part between brace and chord
f_y	tensile yield stress of steel	t_0	chord thickness
f_{y0}	yield stress of chord	t_1	brace thickness
k_p, Q_f, ψ_n	parameters account for the influence of chord longitudinal stress	v	Poisson's ratio
P	axial load	β	brace to chord diameter ratio (d_1/d_0)
P_{CC}	design strength obtained from Chinese code (GB 50017-2003)	2γ	chord diameter to thickness ratio (d_0/t_0)
P_{EC}	design strength obtained from Eurocode 3 (EN 1993-1-8)	δ	chord deformation
P_{API}	design strength obtained from API standard (API-RP2A)	δ_1	flange indentation of chord concave side
P_{AWS}	Design strength obtained from AWS standard (AWS D1.1/1.1M)	δ_2	flange indentation of chord convex side
P_{IIW}	design strength obtained from IIW specification (IIW Doc. XV-E-07-378)	δ_3	deflection of chord side wall
P_u	ultimate strength	ε_f	elongation after fracture
P_{uc}	ultimate strength of CHS X-joint with curved chord	ε_i	strain
P_{ue}	ultimate strength of empty CHS X-joint	ε_1	first principal strain
		ε_2	second principal strain
		ε_3	third principal strain
		θ	inclined angle between brace and chord
		τ	brace to chord thickness ratio (t_1/t_0)
		Δ	vertical displacement

significant joint strength reduction was obtained for CHS X-joints with small β ratio subjected to tensile or compressive chord stresses. Whereas, the chord stresses including both tensile and compressive stresses have little influence on the static strength of CHS X-joints with large β ratio. In general, the effect of γ ratio on the static strength of CHS X-joints is not that pronounced compared to the β ratio. On the other hand, the tensile chord stress has detrimental effect on CHS X-joints subjected to brace axial tension or compression. Furthermore, the effect of chord stresses on the static strength of CHS X-joints with inclined braces was also investigated by Choo et al. [8]. The influence of brace inclination angle (θ) was considered in the design equations in terms of $\sin\theta$ for thin-walled CHS X-joints. It was shown that the geometric parameters β and θ have more significant effects than the γ ratio on the chord stress effect. In addition, the effect of tensile chord stress on the joint strength is pronounced, which has to be taken into account in the design rules. Elastic–plastic driving force in surface cracks located at weld toes near the saddle point of circular hollow section X and K-joints with strength mismatch between the chord material and welds was investigated by Qian et al. [9,10]. The numerical results showed that a large elastic–plastic crack driving force exists for joints with a high chord radius to wall thickness ratio or with a small brace to chord diameter ratio. Stress concentration factors of dragline tubular joints were experimentally investigated by Pang et al. [11]. Long-term fatigue analysis of welded multi-planar tubular joints for a fixed jacket offshore wind turbine designed for a North Sea site in a water depth of 70 m was performed by Dong et al. [12]. Behavior of transverse or longitudinal T-type plate-to-CHS connections loaded under branch plate tension or compression was numerically investigated by Voth and Packer [13]. An energy-based approach to estimate the elastic–plastic energy release rate for shallow surface cracks located at the weld toe at the chord crown point near the tension brace in the CHS K-joint was proposed by Zhang and Qian [14]. A parametric numerical study was conducted to compare the fatigue performances of gapped and partially overlapped circular hollow section (CHS) K-joints under different loading conditions by Lee et al. [15]. The ultimate capacity of welded steel tubular joints under axial load at elevated temperatures was numerically investigated by Ozyurt et al. [16].

On the other hand, some researches were also carried out on concrete-filled CHS, square hollow section (SHS) and rectangular hollow section (RHS) tubular joints. An experimental investigation was conducted by Tebbett et al. [17] on both grouted and ungrouted CHS T-joints. The ultimate strengths of tubular joints under axial compression, axial tension and in-plane bending were significantly enhanced by filling the concrete in the tubes. In addition, the punching shear failure of the chord face observed in the empty tubular joints was also prevented by filling the concrete in the tubes. A large number of concrete-filled SHS and RHS T-, X- and K-joints were tested by Packer [18] using bearing plates to transmit transverse compression load to the concrete-filled chord members to prevent the squashing failure of the compression brace members. Special attention was given to the comparison between the full and partial concrete filling in the chord members of the tubular X-joints. A wide range of concrete-filled stainless steel SHS and RHS T- and X-joints were investigated by Feng and Young [19,20]. It was recommended that the contribution of stainless steel tubes should be included in the design rules since it has significant effects on the ultimate bearing capacity of concrete-filled stainless steel tubular joints. An experimental investigation of structural fire behavior of steel beam to concrete filled tubular column assemblies using different types of joints was conducted by Ding and Wang [21]. The relatively simple joints were able to allow the beams to develop substantial catenary action so that the final failure times and beam temperatures of the assemblies were much higher than those obtained by assuming the beams in pure bending. A new type of connections-ring beam joints with a discontinuous outer tube between the concrete-filled twin steel tubes columns and reinforced concrete beams was introduced by Zhang et al. [22]. The joints with good aseismatic behavior can easily achieve the anti-seismic design principles. Seismic behavior of extended end plate connections to circular or square concrete-filled steel tubular columns using blind bolts was investigated by Wang et al. [23]. The blind bolted extended end plate connections with circular or square CFST columns exhibited large hysteretic loops, good ductility, and excellent energy dissipation capacity. The heat transfer analysis of concrete-filled steel circular hollow sections subjected to fire was numerically investigated by Wang and Tan [24]. Fracture