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Experimental Study on Behavior of CFRP-Strengthened Circular Hollow Section Gap K-Joints

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ABSTRACT
A practical technique of Fiber Reinforced Polymer (FRP) application was proposed to promote joint capacity of general tubular K-joints fabricated from circular hollow section members. It consisted of three practical steps and made the best use of both unidirectional and bidirectional FRP materials. Using this technique, three tubular gap K-joints strengthened with Carbon Fiber Reinforced Polymer (CFRP) sheets were tested under static axial force in braces, whilst one additional joint was served as reference joint without CFRP. The results of failure modes, deformation, strain distribution and joint capacity were presented and compared. It was found that performance of tubular K-joints were significantly promoted after CFRP application using the proposed strengthening technique, which demonstrated the substantial contribution from CFRP composites.

KEYWORDS: *Circular hollow section gap K-joints, Carbon Fiber Reinforced Polymer, FRP installation technique, experimental investigation, ultimate capacity*

1. INSTRUCTIONS

Fiber Reinforced Polymer (FRP) has been rapidly spread in the field of civil engineering, due to its excellent mechanical properties, comparing with traditional construction materials, including great durability, high strength-to-weight ratio, ease of installation and shape flexibility [1], which creates significant possibilities to promote ultimate capacity of infrastructures, to extend service life of offshore structures. In particular, because of excellent shape flexibility and corrosion resistance, high efficacy of FRP application has been validated in rehabilitation of tubular metallic structures (mainly for tubular members) by externally bonding FRP on metallic tubes. However, in the case of tubular joints, relevant research on FRP application has not yet been extensive. So far, relevant research of FRP application were within two types of tubular joints: T-joints and K-joints. Both static and fatigue performance of FRP-strengthened/repaired T-joints have been analyzed comprehensively [2-7] by both numerical and experimental investigation. However, as for K-joints, Although FRP installation on damaged tubular K-joints was investigated experimentally[8-10], researchers has rarely reported the effect of FRP application on undamaged tubular K-joints which extremely require rehabilitation because of deterioration, under-strength structural members or increase of load demands. Moreover, it is worthy to mention that, chord plastification and chord punching shear were governing modes for K-joints, and FRP installation technique proposed in Reference[8, 10] may be not efficient for strengthening undamaged tubular K-joints.

In this paper, a practical technique of FRP installation is proposed to strengthen undamaged CHS tubular K-joints. Using this technique, three tubular gap K-joints were wrapped with CFRP sheets differently and tested with static force in braces, whilst another one joint was served as reference specimen for comparison purpose. The results revealed that the proposed FRP installation technique was efficient to promote performance of in-service tubular K-joints.

2. SPECIMENS AND FRP INSTALLATION

2.1 Specimens

Fig. 2.1 shows the dimensions of a CHS gap K-joints, and the shadow region is where FRP is attached. Four specimens were manufactured for testing, as listed in Table 2.1. CFRP were selected to strengthen the joints, because of its relatively higher stiffness than other FRP composites. Specifically, specimen J0 without reinforcement was tested as a reference joint to compare with specimens reinforced with CFRP sheets, that is, J1, J2 and J3. Both layers and length of bidirectional CFRP sheets were selected as variables to investigate their effect on the properties of FRP-strengthened joints. The tubular joint is made of low carbon steel grade Q235B in accordance with Chinese code GB/T700-2006. Both unidirectional CFRP and bidirectional CFRP sheets were applied to strengthen the joints. Table 2.2 gives the material properties of steel Q235B and CFRP sheets.

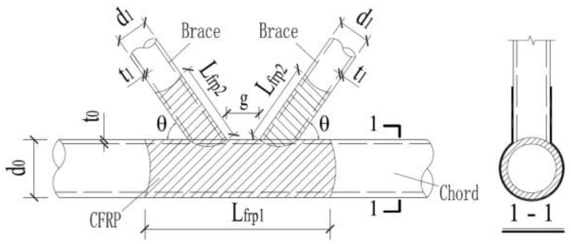


Figure 2.1 Dimensions and parameter definitions of a strengthened gap K-joints

Table 2.1 Test Specimens

Joint	Dimensions of steel tubes				Parameters of CFRP sheets			
					Unidirectional		Bidirectional	
	$d_0 \times t_0$ (mm)	$d_1 \times t_1$ (mm)	θ (degree)	g (mm)	Layer	L_{frp2} (mm)	Layer	L_{frp1} (mm)
J0	219 × 8	133 × 6	55	40	0	0	0	0
J1					3	300	4	600
J2							2	1000
J3							4	1000

Table 2.2 Material properties of steel and CFRP sheets

Material	Thickness t(mm)	Modulus E(GPa)	Yield Strength f_y(MPa)	Tensile Strength f_u(MPa)
Steel Q235B	/	206	310	480
Bidirectional CFRP	0.167	297	/	2373
Unidirectional CFRP	0.211	134	/	1649

2.2 CFRP Installation

Before applying CFRP to the joints, the surfaces of the brace and chord were sandblasted and cleaned with acetone, hence, promoting bond conditions between CFRP and steel. The clean dry brush was finally applied to remove dust. A practical technique of FRP installation was proposed here, consisting of three major steps.

1) Several layers of bidirectional CFRP sheets were applied over the bonding area of the chord, keeping one direction of the fibers parallel with axis of the chord, as shown in Fig. 2.2. In this way, CFRP sheets confined radial deformation of the chord, and hence, delaying the failure mode of chord plastification.

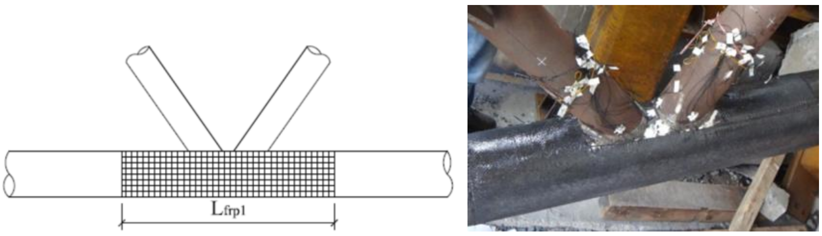
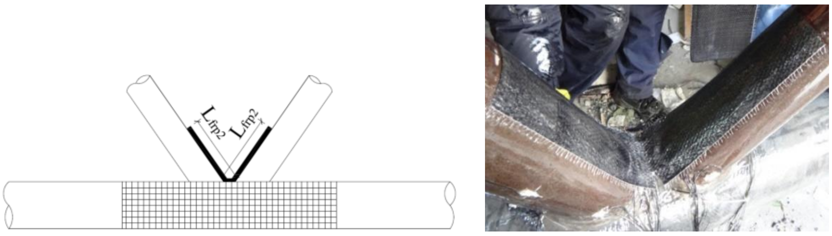


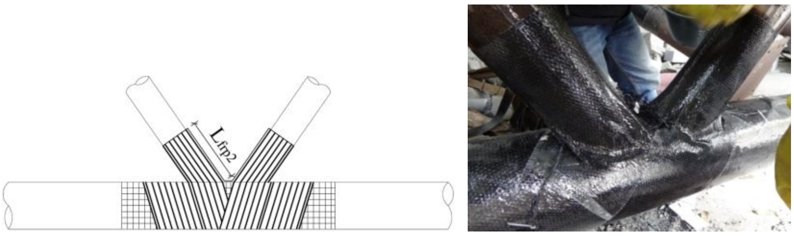
Figure 2.2 First step of CFRP Installation

2) Unidirectional CFRP sheets were wrapped over both braces and chord, keeping direction of the fibers parallel with axis of braces. In detail, one patch of unidirectional CFRP sheet was attached to two braces, in order to

enhance the connection between two diagonal braces, as shown in Fig. 2.3(a). Subsequently, four patches of unidirectional CFRP sheet were wrapped over the chord. One end of each patch was anchored on one brace, and the other end was anchored on chord, as shown in Fig. 2.3(b). In this way, unidirectional CFRP sheets delay the failure mode of chord punching shear by enhancing the connection between braces and chord.



(a) CFRP sheets attached to two braces



(b) CFRP sheets wrapped to brace and chord
Figure 2.3 Second step of CFRP Installation

3) Unidirectional CFRP sheets were wrapped around the braces and chord respectively for three rounds (Fig.2.4), so that CFRP sheets in previous steps were confined well. After all the steps have been completed, the specimen was cured for over two weeks before test.

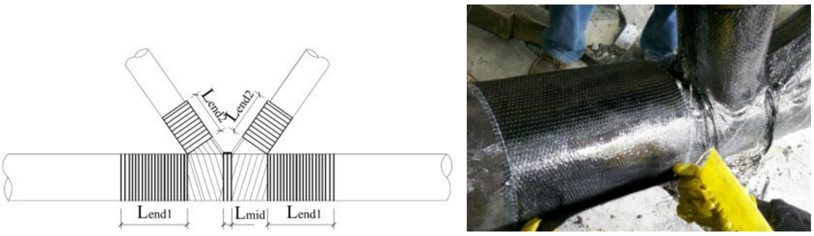


Figure 2.4 Third step of CFRP Installation

2.3 Test Setup and Procedure

Fig. 2.5 shows the test set up, which was located at State key laboratory for Disaster Reduction in Civil Engineering in Tongji University, China.

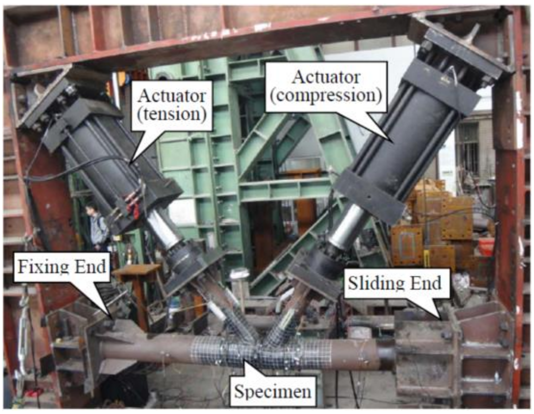


Figure 2.5 Test setup

Each specimen was fixed-supported at one end of the chord and sliding-supported at the other end. Two actuators were used to provide force so that one brace of the specimen was under axial tension and the other brace was under axial compression, simultaneously. On each specimen, 16 uniaxial strain gauges were installed near the ends of tubes to help check loading conditions and boundary conditions. 4 rectangular strain gauge rosettes were applied on steel substrate along intersecting lines of the joints, so as to record distribution of stress and development of plastic zones in each specimens. Additionally, 7 linear variable differential transformers (LVDT) were installed to measure deformation and relative displacement between selected points.

3. TEST RESULTS AND DISCUSSION

3.1 Experimental phenomenon and failure mode

Fig. 3.1 exhibits the failure states of J1, which was the representative of CFRP-strengthened tubular joints, to compare with performance of J0 which was reference joint without CFRP sheets. Both in J0 and J1, chord plastification was first observed. Subsequently, a large crack occurred along intersection between chord and the brace under tension. However, ovalization and permanent deformations of J1 was much smaller than that of J0. It indicates that CFRP sheets do not change or prevent the primary failure modes of the tubular joints but effectively delayed the development of failure mode. Additionally, observed initial CFRP composite failure of J1, J2 and J3 was at 85%, 74% and 88% of the ultimate load, respectively, which illustrates the contribution of CFRP sheets to joint capacity. Experimental phenomena was recorded sequentially in Fig. 3.2.

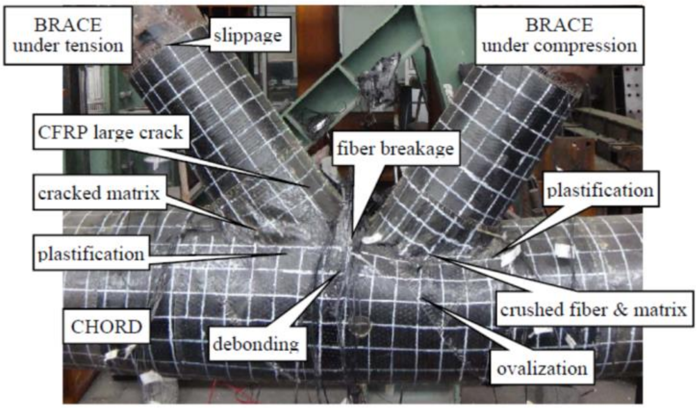


Figure 3.1 Failure mode of J1

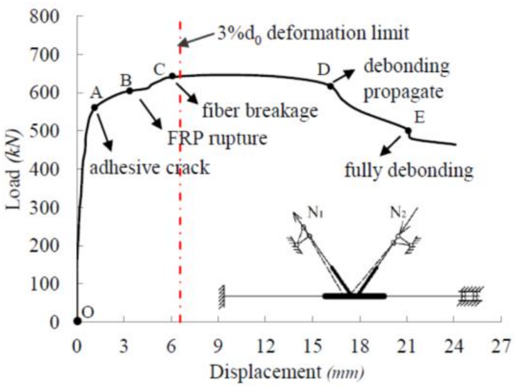


Figure 3.2 Typical experimental phenomena of J1

3.2 Load-displacement and ovalization

Fig. 3.3 exhibits the load-displacement experimental curves of four specimens. Load bearing capacity of the specimens were determined by comparing ultimate strengths with ultimate deformation limit (i.e. 3% the CHS connecting face diameter), as per CIDECT [11]. In detail, peak load of the curves was picked to be served as ultimate strengths. Besides, the averaged displacement recorded from LVDTs was subtracted by axial deformation of braces between two ends of each LVDT. As shown in the figure, 4 layers of bidirectional CFRP sheets helped both J1 and J3 to obtain almost 20% increase in the peak-load, whilst J2 only obtained 8.5% increase due to fewer layers of bidirectional CFRP sheets. As shown in Fig. 3.4, CFRP sheets effectively reduced the ovalization deflection of tubular joints. It can be demonstrated that both layers and length of bidirectional CFRP sheets can help to reduce ovalization effectively.

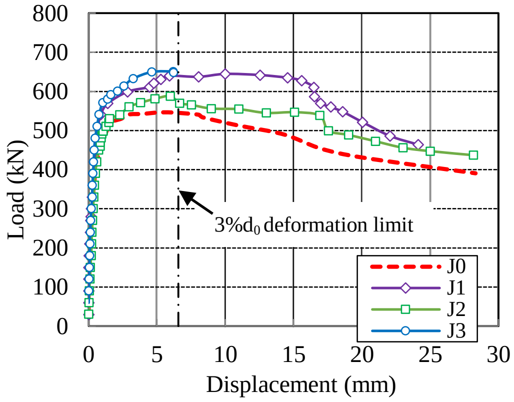


Figure 3.3 Load-displacement curves

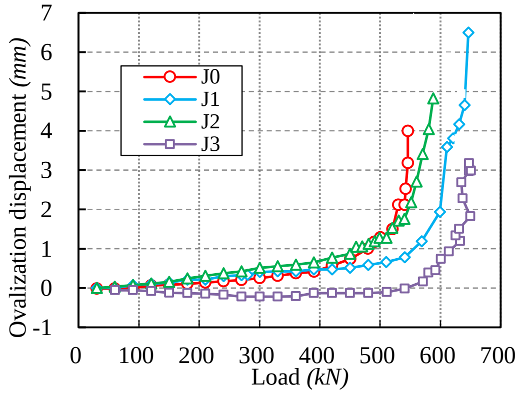


Figure 3.4 Load-ovalization curves

3.3 Strain distribution

Strain intensities of steel substrate were collected from four rosettes that were installed around intersection lines of each specimen. By observing the curves in Fig. 3.5, it can be concluded that CFRP sheets helped to reduce stress concentration efficiently, which is highly promising to increase fatigue life of the joints. Also, CFRP sheets reduced the strain magnitude a lot and delayed the yielding of steel substrate, hence, hindering the development of chord plastification in joints, which helps the joint to obtain a higher load bearing capacity.

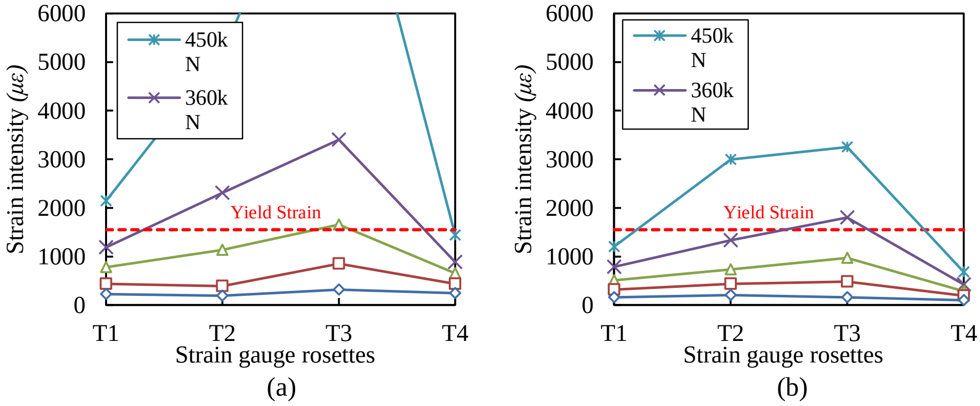


Figure 3.5 Strain intensity distribution in specimens: (a) J0 (b) J1

3.4 Ductility and strength redundancy

Experiment data was further analyzed for ductility and strength redundancy, which were both important indexes of joint capacity, as provided in Table 3.1. Specifically, ductility was evaluated by calculating the ratio of ultimate deformation (δ_u) to yield deformation (δ_y). Similarly, strength redundancy was based on the ratio of ultimate strength (N_u) to yield strength (N_y). In detail, N_u was defined as the load bearing capacity of a joint, and corresponding deformation was δ_u. As presented in the table, CFRP sheets had promoted ductility of the tubular joints evidently. This promotion was more significant for braces under tension of J1 and J3, so that ultimate deformation limit prevailed the occurrence of the ultimate strength, as highlighted in bold in Table 3.1. However, it seems abnormal that J2 had less ductility than the reference specimen. This may due to problems of poor manufacturing or the processing of CFRP installation. Moreover, effect of CFRP sheets on increasing strength redundancy was also observed in terms of braces under compression, whilst this effect was not evident in terms of braces under tension.

Table 3.1. Ductility and estimated strength redundancy of tubular gap K-joints

Joint	Ductility comparison						Strength redundancy comparison					
	Brace under compression			Brace under tension			Brace under compression			Brace under tension		
	δ_u (mm)	δ_y (mm)	δ_u / δ_y	δ_u (mm)	δ_y (mm)	δ_u / δ_y	N_u (kN)	N_y (kN)	N_u / N_y	N_u (kN)	N_y (kN)	N_u / N_y
J0	5.11	0.66	7.74	2.81	0.60	4.68	542	431	1.26	542	426	1.27
J1	5.91	0.52	11.36	**6.57**	0.42	15.64	646	450	1.44	**623**	479	1.30
J2	5.97	0.63	9.48	1.83	0.48	3.82	588	440	1.34	588	480	1.22
J3	6.19	0.46	13.46	**6.57**	0.33	19.91	651	480	1.36	**640**	522	1.23

4. CONCLUSIONS

The following conclusions were made, based on the investigation results throughout this paper.
1) An efficient technique of FRP installation was proposed and validated to strengthen undamaged tubular K-joints of in-service structures. It was aimed to delay the governing failure mode of chord plastification and chord punching shear, which consisted of three practical steps and made the best use of both unidirectional and bidirectional FRP materials.
2) Performance of tubular K-joints were significantly promoted after CFRP application using the proposed strengthening technique. In summary, governing failure modes was efficiently hindered but not prevented; ultimate strength capacity of tubular joints was enhanced a lot; deflection and ovalization effect was reduced; stress distribution was both improved and decreased; Ductility and strength redundancy was increased.
3) Failure modes of CFRP composite, such as adhesive crack and fiber breakage, were recorded and summarized. Specifically, CFRP composite helped the joints to bear external load without any sign of failure until about 80% of peak load.

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