# REINFORCING CORRODED CHS JOINTS WITH HYBRID FRP-UHPC COVER

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For tubular structures in marine or coastal areas, the corrosion risk is an unavoidable issue that threatens the safety of the structures. The restoration of such structures is not so easy, since the high complexity of the structure layout, especially for the joint area with several intersecting tubular elements. The hybrid fibre-reinforced polymer(FRP) and ultra-high performance concrete(UHPC) is introduced to reinforce the rusty circular hollow section (CHS) joint, by which the FRP plays as the outer cover to confine the infill concrete as well as to prevent further corrosion of the joint, and the UHPC filled between the FRP and the chord to increase the rigidity of the chord wall along the radius direction. The design of the hybrid reinforcing method is presented, and a series of parametric analyses is done to improve the configuration of the FRP and the UHPC. It was found that the proposed hybrid method is effective to reinforce the compressive strength of rusty CHS T-joints, the reinforcing efficiency is determined by the thickness of FRP tube and UHPC layer. For hybrid restored joints with thicker restoration cover, the sandwich structure leads to a high joint strength and rigidity.

*KEYWORDS*: Corroded; CHS joints; reinforcing; hybrid; FRP; UHPC

## 1 Introduction

The circular hollow section (CHS) tubular steel joints in coastal areas always face with the threat of corrosion, which reduce the strength, plasticity and other mechanical indicators of the joints (Teixeira 2017; Yang 2019). Therefore, the restoration of rusty steel CHS structures and joints is essential to gurantee the structural safety as well as to elonganate the service life of the structure.

The fibre-reinforced polymer(FRP)-concrete-steel double-skin tubular members(DSTM) initiated by Yu (2006) and Teng (2007) have been widely used in reinforcement owing to convenient construction and prominent strengthening effect. Applying this hybrid DSTMs to rusty joints restoration might not only improve the bearing performance of the defective steel members, but also avoid the potential corrosion in the future (Teng 2007). Zhang (2017) found that hybrid double-skin tubular columns(DSTCs) process excellent ductility than normal concrete even when high-strength concrete(HSC) is used. Idris(2014) conducted an experimental study on the flexural behavior of FRP-HSC-steel composite beams, by which the double-skin tubular beams (DSTBs) exhibit excellent load–deflection behaviors with high inelastic deformations and minimal strength degradations. However, relatively large slips were found at the concrete–steel tube interface of DSTBs, except when the interface bond is enhanced by mechanical connectors. Zhao(2016) presented the experimental study on large-scale hybrid DSTBs, and proved that headed shear studs are effective to ensure the composite action between the chord and the concrete.

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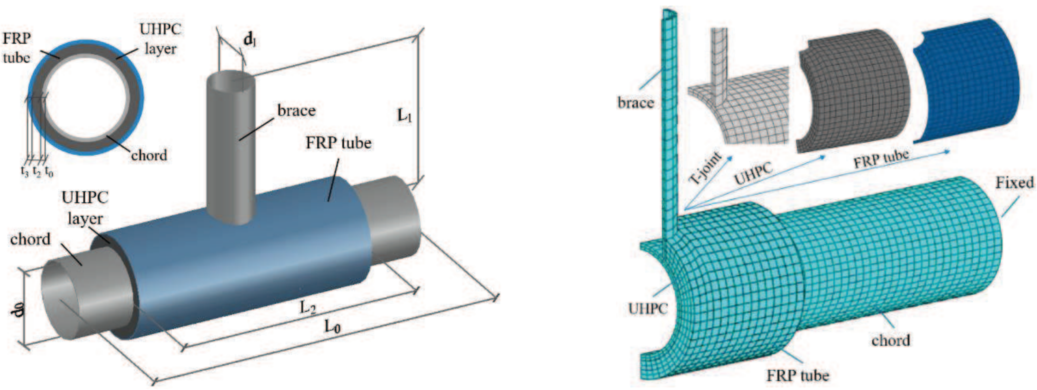
Although the research on compressive columns or flexural beams reinforced with hybrid DSTMs are abundant, the application of DSTMs for the reinforcement of CHS steel joints was seldom reported. To reinforce the corroded CHS steel joints as well as to prevent further corrision, a hybird method is introduced to restorate the joint, The configuration of the hybrid restoration methodology is shown in Fig.1(a), in which the FRP tube along with the ultra-high performance concrete(UHPC) sandwhich is used to wrap the chord at the intersection area.

Considering the local bearing characteristics of the joint is different from the global load bearing performance of the column and beam, the behavior of the FRP-UHPC reinforced joint under brace compression need to be further clarified. To this end, the restoration effect of hybrid cover on the corroded CHS T-joints under brace compressive loading is evaluated in this paper. A series of finite element models are established and verified by existing experimental results. The design of the hybrid FRP-UHPC cover is optimized by a series of finite element parametric analysis, including the corrosion level, the section configuration, the concrete strength, and the geometric size of the FRP tube. The role of the hybrid FRP-UHPC cover is discussed and the failure modes of the restored CHS joints under brace compressive loading are summarized. Finally, the application range of the hybrid FRP-UHPC cover for joints with different corrosion degree are proposed.

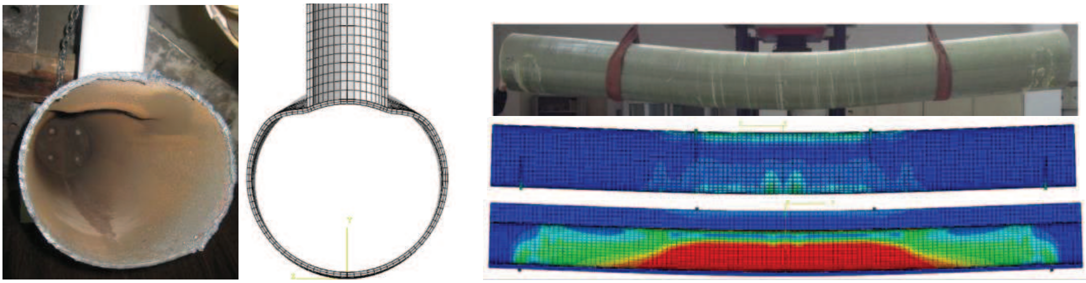



(a). Configuration of hybrid cover T-joint (b). 1/4 FE model meshing

Fig. 1 Details of hybrid FRP-UHPC cover restored T-joint

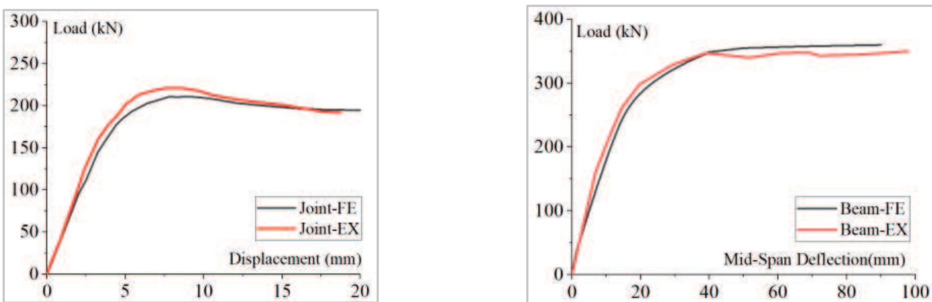
## 2 Numerical Model and Experimental Validation

The finite element (FE) package ABAQUS is adopted to simulate the aforementioned hybrid FRP-UHPC cover restored CHS joints. The solid element C3D8R is used to model the tubular and the UHPC, while the shell element S4R is used to model the FRP tube. Between the chord and the UHPC, the Mohr–Coulomb friction model is applied in the tangential direction, while the “Hard contact” is used in the normal direction for the contact. The meshing of the restored joint is shown in Fig. 1 (b), in which a quarter of the joint is modeled to save computing time (Chang &Xia 2014). To evaluate the reliability of the model, the experimental specimens of unreinforced T-joint by Lesani(2014), and hybrid FRP-concrete-steel double-skin tubular beam by Zhao(2016) are quoted for comparison. The geometric parameters, the material properties and the test setups can be found in literature Lesani(2014) and Zhao(2016). The reliability of the numerical model is validated from two aspects, namely the failure modes and the load-displacement curves. As shown in Fig. 2, the numerical results agree well with the failure modes of the experimental tests. By further comparing the load-displacement curves in Fig. 3, it can be found that the FEM curves fit well with that of the experiments. Thus, the accuracy of the FE model is satisfactory.



(a). Unreinforced T-joint (b). Hybrid FRP-concrete-steel DSTB with shear connectors

Fig.2 Comparisons of the failure modes




(a). Unreinforced T-joint (b). Hybrid reinforced beam

Fig.3 Comparisons of the load-displacement curves

## 3 Parameter Analysis

### 3.1 *Parametric Study Strategy*

To further understand the mechanism of the hybrid FRP -UHPC cover for the restoration on CHS joints, the aforementioned FE models are expanded for parametric analysis.The yield strength of the steel is 345 N/mm$^2$, the elastic modulus and poisson ratio of the steel tube is $E$=210,000 N/mm$^2$, $\mu$= 0.3. The material properties of the FRP and UHPC are quoted from Lesani (2013) and Zhou(2018), respectively. For the FRP, the "Hashin" damage criteria was utilized for strength assessment(Lesani 2013; Lesani 2014). The compressive load was applied from the brace end and the two ends of the chord were pin restrainted (Nassiraei 2016). Preliminary analysis demonstrates that the corrosion degree, and the geometry of the FRP and UHPC are key parameters that dominate the performance of members (Teixeira 2017; Yu 2006; Teng 2007). Thus the section loss ratio of the chord $\Delta$, the thickness of the UHPC $t_2$, and the thickness of the FRP tube $t_3$, and the length of UHPC $L_2$ are determined as the main paramenters and changed as shown in Table 1.

Table 1 Parametric matrix of restored T-joints

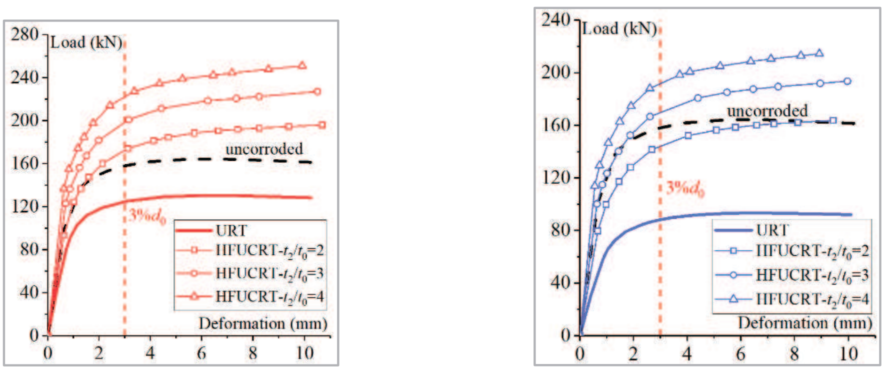
| Description | Parameter | Benchmark | Expand |
|---|---|---|---|
| the section loss ratio of the chord-(the thickness of the rusty chord) | $\Delta$-($t_0'$ )(mm) | 0%-(7) | 15%-(6), 30%-(5) |
| the thickness of the FRP tube | $t_3$ (mm) | 2 | 4, 6 |
| the thickness of the UHPC | $t_2/t_0$ | 3 | 2, 4 |
| the length of the hybrid FRP -UHPC cover | $L_2/d_1$ | 6 | 4, 8 |

Where $t_0'$: the actual thickness of the chord; $t_0$: the thickness of the chord before corrosion; $t_2$: the thickness of the UHPC; $d_1$: the diameter of the brace; $L_2$: the length of the hybrid FRP -UHPC cover.

### 3.2 *Influence of the Thickness of the UHPC*

The section loss ratio Δ, namely the loss rate of the chord section area after corrosion, is adopted to measure the corrosion degree of the chord. When $t_0'=t_0$ =7mm, Δ=0%; when $t_0'$=6mm, Δ=15%; and when $t_0'$=5mm, Δ=30%. The load-deformation curves for unrestored T-joints(URT) and HFUCRT with different Δ are shown in Fig. 4. It can be seen that the compressive strength of the joints decreased significantly as the corrosion degree increased. For example, when Δ increased from 0 to 30%, the ultimate strength of the T-joint declined 44%.

The hybrid FRP -UHPC cover can effectively fetch up the compressive performance degradation owing to corrosion. According to Fig.4 (a-b), when $t_2/t_0$ =3, the ultimate strength increased 60% and 94% respectively, comparing with URT with Δ=15% and Δ=30%. On the other hand, the restoration efficiency increased as the thickness of the UHPC increased. For example, when Δ=15%, the ultimate strength of HFUCRT augmented 29% when $t_2/t_0$ rose from 2 to 4. Meantime, the ultimate strength of HFUCRT with $t_2/t_0$=4 was 41% higher than uncorroded URT. Therefore, a thicker UHPC results in a stronger restored joint, which might be even stronger than the original uncorroded one.




(a). Restored joints with Δ=15% (b). Restored joints with Δ=30%

Fig.4 Influence of the Corrosion Degree of the Chord

### 3.3 *Influence of the Thickness of the FRP Tube*

To further understand the role of the thickness of the FRP tube to increase the strength of the corroded joint, the parameter $t_3$ was changed. A thicker FRP tube create a firmer restraint on the UHPC sandwhich, hence to improve the compressive performance of the joint. As shown in Fig. 5, when $t_3$ was increased from 2mm to 6mm, the ultimate load increased 19.4% and 20.2% respectively for HFUCRT with Δ=15% and Δ=30%. In addition, when Δ=15%, the compressive strength of HFUCRT with $t_3$=6mm was 56% higher than the uncorroded joint.

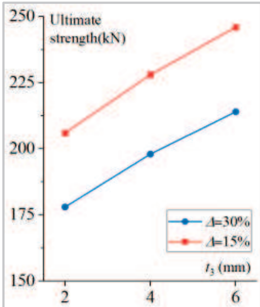



Fig.5 Influence of the Thickness of the FRP Tube

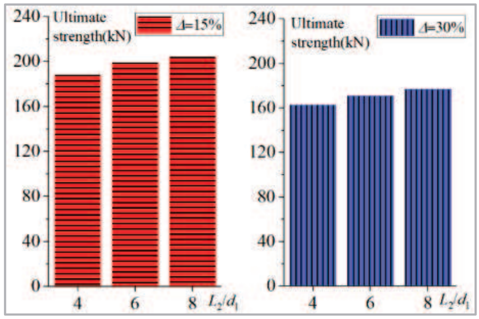



Fig.6 Influence of the length of the hybrid FRP -UHPC cover

### 3.4 *Influence of the length of the hybrid FRP -UHPC cover*

Fig. 6 demonstrates the influence of the length of the hybrid FRP -UHPC cover on the ultimiate strength of the HFUCRT. It can be seen that the length of the hybrid cover has little influence on the strength of the HFUCRT. When $L_2/d_1$ increased from 4 to 8, the ultimate strength of restored joints with Δ=15% and Δ=30% improved 8.6% and 8% respectively. Thus, it is unnecessary to lengthen the hybrid cover. Considering the bonding effect between rusty tubular and hybrid cover, the minimum length of the restoration cover set as $L_2/d_1$=6 is enough.

## 4 Reinforcement mechanisms

Fig. 7 illustrates the deformation and stress distribution of the HFUCRT. The ovalization of the chord at the brace-chord intersection area was delayed by the restraint of the hybrid cover. As shown in Fig. 7, a local sandwhich structure is formed by the restoration, and the FRP-UHPC cover deformed cordinately with the chord as brace compression load is applied. Meantime, the FRP-UHPC cover share the stress with the steel tubular. Thus, the deformation of the joint is reduced and the ultimate strength is enhanced.

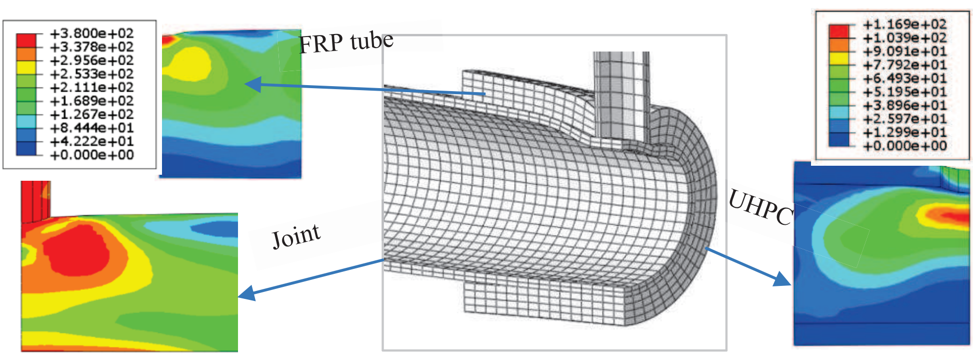



Fig. 7. Deformation and stress distribution of the HFUCRT

## 5 Conclusion

The hybrid FRP-UHPC cover is introduced into rusty CHS T-joint restoration. A series of finite element parametric analysis is conducted to understand the effect of hybrid FRP-UHPC cover reinforcement on the compressive behavior of the corroded CHS T-joints. The role of the hybrid