FEASIBILITY OF WRAPPED FRP CIRCULAR HOLLOW SECTION JOINTS

PEI HE[1] and MARKO PAVLOVIC[2]

[1]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Postbus 5, 2600 AA Delft, the Netherlands*
E-mail: P.He@tudelft.nl

[2]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Postbus 5, 2600 AA Delft, the Netherlands*
E-mail: M.Pavlovic@tudelft.nl

The concept of an innovative fiber reinforced polymer (FRP) joining technology by wrapping is presented as an alternative to traditional welding technology to connect circular hollow section (CHS) braces (diagonals) to chords. The aim is to considerably enhance fatigue endurance and corrosion resistance of tubular hollow section joints used in off-shore or hydraulic structures, and steel bridges. Small-scale wFRP uniaxial and X-joints are tested with monotonic tensile and cyclic loading. Digital Image Correlation (DIC) technique is used to measure displacements and strains in order to support hypotheses of joint mechanical behavior. The wFRP joint is created by glass fiber reinforcement mixed with thermoset resins wrapped around the zone of the joint between the braces and the chord. The testing results are satisfactory and promising, indicating that high strength steel (HSS) improves the static behavior of wFRP joints; the challenging angle does not jeopardize but has a favorable influence on the static and dynamic behavior of wFRP X-joints. Further research need to be conducted to prove long-term behavior of the innovative joints under permanent loading and harsh marine environment in off-shore application.

Keywords: FRP, CHS, wrapped joints, off-shore, fatigue endurance, DIC

1 Introduction

Circular hollow sections (CHS) are extensively used in off-shore structures, hydraulic structures and steel bridges, as shown in Figure 1, due to excellent durability and high cost efficiency (Wardenier 2010). However, application of CHS is significantly hampered by the design, execution and fatigue endurance of joints. In the traditional design method of CHS joints, the brace and chord members are connected through welding technology and mild steel (MS) is utilized as fabrication material.

Jacket off-shore supporting structures and steel truss in bridges are subjected to heavy and cyclic loading, requiring excellent fatigue endurance of the joints. Unluckily, application of welding reduces fatigue resistance of CHS joints compared to the single member. Main reasons are reduced fracture toughness of the material in the heat affected zone of the weld, and stress concentration resulted from weld eccentricity and local weld geometry. Furthermore, welding costs are predominant in fabrication of off-shore jacket supporting structures.

Utilization of high strength steel (HSS) makes it possible to reduce thickness of joint members, thus decreasing self-weight of off-shore jacket structures and realizing longer spans of

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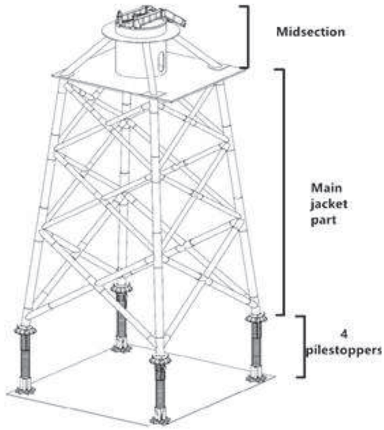
steel bridges. However, due to limited fatigue endurance of welded CHS joints, thicker profile is indispensable and employment of HSS is hindered.

To reach full application potential of CHS, the concept of an innovative fiber reinforced polymer (FRP) joining technology is proposed as an alternative to traditional welding technology, as shown in Figure 2. CHS brace members (diagonals) and chord members are bonded together by FRP wrapping. Superiority of using FRP composite material to create transition pieces between steel members is that they can be shaped in an optimal manner to decrease stress concentration at the bonded interface. Furthermore, extremely thin bond lines can be achieved through direct contact between steel surface and FRP wrapping, reducing the risk of cohesive failure of wrapped FRP joints. Fatigue endurance of wFRP CHS joints is expected to improve considerably compared to welded ones due to complete prevention of welding. Corrosion resistance is also enhanced because corrosion critical region of the joint is protected by FRP wrapping.



a) Off-shore wind turbine jacket supporting structures

b) Support structures of hydraulic barriers

c) Truss steel bridges

Fig 1. Engineering application of CHS

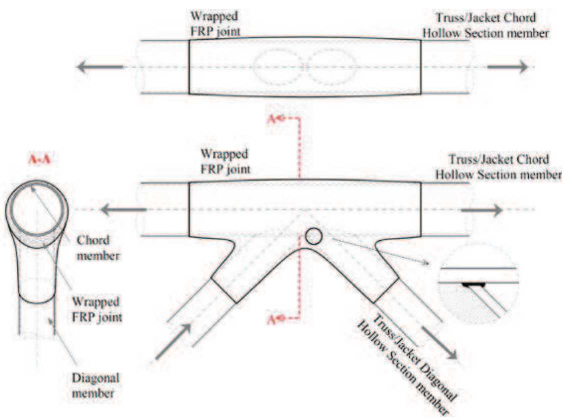


Fig 2. General configuration of the wrapped FRP joint – an example of K-joint geometry for CHS members

2 State of the Art

Fiber reinforced polymers (FRP) consist of continuous high strength fibers embedded in a polymer matrix (Mallick 2007). The most commonly used fibers are glass fibers, carbon fibers, and aramid fibers, while thermoset polymers, e.g. unsaturated polyesters, epoxy resins and vinyl ester resin, are normally selected as matrix material. The strength and stiffness of FRP laminate are dependent on fiber orientation and fiber volume fraction. Fiber Reinforced polymers (FRP) have been proved to be effective to rehabilitation, retrofit and upgrade of timber, masonry and concrete structures in civil engineering field. Interest has increased considerably with regard to application of FRP on retrofitting of steel structures, e.g. steel girders, pipelines and hollow sections, etc. (Hollaway 2002, Shaat 2004, Zhao 2007). However, the majority of studies are limited to strengthening of steel members.

Recently, strengthening of welded tubular joints by FRP have been investigated by several authors. Jiao and Zhao (2004) investigated the behavior of carbon fiber reinforced plastics (CFRP) strengthened butt-welded very high strength (VHS) circular steel tubes, and a significant strength increase was achieved using CFRP–epoxy strengthening technique; Xiao and Zhao (2012) successfully increased flexural stiffness and fatigue life of cracked RHS-to-RHS T-connection repaired by CFRP; Aguilera and Fam (2013) successfully utilized bonded FRP plates to strengthen welded rectangular hollow section T-joints against web buckling induced by transverse compression; Lesani, Bahaari and Shokrieh (2013, 2014 and 2015) compared numerical and experimental results of FRP strengthened and un-stiffened tubular welded T/Y joints under axial compressive loads, showing that FRP wrapping has significant influence on the ultimate load capacity of the connections and has considerably improved connection behaviour; Hosseini, Bahaari and Lesani (2019) investigated stress concentration factors (SCF) in FRP strengthened tubular T-joints subjected to brace axial loading, in-plane and out-of-plane bending moments, and concluded that FRP strengthening method is effective to reduce the SCFs and consequently extend the fatigue life cycle of tubular T-joints.

A new idea of non-welded structural hollow section joints adhesively bonded by FRP has been proposed by Pavlovic (2018), followed by preliminary experiments and comparison of mechanical behaviour between wrapped FRP CHS uniaxial and X90 joints, and welded ones, aiming to gain understanding of the new joint and propose future recommendations.

3 Small-scale experiments set-up

The small-scale experiments are conducted in Stevin Lab Ⅱ of TU Delft - CiTG, to validate feasibility of the concept of wrapped FRP joints, following the preliminary work conducted by

Pavlovic (2018). This main goal can be further divided into three objectives:

(i) to understand the effect of high strength steel (HSS) on the static behavior of wFRP uniaxial joints;
(ii) to investigate the influence of angles on the static behavior of wFRP X-joints;
(iii) to further characterize the fatigue behavior of wFRP X-joints and show it's favorable performance over welded CHS joints.

The tested CHS joints are mainly two small-scale specimen types: (1) uniaxial joints of HSS and (MS) hollow section Φ63.5×3.6 mm; (2) X45 and X30 joints of MS Φ60.3×4 mm brace members and Φ108×5 mm chord members. The joints are connected by wrapping around the connection area with glass fiber reinforcement and thermoset polymer resin. The series and geometry of the joints are shown in Figure 3.

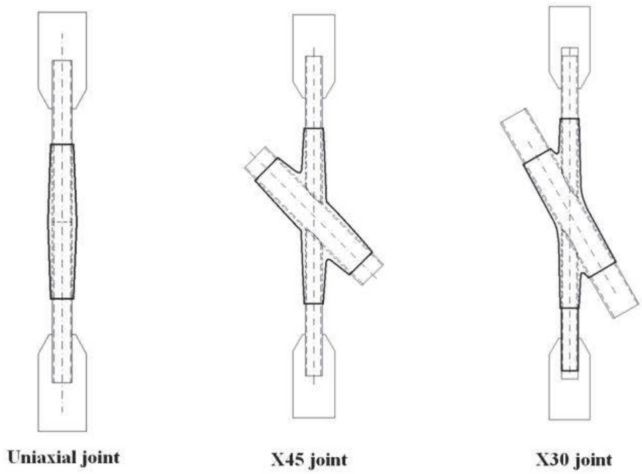


Fig 3. Series and geometry of small-scale wrapped FRP joints

Monotonic static loading and cyclic loading are applied to series of specimens in displacement and load control regime, respectively. Digital Image Correlation (DIC) method is utilized to improve displacement and strain measurement feasibility.

4 Discussion of the Results

Firstly the static experimental results of uniaxial joints are presented. Three specimens with HSS (S690), labelled as Pi 6-1, Pi 6-2, Pi 6-3, and three specimens with (MS) (S355), labelled with Pi 5-1, Pi 5-2, Pi 5-3, are loaded with monotonic tensile force until failure. The corresponding testing results are shown in Figure 4 and Figure 5.

Figure 4 shows that HSS considerably enhances static behavior of wFRP uniaxial joints, with both average linear load limit and tensile strength improved by 49% and 75%, respectively, compared to MS specimens. HSS specimens show more brittle behavior, with the failure displacement 30% lower than for MS specimens. This is in agreement with the behavior of HSS vs. MS material. The ductility of the wrapped FRP joints with HSS still shows quite ductile behavior for an bonded joint.

From the curves of MS specimens, apparent constant load plateau can be observed, with corresponding tensile stress in CHS equal to 428 MPa (290 kN/677.45 mm^2). This stress level corresponds to yield strength of the tested CHS profiles which is higher than nominal value for S355 material. Therefore, load plateau of the wrapped FRP joint with MS is caused by yielding of MS CHS outside the wrapped joint region. This is confirmed by large strain on two sides of the joint shown in Figure 5a as major strain form DIC results, at the loading stage just before the final failure. Relatively large plastic yielding strains of approx. 4-5% at the FRP-steel interface trigger the final debonding failure of the joint, see Figure 5c.

Results of DIC on HSS specimens in Figure 5b show that the yielding of steel outside the wrapped region does not happen. The major principal strain is distributed gradually over the region of FRP wrapping right before the failure. The specimen fails due to delamination of the FRP laminate near the edge of the wrapping area, i.e. the cyan ring at the right-hand side end of the wrapping in Figure 5b. The failure path is indicated by solid lines in Figure 5d. The delamination initiates near the edge of the wrapping developing further through the plies toward the FRP-steel interface at the connection of two CHS profiles in the middle. The ultimate load of

HSS specimens correspond to stress of 812 MPa in CHS profiles which is close to ultimate strength of the S690 material.
The conclusion is that for MS and HSS the yielding and ultimate resistance of the CHS profiles, respectively, can be achieved by uniaxial wrapped FRP joints.

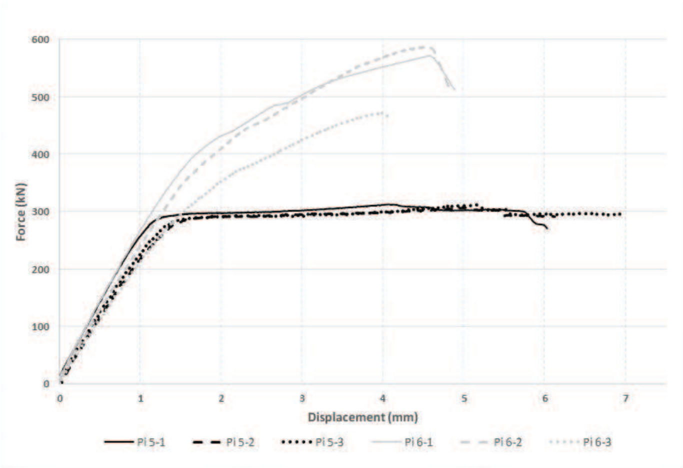
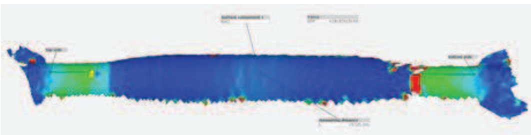
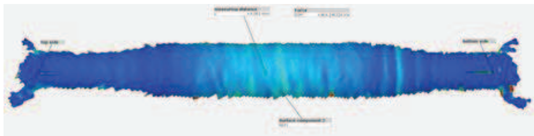


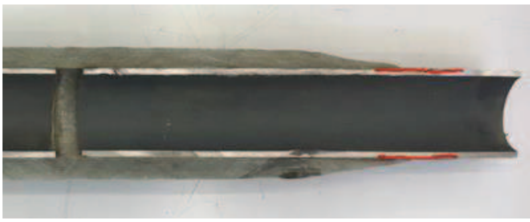
Fig 4. The force-displacement loading curve of wrapped FRP uniaxial joints



a) Major strain distribution of the MS specimen



b) Major strain distribution of the HSS specimen



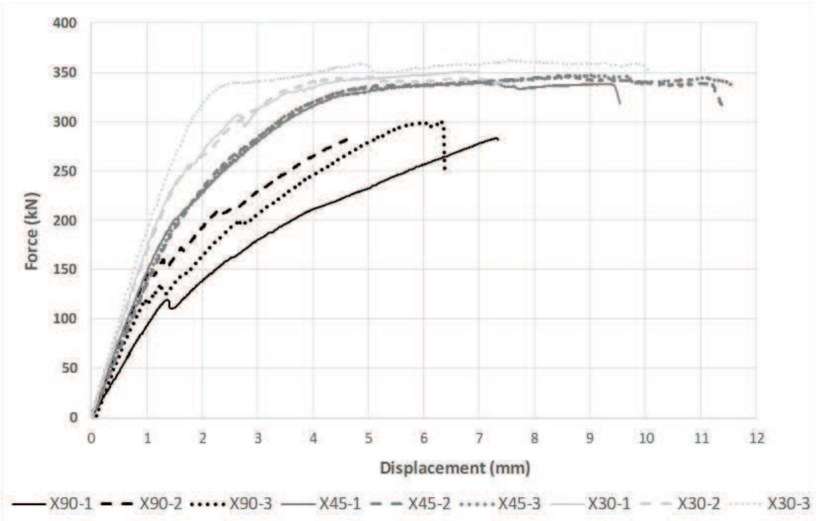
c) Failure characteristics of the MS specimen

d) Failure characteristics of the HSS specimen

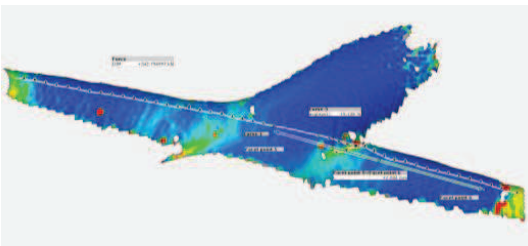
Fig 5. Major strain distribution (just before failure) and failure patterns of HSS and MS specimens

It could be expected that smaller angles of wrapped X-joints could jeopardize the mechanical performance of the joints due to difficult wrapping in the sharp corners. To investigate the influence of angles on the static behavior of small-scale X-joints, three X45 and three X30 specimens are loaded with monotonic tensile force until failure. The load-displacement curves are compared with three X90 specimens tested previously (Pavlovic, 2018) in Figure 6a. The three series of specimens have the same dimensions of CHS profiles and FRP wrapping. The conclusion is that the challenging joint angles does not jeopardize but has a favorable influence on the static behavior of X-joints. Compared to X90 joints, X45 and X30 specimens reach 65% and 135% higher linear load limit, respectively. The tensile strength of X45 and X30 are 19% and 22% higher compared to X90, respectively. Even the ductility is improved by 76% and 34%, respectively. The linear behavior and tensile strength is inversely proportional to the joint angle.

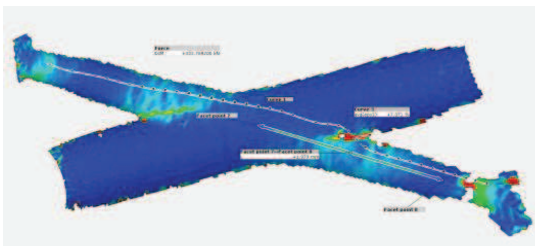
The distribution of principal major strain for one X45 and one X30 joint from DIC results are shown in Figure 6b and 6c, just before the failure. Stress concentrations, up to 6% major strain at the surface of FRP wrapping are dominating in the region of the sharp corner. Nevertheless, the FRP does not suffer breakage and the final failure in all the tested specimens is debonding of the brace CHS member from the FRP wrapping. The conclusion is that FRP wrapped joints with challenging angles can be made to withstand the loads which are even higher that the yielding resistance of the brace CHS member.



a) Force-displacement curves of X-joints



b) Major strain distribution (the X45 specimen)



c) Major strain distribution (the X30 specimen)

Fig 6. Results of static experiments on wrapped X-joints with different angles

In order to characterize the fatigue resistance of wFRP X-joints, three wFPR X45 joints (Pi 1-1, Pi 1-2, Pi 1-3) are tested in cyclic loading regime at different load (stress) ranges (-100~100 kN, 10~110 kN, 15~165 kN). Final failure of joint is not obtained even after 7 mil. cycles for the loading range corresponding to 143 MPa in the CHS brace member. Instead, a steady stiffness degradation, up to 40% is observed over the cycles. Therefore, the number of cycles shown in preliminary S-N curve in Figure 7 is obtained at 10% stiffness degradation of the joint. The stress used in the S-N curve is calculated as a nominal stress in the brace member, i.e. the load range divided by the cross sectional area of CHS60.3x4mm profile. Results of the wrapped X45 joint in the S-N curve are compared to an estimated curve for a welded CHS joint of same dimensions. The stress concentration factor (SCF) and the S-N curve of welded X45 joints are calculated based on *DNV-RP-C203*. The S-N curves indicate superior fatigue endurance of the wrapped FRP joint over the equivalent welded CHS joint. Cyclic loading on wrapped joints is stopped at reaching 40% of the joint stiffness degradation. Afterwards, the monotonic static load is applied to check the residual static resistance of the joint. Approximately 340 kN is reached, showing no degradation of static resistance of the wrapped X45 joint.

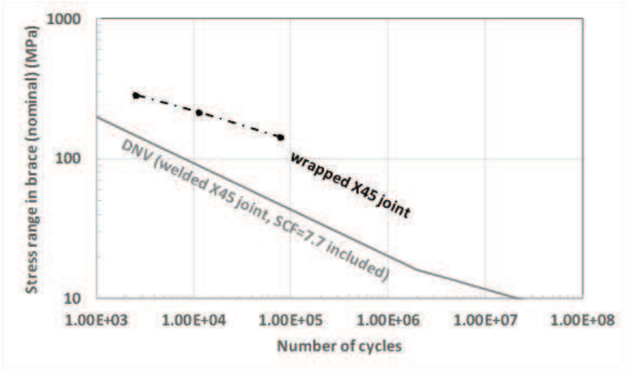


Fig 7. Comparison of preliminary S-N curve of wrapped X45 joints vs. equivalent welded joint

5 Conclusions and Outlook

Innovative wrapped FRP small-scale uniaxial and X-joints of CHS are tested with monotonic tensile and cyclic loading, to evaluate feasibility of this connection concept. Very satisfactory and promising testing results are obtained and concluded below:

- HSS significantly improves both linear behavior (49%) and tensile strength (75%) of uniaxial specimens. It is shown that tensile resistance of the wrapped FRP joint can reach the full resistance of the steel profile (brace or chord member) even in case of high strength steel CHS.
- The challenging angle does not jeopardize but has a favorable influence on the static behavior of wFRP X-joints. Compared to X90 joints, X45 and X30 specimens have, 19% and 22% higher of tensile resistance.
- Wrapped FRP joints show promising fatigue endurance over equivalent welded CHS joints. Preliminary S-N curve for X-joints under 45 degree angle shows an order magnitude larger number of cycles to failure. Wrapped FRP joints show steady stiffness degradation with no degradation of residual static resistance even after 40% of stiffness degradation at 7 mil. cycles.

Further testing is indispensable to prove validation at real scale, and long-term behavior under permanent loading, harsh marine environmental conditions and UV-radiation. The ongoing validation by Finite Element Modelling will provide better insight on stress concentrations, failure modes, with the aim to give input for optimized design for the wFRP joints.

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