EXPERIMENTAL INVESTIGATION ON STRESS CONCENTRATION OF CFRP-STRENGTHENED CHS GAP K-JOINTS

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An increasing number of ageing steel structures need to be repaired or strengthened for various reasons. Among different strengthening methods, the use of Carbon Fibre Reinforced Polymer (CFRP) has become an attractive option for its advanced performance. This paper presents an experimental investigation on stress concentration factor (SCF) of gap K-joints fabricated from Circular Hollow Section (CHS) members. A series of CHS gap K-joints were strengthened through a combination use of unidirectional and bidirectional CFRP sheets, and tested under axial loading for hot spot stresses before and after strengthening, respectively. Effects of the number of CFRP layers (both unidirectional and bidirectional) and three main non-dimensional geometric parameters were investigated, including the ratio of chord diameter to wall thickness 2γ, the ratio of brace diameter to chord diameter β, the ratio of brace wall thickness to chord wall thickness τ. The experimental results showed that CFRP strengthening could generally decrease the SCFs of CHS gap K-joints. On average, the maximum SCFs in the chord and brace decreased by 20% and 15%, respectively. In addition, the CFRP strengthening efficiency was found closely related to the number of CFRP layers and the wall thicknesses of CHS members within the adopted ranges. Comparatively, parameter β was found no significant correlation with the CFRP strengthening efficiency.

Keywords: Carbon Fibre Reinforced Polymer (CFRP), Circular hollow section (CHS), Gap K-joint, Stress concentration factor (SCF), Experimental investigation.

1 Introduction

In the last decades, Carbon Fibre Reinforced Polymer (CFRP) has been increasingly used in strengthening or repairing of steel structures because of its excellent structural performance including high strength-to-weight ratio, durability, corrosion resistance, fatigue resistance, easy construction and shape flexibility (Zhao and Motavalli 2014).

So far, extensive research has been conducted on fatigue strengthening of steel members such as steel plate and steel beam (e.g. (Colombi et al. 2003, Liu et al. 2009, Täljsten et al. 2009, Kim and Harries 2011, Borrie et al. 2016, Yu and Wu 2018)). It has been demonstrated that CFRP strengthening can effectively improve the fatigue behavior of steel plates or beams, especially in the cases where high or ultra-high modulus CFRP (Liu et al. 2009, Täljsten et al. 2009) or

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prestressed CFRP (Colombi et al. 2003, Täljsten et al. 2009) are used. However, there is still a lack of research on fatigue strengthening of welded tubular joints which are much more prone to fatigue failure than conventional members due to serious stress concentration near the weld intersection. Xiao and Zhao (2012) once repaired one SHS-to-SHS (square hollow section) T-connection and three RHS-to-RHS (rectangular hollow section) cross beam connections using CFRP to retrofitting their fatigue resistance under in-plane bending.

K-joint made of circular hollow sections (CHS) is a typical type of joint in tubular structures. Due to the complex geometry, CHS K-joints are difficult to be strengthened or repaired using conventional methods. Pantelides et al. (2003) and Fam et al. (2006) successively retrofitted aluminum CHS K-joints using Glass Fiber Reinforced Polymer (GFRP) and CFRP sheets. More recently, Fu et al. (2016) applied an improved CFRP strengthening technique to steel CHS K-joints to enhance their ultimate static capacity.

This paper presents an experimental investigation on hot spot stress of CFRP-strengthened CHS gap K-joints as the first step to learn the fatigue behavior of such composite joints. The adopted strengthening strategy for CHS gap K-joints was firstly introduced. Then the hot spot stress tests were reported for joints before and after CFRP strengthening. Through comparisons in terms of stress concentration factor (SCF), the efficiency of CFRP strengthening was examined.

2 Preparation of test specimens

2.1 *Specimens and material properties*

In this paper, eight CHS gap K-joints were manufactured for hot spot stress testing. Figure 1 shows the geometric configuration of the specimen. The geometric information and CFRP strengthening parameters of each test specimen are listed in Table 1. Among the eight specimens, the first five have the same nominal geometric parameters but different numbers of CFRP layers. While the other three specimens have different geometric parameters. All the specimens were firstly tested for hot spot stresses before CFRP strengthening. Then, the specimens were strengthened with CFRP and tested for hot spot stresses again.

The CHS tubes were made from low carbon structural steel of grade Q235, which conforms to Chinese standard GB/T700-2006. Two types of CFRP sheets were employed for strengthening. They are bidirectional CFRP with a nominal thickness of 0.211mm and unidirectional CFRP with a nominal thickness of 0.167mm. The measured tensile modulus are 130GPa and 250GPa respectively for the bidirectional CFRP and unidirectional CFRP. The corresponding epoxy resin adhesive has a measured tensile strength of 51MPa with a modulus of 2.2GPa.

Table 1. Parameters of test specimens

Specimen no.		Nominal geometric parameters						Number of CFRP layers	
Before strengthening	After strengthening	Chord (mm) $d_0 \times t_0$	Brace (mm) $d_1 \times t_1$	θ (°)	2γ	τ	β	Chord CFRP (n_{cf0})	Connecting CFRP (n_{cf1})
K1-13	CK1-13	219×8	127×6	45	27.4	0.75	0.58	1	3
K1-43	CK1-43	219×8	127×6	45	27.4	0.75	0.58	4	3
K1-23	CK1-23	219×8	127×6	45	27.4	0.75	0.58	2	3
K1-21	CK1-21	219×8	127×6	45	27.4	0.75	0.58	2	1
K1-25	CK1-25	219×8	127×6	45	27.4	0.75	0.58	2	5
K2-23	CK2-23	219×6	127×4.5	45	36.5	0.75	0.58	2	3
K3-23	CK3-23	219×8	127×8	45	27.4	1.00	0.58	2	3
K4-23	CK4-23	219×6	89×4.5	45	36.5	0.75	0.41	2	3

Note: *the average wall thickness of the two brace members is given.

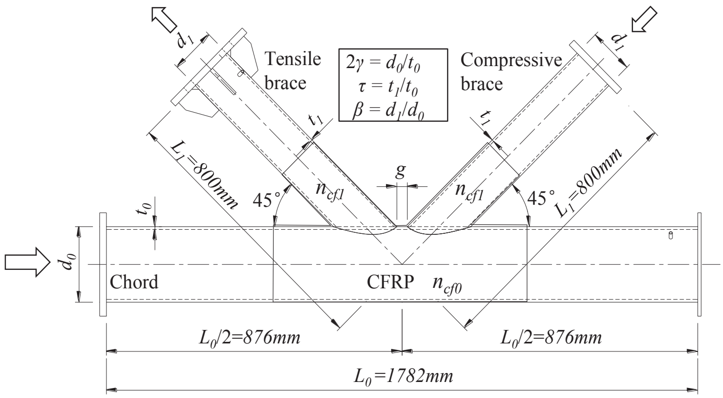


Figure 1. Geometric configuration of a CHS gap K-joint specimen

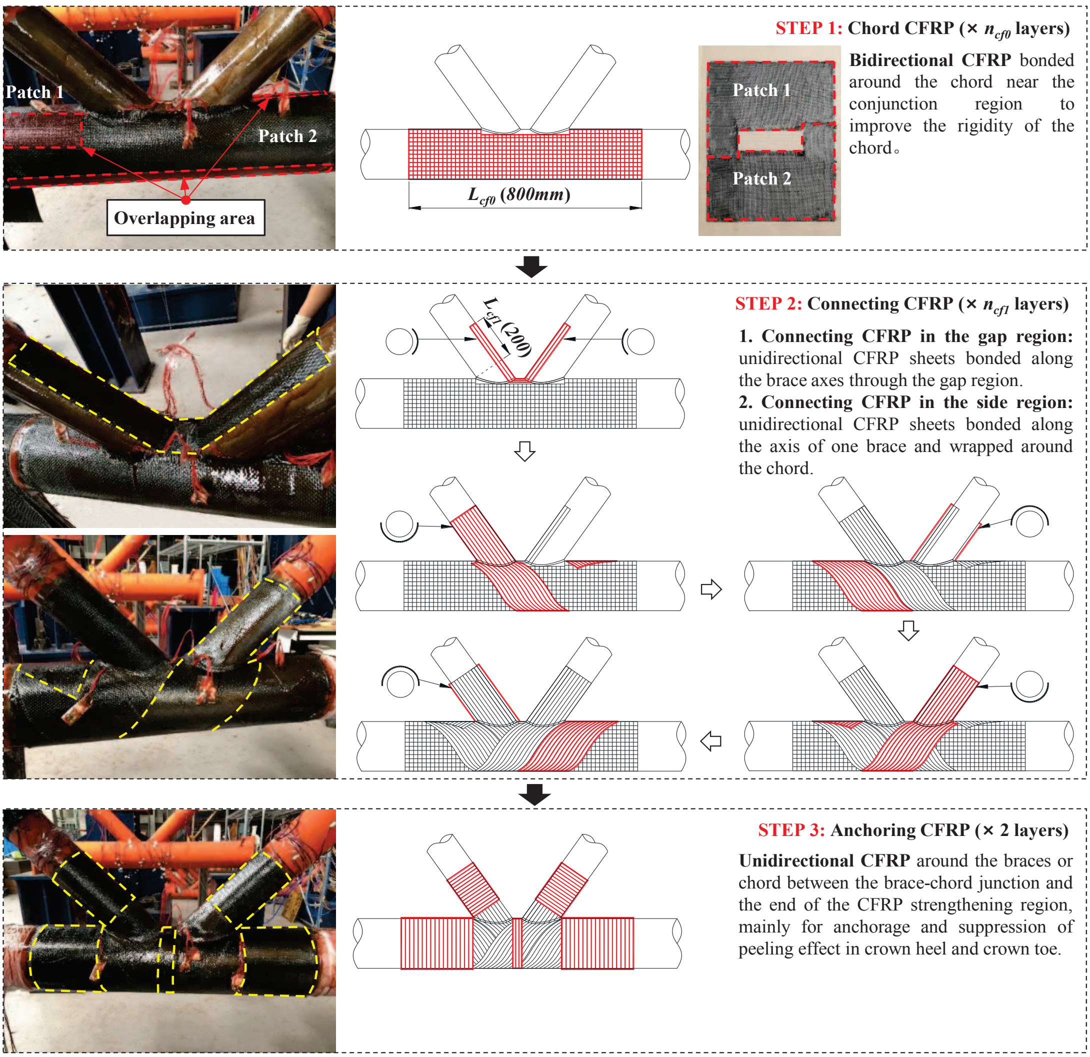


Figure 2. Classification and installation of CFRP in CHS gap K-joints

2.2 *Strengthening CHS gap K-joint with CFRP sheets*

Before the installation of CFRP sheets, all the specimens were sandblasted and cleaned using steel brush and acetone (or alcohol). Then, both bidirectional and unidirectional CFRP sheets were bonded around the CHS tubes using structural epoxy resin adhesive to strengthen the gap K-joints. Figure 2 illustrates the main process of strengthening CHS gap K-joints using three categories of CFRP sheets, namely Chord CFRP, Connecting CFRP and Anchoring CFRP respectively.

As shown in Figure 2, bidirectional Chord CFRP was firstly installed. Each layer of Chord CFRP consists of two patches of L-shaped bidirectional CFRP. The coverage length of the Chord CFRP (L_{cf0}) was 800mm. Then unidirectional Connecting CFRP was installed. Each layer of Connecting CFRP consists of five unidirectional CFRP sheets, one of which is bonded in the gap region and the other four are bonded in the side region in order. The coverage length of the Connecting CFRP in the brace (L_{cf1}) was 200mm. Finally, the unidirectional Anchoring CFRP was tightly wrapped around the entire strengthening regions outside the crown heel for at least two circles. It is believed that the Anchoring CFRP can to some extent suppress the peeling effect (Xiao and Zhao 2012) at the crown heel and crown toe.

3 Test setup

Figure 3 shows the test setup for hot spot stress of CHS gap K-joints before and after CFRP strengthening, respectively. One brace was pin connected to the frame (tensile brace) and the other one was pressed against an arc bearing (compressive brace). Axial force was applied to the top end of the chord through a jack fixed to the frame.

Strip strain gauges were employed to capture the hot spot strain (stress) along the brace-chord intersection lines. As shown in Figure 4, the gauges were placed perpendicular to the weld in the chord and along the brace axis, according to CIDICIT (Zhao et al. 2001). For each specimen, hot spot stress at each crown heel (i.e. B0C, B0T, C0C and C0T), saddle (i.e. B90C, B90T, C90C and C90T) and crown toe (i.e. B180C, B180T, C180C and C180T) were measured.

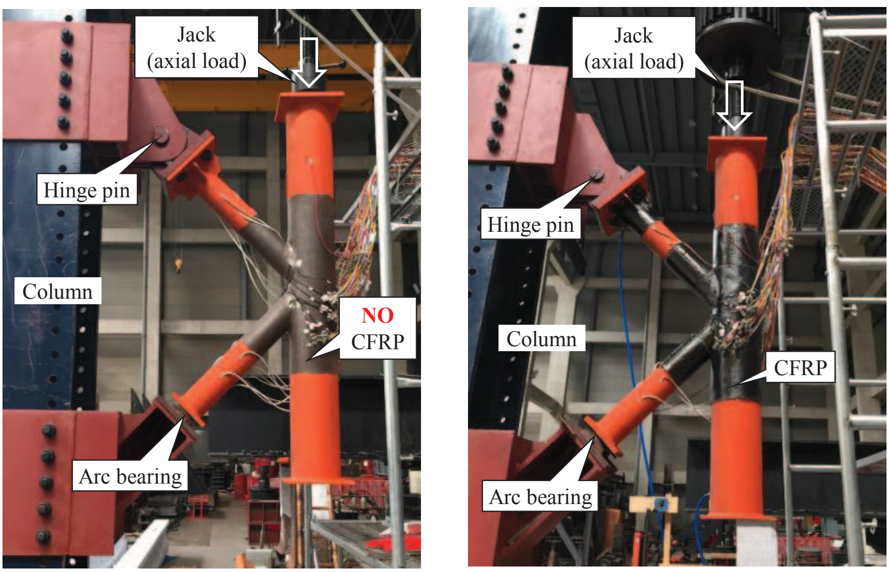


Figure 3. Test setup for hot spot stress of CHS gap K-joint before and after strengthening

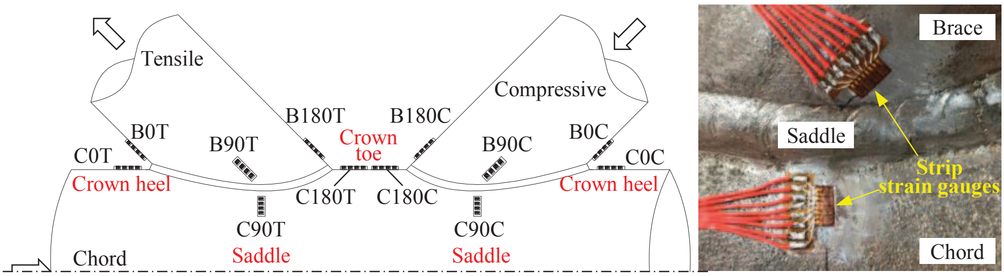


Figure 4. Measuring points for hot spot stress

4 Test results and discussion

Both linear and quadratic extrapolations were performed to determine the measured hot spot strains. It was found that the nonlinearity of the strain (stress) gradient near the weld toe was not significant in the tested CHS gap K-joints. The larger value between the linear and quadratic extrapolation results was adopted (Tong et al. 2017). Then the hot spot strains were converted to hot spot stress by multiplying by a factor of 1.2, which is recommended for tubular joints made of SHS tubes (van Delft et al. 1987). Finally, the hot spot stress was normalized by the nominal stress in the brace to define the stress concentration factor (SCF).

4.1 *Comparison between the unstrengthened and strengthened joints*

Figure 5 illustrates a comparison between the unstrengthened and strengthened joints in SCF. As can be seen from Figure 5, the SCFs of the CFRP-strengthened joints (SCF_{CFRP}) were generally smaller than those of the unstrengthened counterparts (SCF_0). On average, the SCF_{CFRP} was about 20% smaller than SCF_0 for the chord, and about 15% for the brace. Additionally, the reduction was found no significant difference between the cases of tension and compression.

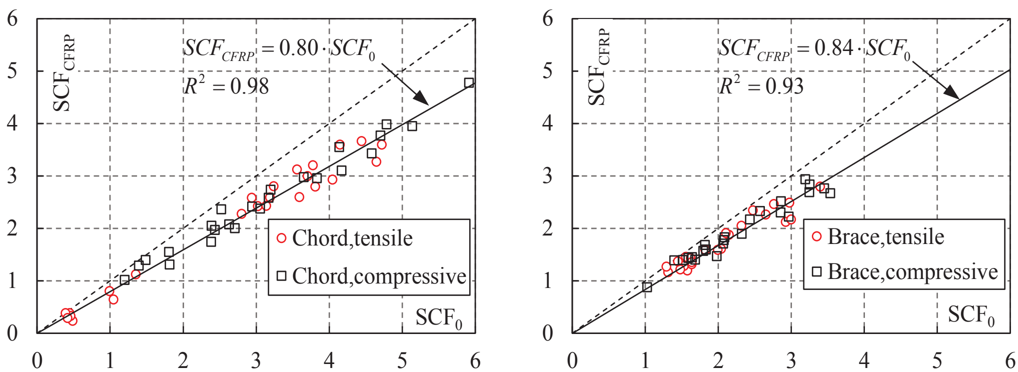


Figure 5. Comparison of SCFs before and after CFRP strengthening

4.2 *Effect of CFRP layers on CFRP strengthening*

Figure 6 illustrates the relationship between the number of CFRP layers and the SCF reduction coefficient ψ, which is defined as the ratio of SCF_{CFRP} to SCF_0. Generally, the SCF reduction coefficients ψ decreases with the increase of n_{cf0} and n_{cf1} within the ranges investigated, i.e. $n_{cf0} \leq 4$ and $n_{cf1} \leq 5$. While for case of crown toe, no significant correlation was found between ψ and n_{cf0}. This is mainly due to the limitation of the current strengthening strategy that the Chord CFRP fails to cover the entire gap region, including the crown toe (see Figure 2).

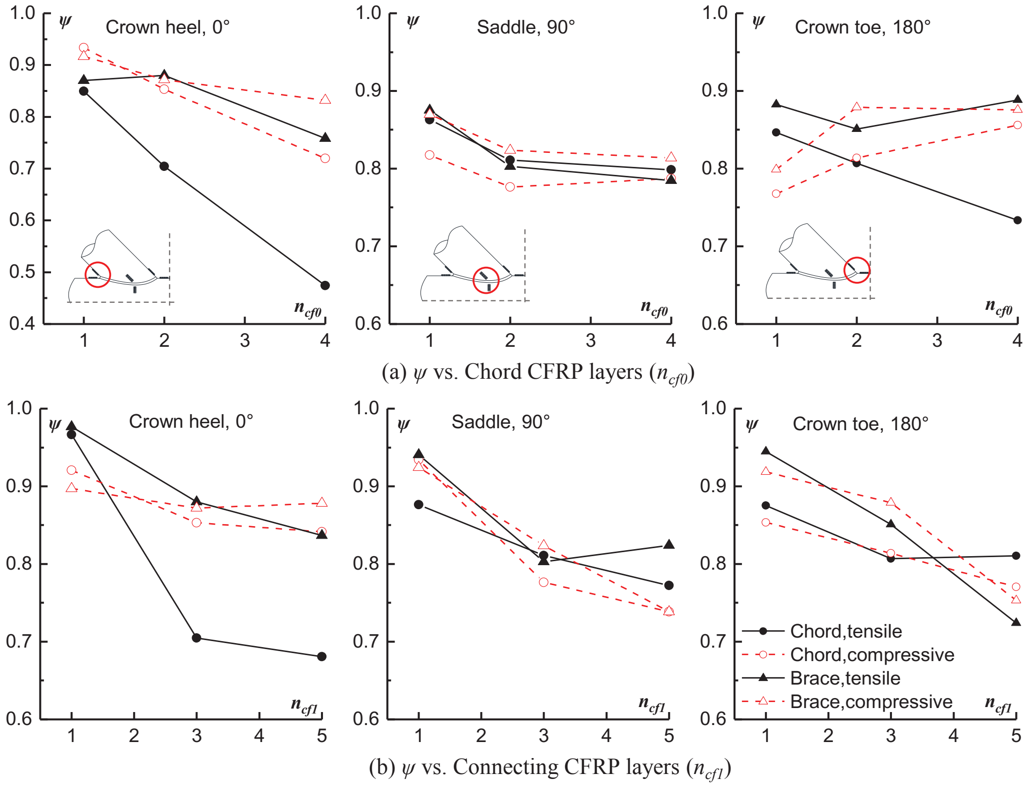
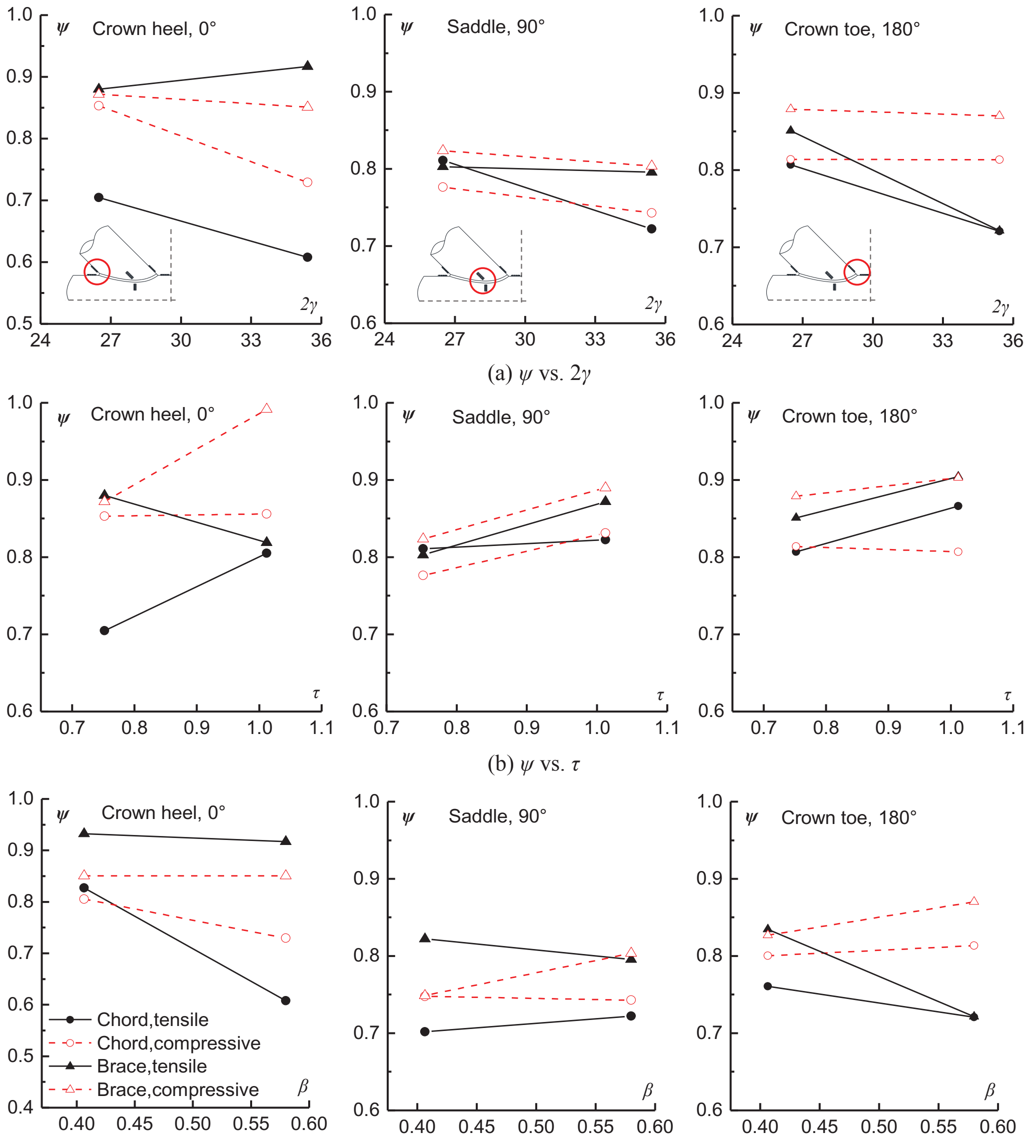


Figure 6. Effect of number of CFRP layers on SCF reduction coefficient ψ.

4.3 *Effect of geometric parameters on CFRP strengthening*

Figure 7 illustrates the effects of the three key non-dimensional geometric parameters on SCF reduction coefficient. From Figure 7 (a) and (b), it can be found that the SCF reduction coefficient slightly decreases with the increase of parameter 2γ, but slightly increases with the increase of parameter τ in most cases. For the examined specimens, i.e. CK1-23, CK2-23 and CK3-23 (see Table 1), the increase of 2γ means thinner chord wall and brace wall, while the increase of τ means thicker brace wall. Hence it can be inferred that the efficiency of CFRP strengthening is actually related to the wall thickness of the tubes of CHS gap K-joints. Specifically, with the same CFRP strengthening parameters, the efficiency of CFRP strengthening in reducing hot spot stress would increases with the decrease of wall thickness of the tubes.

With regard to parameter β, no significant correlation between ψ and β was found in the current experimental results.



(a) ψ vs. 2γ

(b) ψ vs. τ

(c) ψ vs. β

Figure 7. Effect of geometric parameters on SCF reduction coefficient ψ.

5 Conclusions

A strengthening strategy for CHS gap K-joints using both bidirectional and unidirectional CFRP sheets was introduced. A series of CHS gap K-joints were strengthened with CFRP and tested for hot spot stress before and after strengthening. Based on the experimental results, the following observations and conclusions can be drawn:

- The CFRP strengthening strategy can effectively reduce the SCFs of CHS gap K-joints.
- Generally, within the examined CFRP strengthening parameters, i.e. properties of CFRP and adhesive, number of CFRP layers, the SCF was decreased by about 20% for the chord and about 15% for the brace, on average.

- The SCF reduction coefficient ψ was generally negatively related to the number of CFRP layers (i.e. n_{cf0} and n_{cf1}), except for the case of ψ corresponding to crown toe versus n_{cf0}.
- The SCF reduction coefficient ψ was generally positively related to the wall thickness of the tubes in a CHS gap K-joint. Comparatively, parameter β was found no significant correlation with the efficiency of CFRP strengthening.

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