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M H. Kabir
Queensland University of Technology

S Fawzia
Queensland University of Technology

T HT Chan
Queensland University of Technology

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DURABILITY STUDY OF CFRP STRENGTHENED STEEL CIRCULAR HOLLOW SECTION MEMBERS UNDER MARINE ENVIRONMENT

M.H. Kabir
School of Civil Engineering and Built Environment, Faculty of Science and Engineering, Queensland University of Technology, 2 George Street, Brisbane, QLD 4000, Australia.
md.kabir@student.qut.edu.au

S. Fawzia*
School of Civil Engineering and Built Environment, Faculty of Science and Engineering, Queensland University of Technology, 2 George Street, Brisbane, QLD 4000, Australia.
sabrina.fawzia@qut.edu.au (Corresponding Author)

T.H.T. Chan
School of Civil Engineering and Built Environment, Faculty of Science and Engineering, Queensland University of Technology, 2 George Street, Brisbane, QLD 4000, Australia. tommy.chan@qut.edu.au

ABSTRACT

Galvanic corrosion is a common phenomenon in Carbon Fibre Reinforced Polymer (CFRP) strengthened steel structures in wet environments and submerged conditions, which reduces durability by weakening the bond between the CFRP and steel substrate. CFRP materials have already been proven to have superior resistance to corrosion and chemical attacks but the adhesive and steel are generally affected by long-term exposure to moisture, especially in conjunction with salts resulting from deicing of ocean spray. This paper presents the results of a research program to improve the durability of CFRP strengthened steel circular hollow section (CHS) members by treating the steel surface with an epoxy based adhesion promoter and inserting Glass Fibre Reinforced Polymer (GFRP) as a galvanic corrosion barrier against simulated sea water. It also presents the effects of accelerated corrosion on the bond of CFRP strengthened hollow steel members. The program consisted of four CFRP strengthened steel beams and one unstrengthened steel beam. Two strengthened beams were used as control while the other two beams were exposed to a highly corrosive environment to induce accelerated corrosion. The corrosion rate was considered 10% which represents a moderate level of loss in the cross-sectional area of the steel tube throughout its intended service life. The beams were then loaded to failure under four-point bending. The research findings indicate that the accelerated corrosion adversely affected the ultimate strength of the conditioned beams and the embedded glass fibre enhanced the bond durability.

KEYWORDS

CFRP, GFRP, steel CHS, strengthening, corrosion, sea water, durability.

INTRODUCTION

The use of tubular steel sections as structural and non-structural elements has been becoming more popular for constructing of various onshore and offshore structures because of behaving in superior manner to other open sections (Wardenier 2001). However, many such structures are deteriorating due to loss of material properties, exposure to severe environment, or increase in service loads. It is well known that the CFRP composites as external reinforcement in strengthening steel structures have recently attracted great attention due to their numerous advantages. Successful applications of CFRP for strengthening steel structures can be found recently in literatures (Fawzia et al. 2006; Fawzia et al. 2007; Seica and Packer 2007; Haedir et al. 2009; Fawzia et al. 2010; Fawzia 2013). However, the durability of CFRP strengthened steel structures under service environments is still a significant concern which has not been sufficiently addressed till now. In most bonded CFRP strengthening systems, the infiltration of water is considered a most detrimental factor to destroy the bond between the interface of adhesive and steel substrate. Recently a few attempts have been made to investigate the durability of CFRP strengthened steel structures under natural and simulated (5% NaCl) saline water. The results have shown that there is a significant reduction in strength and stiffness under saline water (Nguyen et al. 2012; Seica and Packer 2007; Dawood and Rizkalla 2010). These reductions may have happened because of interfacial attacks, adhesive degradation and galvanic corrosion. Hence, it is imperative to prevent the infiltration of water and galvanic corrosion in order to enhance the bond durability under wet or submerged environments. Research has found that galvanic corrosion between the adhesive and steel surface can be prevented by using various techniques such as water resistant sealant, nonconductive layer of fabric (GFRP) between the carbon and steel, an isolating epoxy film on the steel surface such as primer or a silane coupling agent and moisture barrier (West 2001; Dawood 2008; Tavakkolizadeh and Saadatmanesh 2001). These techniques can be used as preventative measures in a variety of structures including CFRP strengthened steel hollow members, which are common in offshore structures and often experience flexural stresses under aggressive marine environmental conditions. However, the durability of CFRP strengthened structures as presented by various researchers is limited to a certain period of time which may not represent the total durability of the structures for their full design lives. To address this critical issue, the current study intends to use a moderate accelerated corrosion process to induce 10% theoretical mass loss of steel tube to represent the durability of the CFRP strengthened steel tubular members for their intended service lives (Al-Saidy et al. 2010). In addition, an embedded GFRP insulation layer in the adhesives is also used to enhance durability against galvanic corrosion under accelerated corrosion condition.

EXPERIMENTAL INVESTIGATION

Material Properties

The proposed CFRP strengthening method consists of five materials, which are steel tubes, normal modulus CFRP MBrace CF 130, two part epoxy impregnation adhesive MBrace saturant, two part MBrace primer, and GFRP. The average yield stress and ultimate strength of the steel tube were found 327 MPa and 383 MPa respectively by coupon test. The average measured tensile modulus and ultimate strength of the CFRP considered in this study were 230 GPa and 2675 MPa respectively and for the cured adhesive were 2028 MPa and 24.80 MPa respectively (Fawzia 2007). The tensile strength and elastic modulus of the MBrace primer were 12 MPa and 700 MPa as well.

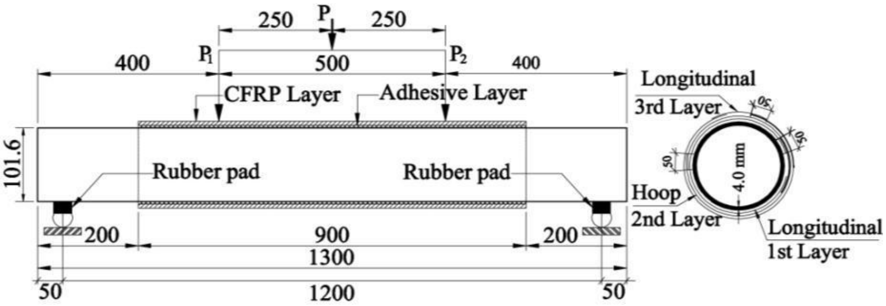


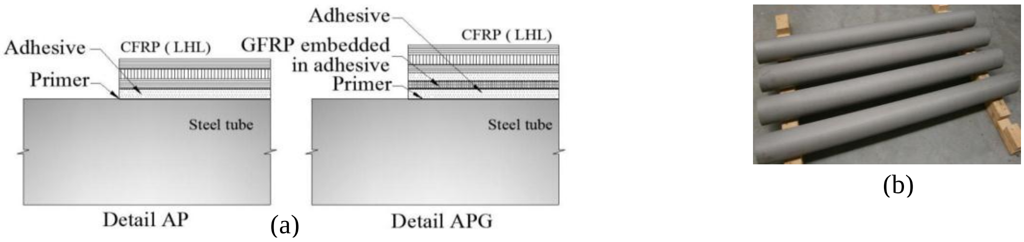
Figure 1. Schematic diagram of test set-up

Test Specimens

A total of five steel tubes with circular cross-sections of 101.6 mm outer diameter and 4.0 mm thickness were cut to required size. Depending on test facility, the length of the circular member was chosen 1300 mm and the effective span was considered 1200 mm for a four-point bending test. A schematic diagram of the test set-up is shown in Figure 1 with all dimensions being in mm.

Strengthening Schemes

Two different bond configurations were considered in the experimental program and shown in Figure 2 (a). Detail AP, represents the bonding of CFRP fabrics (LHL, where L is the longitudinal layer and H is the hoop layer) using adhesive and adhesion promoting primer to enhance the durability of the interfacial zone between steel and adhesive. In detail APG, the detail AP was modified by embedding a unidirectional GFRP layer in the adhesive between the steel and CFRP to act as galvanic corrosion barrier. The tube surface was sand blasted and cleaned with acetone to remove weak layer, deposited dust particles and grease as shown in Figure 2(b). The CFRP sheet was cut into the required dimensions oriented longitudinally, horizontally and longitudinally to the length of the beam was directly applied on top of the adhesive layer for the two detail AP specimens and the other two detail APG specimens. A rib roller was run immediately to press the fabric along the fibre direction against the substrate until visual signs of adhesive were observed bleeding through the fabrics. The whole procedure was done on a wet surface. To achieve a uniform and high quality bond, masking tape was wrapped around the circumference of the CFRP wrapped area and kept for a period of at least 24 hours as shown in Figure 3(a). Then the masking tape was removed and the finished products were cured for about two weeks under ambient temperature to ensure full curing.



(a)

(b)

Figure 2. (a) Schematic representation of bond configuration, (b) Specimens with sand blasted surface

(a)

(b)

Figure 3. (a) Curing with masking tape for 24 hours, (b) Sealing of ends to prevent corrosion inside

(a)

(b)

Figure 4. (a) Corrosion cell set-up, (b) Schematic of corrosion cell

Accelerated Corrosion Process

The accelerated corrosion process proposed by Al-Saidy et al. (2010) was carried out in this study by impressing an electric direct current (DC) of about 2.0 A through the steel tube, which represents an approximate current density of 482 μA/cm^2 and is within the range of current density as mentioned in literature (El Maaddawy and Soudki 2003). Stainless steel reinforcing bars were placed at both sides of each specimen acted as the cathode for the accelerated corrosion process, while the steel tube acted as the anode. The specimens and stainless steel bars were connected in parallel to the positive and negative phase of the DC power supply respectively. The ends of the specimens were capped as shown in Figure 3(b) to prevent corrosion inside the tubes. The specimens were then placed in a rectangular tank filled with simulated sea water (5% salt). The set-up and schematic of the accelerated corrosion cell as a whole are shown in Figures 4(a) and 4(b). To obtain a theoretical mass loss of 10% from the

CFRP strengthened steel tubes both from AP detail and APG detail specimens, an average current of 2.0 A was applied to each specimen for a period of 25 days. The corrosion current was monitored at regular intervals. Faraday's law was used to estimate the mass loss associated with this corrosion process.

Test Set-up and Instrumentation

Tests were conducted using a 230 kN controlled MTS actuator under four-point bending as simply supported condition. The test set-up is shown in Figure 5. The load was applied as a displacement control 'static compression load' at a constant rate and was continued up to failure of each specimen. Two string pots were placed at the mid-span of the beam to measure the average deflection of the specimens. In addition, two LVDTs were mounted on top of the supports to measure support displacement. The readings from the LVDTs and string pots were recorded by computer programmed LABVIEW software. The loads and actuator displacements were also recorded accordingly by the computer programmed station manager software connected to the MTS controller.

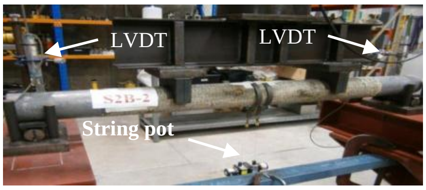


Figure 5. Experimental set-up

EXPERIMENTAL RESULTS

Failure Mode of the Tested Beams

Failure modes of the tested unstrengthened, strengthened control and conditioned beams are shown in Figure 6. It was noticed that the failure occurred to control beams due to local buckling of the tubular hollow section in the compression zone near the loading point where crushing of the fibre layers was found as well. This type of failure indicates that the strengthened beam failed before reaching its full flexural capacity and the mode of failure is similar to that of an over reinforced beam. A minor debonding also occurred at the tension face from both ends of the beam and continued up to the loading points. It probably happened due to huge stress concentration at the ends. On the other hand, the failure modes for the conditioned beams under saline water for 10% mass loss were very different. It was observed that the conditioned beams with and without embedded GFRP failed by complete rupturing of CFRP and yielding of steel at tension face. The fibre at compression face also crushed and steel also yielded. This type of failure mode can be found in under reinforced beams under bending. No end debonding was found in the conditioned beams until failure. This change of failure mode is interesting. The change of failure mode may have happened due to interfacial attacks, plasticization of the adhesive and galvanic corrosion which are common in wet environments.

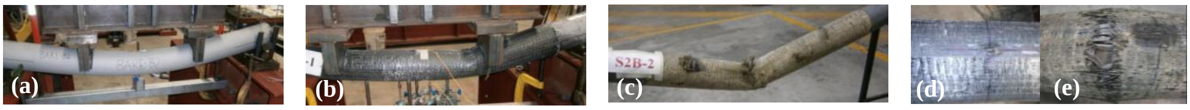


Figure 6. Failure mode (a) Unstrengthened beam, (b) Control beam, (c) Conditioned beam, (d) Tension face of control beam, (e) Tension face of condition beam.

Failure Load

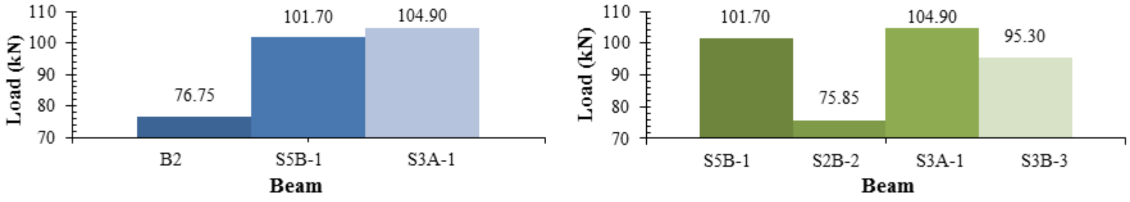
The failure loads for all the beams tested are listed in Table 1. It can be seen that the CFRP strengthened control beams display higher ultimate load than the unstrengthened beam. In addition, the embedded GFRP and the accelerated corrosion environment have affected the ultimate strength of the strengthened beams.

Table 1. Test details and ultimate load of the tested specimens

Exposure condition	Exposure duration	Current flow (A)	Beam ID	GFRP layer	Ultimate load (kN)	Comments
Ambient temperature	NA	NA	B2	NA	76.75	Unstrengthened
	15 days	NA	S5B-1	No	101.70	Strengthened control
	15 days	NA	S3A-1	YES	104.90	Strengthened control
Accelerated corrosion environment	25 days	2.0	S2B-2	No	75.85	Strengthened conditioned
	25 days	2.0	S3B-3	YES	95.30	Strengthened conditioned

Contribution of CFRP and GFRP on ultimate strength of control beams

The experimental results in Figure 7(a) for the strengthened control beams S5B-1 and S3A-1 confirm that the CFRP reinforcement helped to increase ultimate strength through the effective use of the strength of the longitudinal fibre and the restraining action of the hoop-oriented fibres. The strengthening method (LHL, where L is a longitudinal layer and H is a hoop layer) adopted in the current study was able to increase ultimate load to 32.51% and 36.70% for beams without and with embedded GFRP compared to the unstrengthened beam B2. These increments in ultimate load agree well with the findings of Haedir et al. (2009). Moreover, the beam S3A-1 with embedded GFRP shows a 3.15% higher ultimate load than the beam S5B-1, which did not have an embedded GFRP layer. It can thus be concluded that the additional strength was contributed by the embedded GFRP.



(a) (b)

Figure 7(a). Ultimate load for unstrengthened and strengthened beams, (b) Ultimate load for control and saline water conditioned beams

Accelerated corrosion effects on ultimate strength of beams with and without embedded GFRP

Figure 7(b) shows the effects of the accelerated corrosion environment on the ultimate strength of beams S2B-2 and S3B-3. The beams were conditioned under an accelerated corrosion environment for 10% mass loss. It can be seen that the beam S2B-2 without embedded GFRP and conditioned under the accelerated corrosion environment shows a significant drop of strength (24.42%) compared to the unconditioned beam S5B-1. However, the GFRP embedded beam S3B-3 conditioned under the accelerated corrosion environment shows a 9.15% drop in ultimate load compared to the unconditioned beam S3A-1.This trend of reduced ultimate load is in agreement with the findings of Seica and Packer (2007) and Dawood and Rizkalla (2010) under saline water. This trend may be due to interfacial attacks, plasticization of adhesive or galvanic corrosion, which may lead to debonding along the interface of steel and adhesive in wet environments. When the strength reduction of beam S3B-3 with GFRP insulation is compared with that of beam S2B-2 without GFRP insulation, it can be seen that beam S3B-3 shows a 25.65% higher ultimate load than beam S2B-2. This superior behaviour in terms of ultimate load may be attributable to the barrier against galvanic corrosion provided by the GFRP.

CONCLUSION

In this study, the control beams failed by local buckling of walls and crushing of CFRP near loading points and debonding of CFRP at ends. Whereas, the saline water conditioned beams under an accelerated corrosion environment failed by complete rupture of CFRP and yielding of steel with no debonding at ends. CFRP and GFRP have good potential to enhance the ultimate strength of strengthened circular hollow sections (CHS) members. Both the beams with and without embedded GFRP were affected by the accelerated corrosion environment and showed reduced ultimate load capacities than the corresponding control beams. Moreover, the GFRP embedded beam performed better under the accelerated corrosion environmental conditions by reducing the effects of galvanic corrosion.

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