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Experimental and numerical investigations on steel–concrete–PVC SHS joints under axial compression

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HIGHLIGHTS

- Investigation on steel–concrete–PVC SHS joints under axial compression was completed.
- Failure load of joints are remarkably enhanced by grouting the chord.
- Failure loads of joints are weakened with the increase of the hollow ratio.
- The design equations of strength were proposed for steel–concrete–PVC SHS joints.

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ABSTRACT

This paper presents the experimental and numerical investigations on steel–concrete–PVC SHS joints under axial compression, in which PVC pipes were used as the inner tube of chord member and SHS steel tubes were used as the outer tube of chord member. A total of 22 joints with different brace to chord width ratio (β), hollow ratio of chord (φ) and shapes of PVC inner tube of chord were tested, in which two traditional hollow joints and two grouted joints were tested for comparison. The effects of brace to chord width ratio (β), hollow ratio of chord (φ), grout strength and shapes of PVC inner tube of chord on the structural behavior of steel–concrete–PVC SHS joints under axial compression were evaluated. Failure load and initial stiffness of traditional joints are remarkably enhanced by grouting the chord member along its full length, but the ductility is greatly deteriorated. On the other hand, the failure load and initial stiffness of steel–concrete–PVC SHS joints are improved with the increase of the β ratio. Whereas, the failure loads of steel–concrete–PVC SHS joints are weakened with the increase of the φ ratio. Furthermore, the grout strength has insignificant influence on the failure loads of steel–concrete–PVC SHS joints under axial compression. In addition, the steel–concrete–PVC SHS joints with large φ ratio show good ductility. Chord web deflection is larger than the chord flange indentation for steel–concrete–PVC SHS joints. For steel–concrete–PVC SHS joints with small φ ratio, the root of brace yielded first, while in the ultimate limit state, chord member around the joint intersection region were in the elastic phase. For steel–concrete–PVC SHS joints with large φ ratio, chord member around the joint intersection region yielded first, while in the ultimate limit state, the root of brace were fundamentally in the elastic phase. The design equations are proposed based on parametric FE analysis results for steel–concrete–PVC SHS joints under axial compression, which are verified to be more accurate.

1. Introduction

SHS members nowadays are widely used in stadium and airport terminal due to welding accessibility [1]. In these structures, the SHS brace members are usually welded directly to the continuous SHS (square hollow section) chord member to form a welded SHS joint [2]. The chord member is normally subjected to loadings in the radial direction transferred from the welded brace members under axial loadings [3]. It is worth noting that many studies were conducted on SHS joints [4–7]. The stiffness of the SHS tube in the radial direction was found to be much smaller than that in the axial direction, which causes the chord member to be weak in resisting the loadings in the radial direction. Therefore, the chord face failure or punching shear failure often occurred. And the chord side

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Nomenclature

PVC	polyvinyl chloride	P_f	failure load
SHS	square hollow section	P_{SHS}	failure load of traditional SHS X-joint
A	cross-section area of grouted SHS chord	P_{SP}	design strength of steel–concrete–PVC SP X-joint
A_v	cross-section area of void	P_{TEST}	joint strength obtained from test
b_{in}	width of internal member	P_{YB}	yield strength of brace
b_0	overall width of chord	$P_{3\%b_0}$	joint strength at deformation of 3% b_0
b_1	overall width of brace	t	thickness of thinner part between brace and chord
COV	coefficient of variation	t_c	grout thickness
d_{in}	diameter of internal member	t_e	effective thickness
E	elastic modulus of steel tube	t_{in}	wall thickness of internal member
E_p	elastic modulus of PVC pipe	t_0	chord wall thickness
f_{cu}	compressive strength of grout cube	t_1	brace wall thickness
f'_c	maximum uniaxial compressive strength of grout cube	u	chord flange indentation
$f_{p,u}$	compressive strength of PVC pipe	v	chord web deflection
f_u	ultimate tensile stress	w	weld size
f_y	tensile yield stress	β	brace to chord width ratio (b_1/b_0)
f_{y0}	yield stress of chord	δ_u	vertical displacement at ultimate load
k_i	initial stiffness	δ_y	vertical displacement at yield load
L_0	overall length of chord	ε_f	elongation after fracture
L_1	overall length of brace	η	correction factor for shape of internal member
P_{CC}	design strength of grouted traditional SHS X-joint determined from Chinese Code	θ_1	inclined angle between brace and chord
		μ	Poisson's ratio
P_{CP}	design strength of steel–concrete–PVC CP X-joint	φ	hollow ratio of chord
P_{DP}	design strength of steel–concrete–PVC DP X-joint	ω	correction factor for grout strength
P_{FEA}	joint strength obtained from finite element analysis		

wall failure usually occurred for full-width SHS joints in resisting the loadings transferred from the brace members.

Internal and external reinforcements are two main ways to enhance the load carrying capacity of SHS joints, in which grouting chord member is one of the most representative internal reinforcing methods, and welding collar and doubler plates are two typical external reinforcing methods [8–12]. It was demonstrated that grouted joints have distinct advantages compared to their empty counterparts, which include joint strength, resistance to dynamic loads, energy dissipation capacity and fatigue behavior [13]. The experimental investigations were ever conducted on grouted joints under axial compression, axial tension and bending moments [14–17]. Ultimate capacities were greatly enhanced by grouting reinforcement. The enhancement of the ultimate strength of joints under axial compression could be taken into account by the equivalent chord wall thickness recommended by the American Bureau of Shipping [18]. Furthermore, the stresses at the intersection region were distributed more evenly by grouting the chord member. Hence, the design formulae of stress concentration factors (SCF) of empty joints could be used for grouted joints by introducing the reduction factors. On the other hand, however, grouting reinforcement substantially increases the self-weight of the joints, which will challenge the supporting components and deteriorate the seismic behavior of the whole structure [19]. Therefore, the concrete-filled double-skin joints were developed by grouting the void between the outer tube and inner tube only, which could greatly improve the joint behavior and somewhat increase the self-weight of the joints. In addition, the empty inner tube of the chord member facilitates building services as piping, electric wiring, heating conduits and plumbing. The previous researches on the grouted T-joints in offshore platform [20,21] demonstrated that the failure modes of double-skin T-joints are similar to their empty counterparts, but the ultimate strengths of double-skin T-joints are greatly enhanced. Furthermore, it is shown from the previous researches on the fatigue behavior of double-skin joints [22–24] that the SCFs of double-skin joints could be calculated using the design formulae of SCFs of empty joints by introducing the equivalent chord wall thickness, in which the wall thickness of internal member was considered, but the effect of grout was ignored. A series of experimental investigation on SCF distribution and strength of concrete filled CHS joints was completed by Chen et al. [25–27].

With the spread of energy conservation idea and development of modern industry, the PVC (polyvinyl chloride) pipe is increasingly used in construction industry due to its characteristics of low price, light weight, waterproof and fireproof. Grouted concrete plays an important role to increase the strength and stiffness of SHS X-joints under axial compression. Although the strength of inner PVC tube is smaller than that of inner steel tube in the radius direction, steel–concrete–PVC double-skin joints is more efficient and economic than steel–concrete-steel double-skin joints to reinforce SHS X-joints.

Hence, the experimental and numerical investigations were conducted in this study on steel–concrete–PVC double-skin joints under axial compression, in which the PVC pipe was used as the internal member and SHS steel tube was used as the outer member of chord. Furthermore, the traditional hollow joints and grouted joints were also investigated for comparison.

2. Experimental investigation

2.1. Test specimens

22 experimental joints including 18 steel–concrete–PVC SHS joints, 2 traditional joints and 2 grouted joints were tested under compression in SHS braces. Traditional hollow joints, grouted joints and steel–concrete–PVC SHS joints were shown in Fig. 1a–c, respectively. There are three types of steel–concrete–PVC SHS joints including CP X-joints, SP X-joints and DP 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, as shown in Fig. 1c. For the CP X-joints, the inner tube of the chord member is circular hollow section (CHS). For the SP X-joints, the inner tube of the chord member is SHS with flat surface perpendicular to the axis of the SHS brace members. For the DP X-joints, the inner tube of the chord member is also SHS, but rotating by 45° along the centerline, which is the so-called diamond hollow section (DHS). The chord member of all specimens