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Experimental and numerical investigations on double-skin CHS tubular X-joints under axial compression

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ABSTRACT

This paper presents the experimental and numerical investigations on double-skin circular hollow section (CHS) tubular X-joints under axial compression, in which PVC pipes were used as the internal members. A total of 22 X-joints with different brace to chord diameter ratio (β), hollow ratio of chord (φ) and shapes of internal members was tested, in which two traditional CHS tubular X-joints and two grouted CHS tubular X-joints were tested for comparison. The joint strengths, failure modes, load-deformation curves, load-strain distribution curves and ultimate capacity evaluation of all specimens are reported. The effects of brace to chord diameter ratio (β), hollow ratio of chord (φ) and shapes of internal members on the structural behaviour of double-skin CHS tubular X-joints under axial compression were evaluated. It is shown from the comparison that the ultimate strength, initial stiffness and ductility of double-skin CHS tubular X-joints benefit from the increase of brace to chord diameter ratio (β). Furthermore, the double-skin CHS tubular X-joints with large hollow ratio of chord (φ) show good ductility. On the other hand, the ultimate strengths of double-skin tubular X-joints significantly increased by grouting the chord member. The ultimate strength and initial stiffness of double-skin tubular X-joints with small hollow ratio of chord (φ) are close to their grouted counterparts. However, the ultimate strength and initial stiffness of double-skin CHS tubular X-joints with large hollow ratio of chord (φ) are much smaller than their grouted counterparts. The corresponding finite element analysis was performed and calibrated against the test results. The design equations are proposed based on the test and numerical results for double-skin CHS tubular X-joints, which were verified to be more accurate.
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1. Introduction

Circular hollow sections (CHS) nowadays are widely used in stadium, airport, and long-span roof due to welding accessibility [1]. In these structures, the CHS brace members are usually welded directly to the CHS chord member to form a welded CHS tubular joint [2]. The chord member is normally subjected to loadings in the radial direction transferred from the welded brace members under axial loadings [3]. Lots of studies in which databases were set up have been made on CHS joints as yet [4–8]. It is well known that the stiffness of the CHS tube in the radial direction is much smaller than that in the axial direction, which causes the chord member to be easily failed by chord face plastification or punching shear failure at the chord flange around the brace and chord intersection region [9]. For a full width CHS tubular joint, the buckling failure of chord side wall usually occurred in resisting the loadings transferred from the welded brace members.

Internal and external reinforcement are two main ways to enhance the load carrying capacity of CHS tubular joints. Doubler plate and collar plate reinforcement are two typical external reinforcing methods [10–14]. On the other hand, grouting reinforcement is one of the most representative internal reinforcing methods. The joint strength, dynamic performance, energy dissipation capacity and fatigue behaviour could be improved by grouting the chord member of CHS tubular joints [15]. The experimental investigations were ever conducted on the static and fatigue behaviour of grouted tubular joints under axial compression, axial tension and bending moment [16–19]. It was demonstrated that the load carrying capacity of tubular joints could be greatly enhanced by grouting reinforcement. The enhancement of the ultimate strength of tubular joints under axial compression could be taken into account by the equivalent chord wall thickness recommended by the American Bureau of Shipping [20]. Furthermore, the stress distribution around the brace and chord intersection region becomes more uniform by grouting the chord member of CHS tubular joints. Hence, the stress concentration factors (SCF) of grouted tubular joints could be conservatively

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Nomenclature

Notation

A	total area of grouted CHS chord
A_v	cross-section area of void
b_{in}	width of internal member
COV	coefficient of variation
d_{in}	diameter of internal member
d_0	chord diameter
d_1	brace diameter
E	elastic modulus
f_{cu}	compressive strength of grout cube
f'_c	maximum uniaxial compressive stress of grout
$f_{p,u}$	compressive strength of PVC pipe
f_u	ultimate tensile stress
f_y	tensile yield stress
f_{y0}	yield stress of chord
k_i	initial stiffness
L_0	chord length
L_1	brace length
P_{BP}	design strength of double-skin BP X-joint
P_{CHS}	design strength of CHS tubular X-joint
P_{CP}	design strength of double-skin CP X-joint
P_{FEA}	joint strength obtained from finite element analysis
P_{SP}	design strength of double-skin SP X-joint
P_{Test}	joint strength obtained from test
P_u	ultimate load
P_{YB}	yield strength of brace
$P_{3\%b0}$	joint strength at deformation of 3%d_0
t	thickness of thinner part between brace and chord
t_c	grout thickness
t_e	effective thickness
t_{in}	wall thickness of internal member
t_0	chord wall thickness
t_1	brace wall thickness
u	chord flange indentation
v	chord web deflection
w	weld size
β	brace to chord diameter ratio (d_1/d_0)
δ_u	vertical displacement at ultimate load
δ_y	vertical displacement at yield load
ε_f	elongation after fracture
ε_i	strain
ε_1	first principal strain
ε_2	second principal strain
ε_3	third principal strain
η	correction factor for shape of internal member
ν	Poisson's ratio
τ	brace to chord wall thickness ratio (t_1/t_0)
φ	hollow ratio of chord
ω	correction factor for grout strength
C	grout strength

calculated by using the design formulae of SCF of hollow section tubular joints. However, the grouting reinforcement greatly increases the self weight of the tubular joints [21]. Therefore, the double-skin tubular joints were developed by grouting the void between the outer tube and inner tube, which could greatly improve the joint behaviour and somewhat increase the self weight of the tubular joints. It is demonstrated from the previous researches on the grouted tubular T-joints in offshore platform [22,23] that the failure modes of double-skin tubular T-joints are similar to their hollow counterparts, but the ultimate strengths are greatly enhanced. Furthermore, it is shown from the previous researches on the fatigue behaviour of double-skin tubular joints [24–26] that the SCFs of double-skin tubular joints could be calculated using the design formulae of SCFs of hollow section tubular joints by introducing the equivalent chord wall thickness, in which the wall thickness of internal member has been considered, but the effect of grout has been ignored.

With the development of the modern manufacture, the PVC pipe is increasingly used in construction industry due to its characteristics of low price, light weight, waterproof and fireproof. Therefore, the special double-skin tubular X-joints with steel outer tube, PVC inner tube and grout in between under axial compression were experimentally and numerically investigated in this study. Furthermore, the traditional CHS tubular X-joints and grouted CHS tubular X-joints were also investigated for comparison.

2. Experimental investigation

2.1. Test specimens

A total of 22 CHS tubular X-joints was tested by applying axial compression force to the CHS brace members, in which 18 specimens were tested with grouted double-skin chord member, 2 specimens were tested with empty CHS chord member and 2 specimens were tested with grouted CHS chord member. All specimens were fabricated with brace members fully welded at right angle to the center of the continuous chord member, as shown in Fig. 1(a)–(c) for CHS tubular X-joints, grouted CHS tubular X-joints and grouted double-skin CHS tubular X-joints, respectively. There are three types of grouted double-skin CHS tubular X-joints including CP X-joints, SP X-joints and BP X-joints by grouting the void between the steel outer tube and PVC inner tube, which depend on the cross-section shape of the inner tube of the chord member. For the CP X-joints, the inner tube of the chord member is CHS. For the SP X-joints, the inner tube of the chord member is square hollow section (SHS) with flat surface perpendicular to the axis of the CHS brace members. For the BP X-joints, the inner tube of the chord member is also SHS, but rotating by 45° along the centerline, which is the so-called bird-beak tube. The chord member of all specimens including the outer tube of the chord member of the double-skin tubular joints is designed as the CHS 140 × 3, which has the nominal outer diameter (d_0) of 140 mm, and the nominal wall thickness (t_0) of 3 mm, with the identical overall length (L_0) of 500 mm. The overall length of inner tube of the chord member of the double-skin tubular joints is identical to that of the outer tube. The brace members of all specimens are designed as the CHS 89 × 2.2 and CHS 114 × 2.5, which have the nominal outer diameter (d_1) of 89 mm and 114 mm, the nominal wall thickness (t_1) of 2.2 mm and 2.5 mm, with the identical overall length (L_1). Hence, the brace to chord diameter ratios ($\beta = d_1/d_0$) of all specimens are 0.64 and 0.81, respectively. The dimensions of test specimens are shown in Table 1, using the nomenclature defined in Fig. 1(a)–(c) for CHS tubular X-joints, grouted CHS tubular X-joints and grouted double-skin CHS tubular X-joints, respectively.

The welds connecting brace and chord members were designed according to the American Welding Society (AWS D1.1/1.1M) Specification [27] and laid using shielded metal arc welding. The weld sizes (w) in the test specimens are all greater than the larger value of 1.5t and 3 mm as specified in the AWS specification,

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