DOI: 10.14256/JCE.1127.2014

Građevinar 5/2015

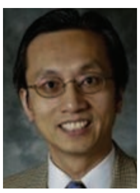
Primljen / Received: 5.9.2014.
Ispravljen / Corrected: 28.1.2015.
Prihvaćen / Accepted: 6.2.2015.
Dostupno online / Available online: 10.6.2015.

Effects of layer orientation of CFRP strengthened hollow steel members

Authors:

Md Humayun Kabir, MSc. CE
Queensland University of Technology, Australia
Faculty of Science and Engineering
md.kabir@student.qut.edu.au

Sabrina Fawzia, PhD. CE
Queensland University of Technology, Australia
Faculty of Science and Engineering
sabrina.fawzia@qut.edu.au



Prof. Tommy H. T. Chan, PhD. CE
Queensland University of Technology, Australia
Faculty of Science and Engineering
tommy.chan@qut.edu.au

Scientific paper - Preliminary report

Md Humayun Kabir, Sabrina Fawzia, Tommy H. T. Chan

Effects of CFRP layer orientation on strengthening of hollow steel elements

This paper studies the effects of orientation of CFRP (carbon fibre reinforced polymer) strip layers on the improvement of bearing capacity of strengthened steel-made circular hollow elements. The four point bending test was conducted, and elements were subjected to bending until failure. The improvement of bearing capacity of strengthened tubular steel elements is presented in terms of failure load, stiffness, composite beam action, and modes of failure. Beams strengthened with CFRP strips with two longitudinal layers and one layer along the periphery performed better than the beams reinforced with one longitudinal layer and two layers along the periphery.

Key words:
CFRP, layer orientation, bearing capacity, strengthening, circular hollow section, bending

Prethodno priopćenje

Md Humayun Kabir, Sabrina Fawzia, Tommy H. T. Chan

Utjecaji orijentacije slojeva CFRP traka na ojačanje šupljih čeličnih elemenata

U ovom se radu proučavaju utjecaji orijentacije slojeva CFRP traka (polimera ojačanih ugljičnim vlaknima) na poboljšanje nosivosti ojačanih čeličnih kružnih šupljih elemenata. Provedeno je ispitivanje savijanjem uz djelovanje sila u četiri točke, a elementi su opterećeni na savijanje do sloma. Poboljšanje nosivosti ojačanih cijevnih čeličnih elemenata analizirano je s obzirom na silu otkazivanja, krutost, kompozitno djelovanje i vrstu sloma. Nosači armirani CFRP trakama s dva uzdužna sloja i jednim po obodu pokazuju bolje ponašanje od nosača armiranih s jednim uzdužnim slojem i dva sloja po obodu.

Ključne riječi:
CFRP, orijentacija slojeva, nosivost, ojačanje, kružni šuplji profil, savijanje

Vorherige Mitteilung

Md Humayun Kabir, Sabrina Fawzia, Tommy H. T. Chan

Einfluss der Ausrichtung von CFK Schichten auf die Verstärkung hohler Stahlelemente

In dieser Arbeit werden Einflüsse der Ausrichtung von CFK (carbonfaserverstärkter Kunststoff) Streifenschichten auf die Verbesserung der Tragfähigkeit verstärkter runder hohler Stahlelemente untersucht. Versuche wurden unter Biegebeanspruchung der Elemente mittels vier Punktlasten bis zum Versagen durchgeführt. Die Verbesserung der Tragfähigkeit verstärkter runder hohler Stahlträger ist bezüglich der Traglast, der Steifigkeit, der Verbundwirkung und des Versagensmechanismus analysiert. Durch zwei Schichten in Längs- und einer Schicht in Umfangsrichtung mit CFK Streifen verstärkte Träger zeigten ein besseres Verhalten als Träger mit einer Schicht in Längs- und zwei Schichten in Umfangsrichtung.

Schlüsselwörter:
CFK, Ausrichtung von Schichten, Tragfähigkeit, Verstärkung, runde Hohlprofile, Biegebeanspruchung

1. Introduction

Tubular members are widely applied as structural and non structural elements in nature, as well as in many civil engineering infrastructure applications, as can be seen in Figure 1. Generally, tubularly shaped members behave in superior manner in terms of compression, torsion, bending in all directions, and aesthetic appearance [1]. Therefore, the use of such structures has been increasing dramatically in form of various onshore and offshore structures. In offshore structures, circular hollow sections are mainly used to form jacket structures, which may cause bending due to wave force. However, a large number of such structures are found structurally inadequate due to design errors, loss of material properties, exposure to severe environments, or increase in service loads. This degradation phenomenon is highly significant to engineers dealing with rehabilitation of metallic structures.

Structural rehabilitation or strengthening may be recommended to restore or increase the strength of these structures, rather than to proceed to their replacement, taking into account effective results, cost, time, and aesthetic appearance. The conventional steel plate welding technique of rehabilitation is an option, but the CFRP is a better option in cases where the weight savings and durability or corrosion are of major concern [2-4]. In addition, the steel plate bending to get a desired shape to strengthen circular hollow steel members is another challenge. Nonetheless, the relatively new carbon fibre reinforced polymer (CFRP) composites have emerged as an excellent solution and a good alternative in these applications, due to their superior physical and mechanical properties, such as their excellent resistance to corrosion and environmental degradation, high longitudinal strength, high fatigue endurance, and reduced weight. Furthermore, they are very flexible and form all kind of shapes, and are easy to handle during construction, especially for hollow steel sections [3, 5, 6]. Due to these superiorities, the use of carbon fibre reinforced polymer (CFRP) composites along with adhesives for the repair and strengthening of metallic structures is a well established practice in the aerospace, marine, automotive and manufacturing industries, but it is also a promising technique for the civil engineering structures. Despite its unique advantages, the CFRP is very susceptible to fire. Considerable research for the fire protection system of CFRP attached with concrete structures has been conducted and provided the information that the fire protection insulation can improve the fire resistance capacity of CFRP [7, 8]. Meanwhile, the adhesively bonded CFRP has already become successful in the repair and strengthening of reinforced-concrete structures [3, 9, 10]. This has recently led to an immense interest in the sphere of research focusing on the use of CFRP materials for the strengthening and repair of metallic structures [11-14]. The combination of two materials, CFRP and steel, is found to increase strength, stiffness, ductility, and structural performance of strengthened systems. The majority of studies conducted to date with the purpose of increasing or restoring structural capacity using adhesively bonded CFRP mainly concern open steel sections such as I-beams and H-beams under bending.

One of the earliest examples of the open steel section strengthening is the improvement of steel I-girders conducted by Mertz and Gillespie Jr [15] to enhance flexural characteristics. The double symmetrical I-sections beams were strengthened with different combinations of adhesive-CFRP laminates and loaded in four-point bending [16]. Colombi and Poggi [17] tested H-steel beams strengthened externally by one layer and two layers of CFRP strips using two different adhesives. The experimental results of strengthened open sections showed an increase in ultimate load and stiffness, depending on the number of layers of CFRP composites.

In recent years, a number of studies have been undertaken with respect to the strengthening of hollow steel sections subjected to compression and tension. The effects of the number of CFRP layers and fibres orientation were examined by Shaat and Fam [18] for the CFRP strengthened square hollow section (HSS) short and long columns under axial compression. Another similar study was conducted by Bambach et al. [19] for composite hollow steel columns tested under pure axial compression, where CFRP layers were oriented transversely and longitudinally, and two different fibre layouts (1T1L, 2T2L) were used. Circular steel tubes were confined transversely using three different layers of glass fibre reinforced polymers (GFRP) and tested under axial compression [20].

Figure 1. Application of circular hollow section (CHS) member [1]: a) Bamboo; b) Aesthetically appealing; c) Bridge with circular girder

A significant increase in the ultimate load carrying capacity of the strengthened hollow sections was established according to the number of CFRP layers and layer orientation, when they were tested under compression. Butt-welded very high strength (VHS) steel tubes with varying geometry, reinforced longitudinally with five layers of unidirectional normal modulus CFRP sheets, were tested under tensile load [21]. In another study [22], circular hollow steel tubular sections were strengthened using five layers of the longitudinally bonded high modulus CFRP, and were tested in axial tension. Their results showed that the bonded CFRP was able to increase strength when tested under tension.

However, a few attempts have so far been made to study the contribution of CFRP composites on the strength restoration or enhancement of circular hollow steel members. In a recent study, Haedir et al. [23] reinforced externally circular hollow sections (CHS) tubular beams designated as compact, non-compact and slender, using CFRP sheets, and the beams were tested in four-point bending. Different CFRP configurations were used to strengthen the beam sections, namely the HHL, HHLL for the compact and non-compact sections, and L, LH, HHL, HHLL, HHHL, HLHL for slender sections. The experimental results showed that compact strengthened sections were able to increase the ultimate strength by about 3 % for HHL, and 45 % for HHLL. However, about 34 % (HHL) and 46 % (HHLL) of ultimate strength were increased for the non-compact section. Similarly, about 60 % (HHL), 84 % (HHLL), and 92 % (HLHL) ultimate strength increments were observed for the strengthened slender sections. Two layers of fabric (LL), with the fibres oriented longitudinally to the length of the tube, were confined with a third layer (H) with the fibres oriented transversely, and were used to strengthen compact circular hollow tubes. This configuration for compact section increased the ultimate load by about 27 % compared to an unstrengthened beam [24]. It is obvious from relevant literature that the number of CFRP layers, and the layer orientation, affect the strength of the sections primarily when they are subjected to compression and bending. It can also be seen that three layers of CFRP configuration, with the HHL and LLH layer orientation, were able to increase the ultimate strength by the maximum of 3 % and 27 % for compact section, and these were the least strength increment among all configurations of CFRP to strengthen non compact and slender sections [23, 24]. Several researchers have proposed to use an adhesion promoter to increase the bond between the steel and CFRP composites. A successful application of adhesion promoter is presented in [25] to treat the surface of the steel-CFRP double-lap shear specimens wherein a significant increase of bond durability was achieved. Likewise, the surface of the sand blasted steel beam can be pre-treated using an adhesion promoter to enhance the bond between the steel and adhesive. This may prevent a premature de-bonding failure, which is common in CFRP strengthened steel structures. To the best of the author's knowledge, the effect of layer orientation of three layers of the LHL CFRP configuration subjected to bending has not as yet been studied for compact sections. When the LHL layer configured beam is tested under bending, the H layer is assumed to confine the first L layer at compression zone, and the outer L layer is assumed to confine the central H layer at tension zone. Generally, the L layer CFRP fibres are fully effective at tension zone, and the H layer effectiveness is considered to be almost zero. Since the H layer is weak at tension zone, and if it is used as the outer layer, it may elongate more than the L layer under service load. At this position, the H layer may allow more moisture infiltration, especially when exposed to marine environment. Therefore, in the current study, the LHL layers variation has been explored, together with the HHL and LLH layers variations, to determine the most efficient wrapping scheme under bending. The contribution of adhesion prompters is also studied for various layer combinations.

2. Experimental program

The experimental program was performed at the Material Testing Laboratory, Banyo Pilot Plant Precinct of the Queensland University of Technology. All experimental tests were conducted under the four-point bending. A total of twelve steel tubes of circular cross-section, measuring 101.6 mm in outer diameter and 4.0 mm in thickness, were cut to required sizes. The length of the circular member, chosen depending on the workability and test facility, amounted to 1300 mm and the effective span amounted to 1200 mm for a four-point bending test. The schematic diagram with dimensions in mm of the test set-up is shown in Figure 2.

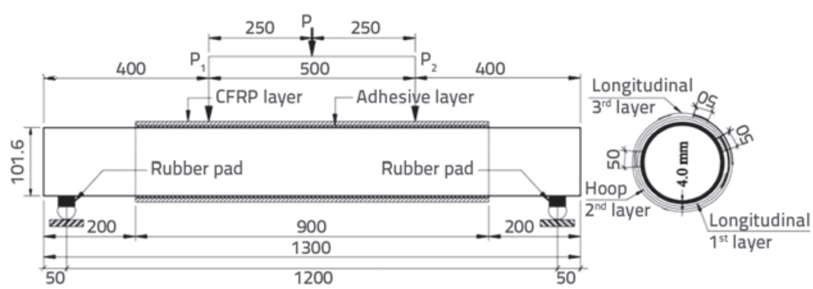


Figure 2. Schematic diagram of test set-up

2.1. Material properties

The proposed CFRP strengthening scheme consists of four materials, and includes steel tubes, a normal modulus CFRP MBrace CF 130, a two part epoxy impregnation adhesive MBrace saturant, and a two part MBrace primer adhesion promoter. The average yield stress, ultimate strength, and modulus of elasticity of the steel tube amounted to 327 MPa, 383 MPa, and 214 GPa, respectively, by the coupon test of three specimens. The CFRP was of the type CF130 unidirectional fabrics, specified by BASF construction chemicals Australia Pty Ltd. The measured elastic modulus was 205 GPa and the nominal tensile strength was 2760 MPa. The two-part impregnation resin designated MBrace saturant is characterised by the tensile strength and elastic modulus of 46 MPa and 2.86 GPa, respectively, as confirmed by the tensile coupon test. The compressive strength of 80 MPa was adopted based on the manufacturer's specification. Figures 3-5 show the typical stress-strain curve for the steel, CFRP, and adhesive. Mechanical properties of the MBrace primer adhesion promoter were not considered in the current study.

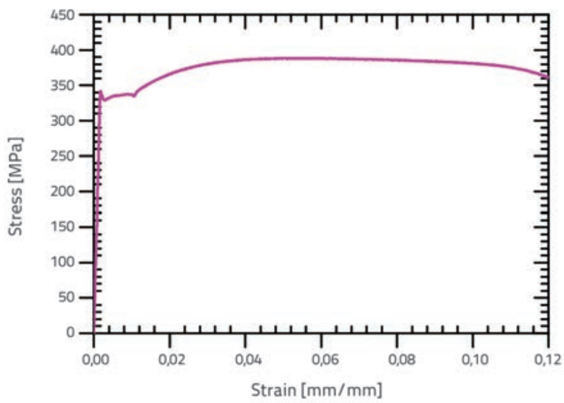


Figure 3. Typical stress-strain curve for steel

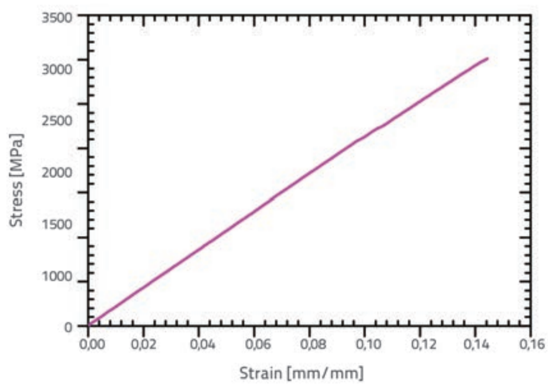


Figure 4. Typical stress-strain curve for CFRP

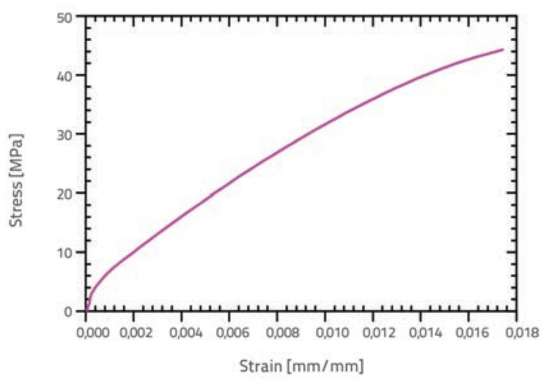


Figure 5. Typical stress-strain curve for adhesive

2.2. Specimen preparation

To achieve the rough and chemically active steel surface for well bonding, the tube surface was sand blasted to a white metal finish, as shown in Figure 6. Then the weak layer, deposited dust particles, and grease, were removed by washing with acetone. Two strain gauges were attached to a specially cleaned surface on the top and bottom of steel beam at mid-length, where the maximum bending moment occurred, so as to record the compressive and tensile strains. The acetone cleaned surface of the three specimens was treated with the adhesion promoter, prior to applying epoxy adhesive and allowing it to dry for approximately 1 hour. The other three specimens were kept untreated. Then the two-part impregnated epoxy adhesive was mixed according to manufacturer guidelines [26] and applied on the pre-treated steel surface during its pot life. The CFRP sheet was cut into the required dimensions and the first layer of CFRP fabrics oriented longitudinally to the length of the beam was directly applied onto the top of an uncured adhesive layer. 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. Then the first layer was confined with the second layer, with the fibres oriented transversely to the tube axis to confine the longitudinal layers, whilst subjected to compressive stresses during bending. Then the third layer of CFRP fabrics was applied onto the second layer in the longitudinal direction by following the procedure similar to the one used for the first layer. The whole procedure was conducted on the wet surface, which implies that the top surface of the lower layer still remained sticky. To achieve a uniform and good quality bond between the CFRP and steel, as well as between CFRP layers, a masking tape was wrapped around the circumference of the CFRP wrapping area and kept for at least 24 hours, as shown in Figure 7.a. Then the masking tape was removed and the finished specimens were cured for at least two weeks under ambient temperature shown in Figure 7.b, to ensure proper completion of curing.

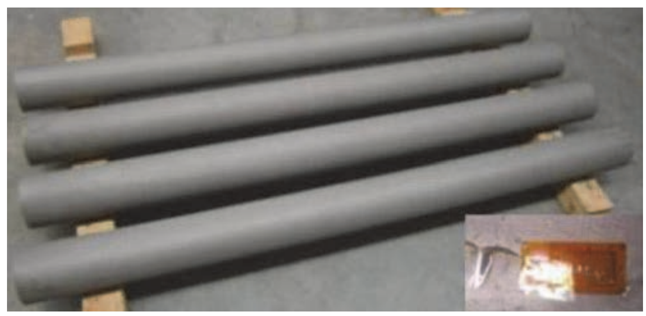


Figure 6. Beam specimens with sand blasted surface and strain gauge

Figure 7. Curing of specimen at ambient condition: a) specimen with masking tape; b) specimen after removal of masking tape

2.3. Test set-up and instrumentation

The tests were conducted using a 230 kN controlled MTS actuator under four-point bending, as a simply supported condition, on two rectangular rubber pads. The test set-up with apparatus is shown in Figure 8. The load was applied as displacement control in a "quasi static manner" at constant rate, and it was continued up to the failure of specimen. At this stage, two additional strain gauges were fixed to the outside of the CFRP-wrapped section, directly over the top of the gauges that had been attached to the steel surface underneath prior to starting the test.

Figure 8. Experimental set-up

Two string pots were placed on each side of the beam at mid-span to measure the average deflection of the specimens. In addition, two LVDTs were mounted on top of the support to measure support displacement. Then the true deflection was determined by deducting the support displacement from mid-span displacement. The readings from strain gauges, LVDTs and string pots were recorded by a computer programmed LABVIEW software. Similarly, the corresponding loads and actuator displacements were recorded accordingly by a computer programmed station manager software connected to the MTS controller.

3. Experimental results

3.1. Failure load

Table 1 shows the service loads or resistance at deflection $L_e/250$, which is considered for all members not supporting articulated brittle partitions at serviceability limit state, and failure loads for all beams. The corresponding ratios of average service and ultimate load of the strengthened specimens $P_{savg}^{(cs)}$ and $P_{uavg}^{(cs)}$, relative to the unstrengthened steel specimens $P_{savg}^{(s)}$ and $P_{uavg}^{(s)}$ tested under bending, are also shown. It can be seen that the beams strengthened with the CFRP display higher service and ultimate load for different layer orientations, compared to the unstrengthened beam. In addition, it can also be seen that load resistance variations for treated beams, due to change of layer orientation, are close to each other.

Table 1. Test details, beam resistance at service and failure, and failure mode of tested beams

Specimen ID	Number of specimens	Specimen surface condition	Wrapping scheme	P_s at $L_e/250$ [kN]	$P_{savg}^{(cs)}/P_{savg}^{(s)}$	P_u [kN]	$P_{uavg}^{(cs)}/P_{uavg}^{(s)}$	Failure mode
B2_US	2	NA	NA	44.10 50.30	-	76.75 78.40	-	Ductile failure
S4B-1	2	Untreated	LHL	60.00 69.00	1.37	94.40 99.75	1.25	Local buckling of wall. crushing of CFRP. and debonding at ends
S5B-1	2	Treated	LHL	64.00 66.00	1.38	101.70 102.00	1.31	Local buckling of wall. crushing of CFRP. and debonding at ends
S6A-1	1	Untreated	HHL	62.00	1.31	98.20	1.27	Rupture of CFRP & yielding of steel at bottom. no debonding at ends
S6B-1	2	Treated	HHL	62.50 62.80	1.33	100.32 99.65	1.29	Rupture of CFRP & yielding of steel at bottom. no debonding at ends
S6A-2	1	Untreated	LLH	62.00	1.31	101.00	1.30	Local buckling of wall. crushing of CFRP. and debonding at ends
S6B-2	2	Treated	LLH	66.00 69.00	1.43	102.00 104.00	1.33	Local buckling of wall. crushing of CFRP. and debonding at ends

3.1.1. Contribution of CFRP, adhesion promoter, and wrapped masking tape, to the service load and ultimate strength of strengthened beams

The three CFRP layer configurations, with various layer orientation, help to increase the ultimate strength through the effective use of the longitudinal fibre strength, and through the restraining action of hoop-oriented fibres, as shown in Table 1. The strengthened techniques (LHL, HHL, and LLH, where L is the longitudinal layer, and H is the hoop layer) implemented in the current study for the compact treated section were able to increase an average ultimate load to the maximum value of about 31.0 %, 29.0 % and 33.0 % for the LHL, HHL, and LLH oriented beams, compared to the unstrengthened beam. Similarly, the load resistance at service was found to increase by about 38.0 %, 33.0 %, and 43.0 %, respectively. However, a previous study [23] shows the maximum ultimate load increase of about 3 % for a compact tubular section (2.70 mm in thickness, and 33.81 mm in outer diameter, and with the CFRP similar to that used in the current study) strengthened using the HHL combination of CFRP, and tested under four-point bending. Likewise, the maximum increment of ultimate load was 27 % for a strengthened compact tubular hollow steel member (4.9 mm in thickness and 168.5 mm in outer diameter, and with the Tyfo CFRP with an average tensile strength and tensile modulus of 500 MPa and 62500 MPa, respectively) tested in another study conducted by Seica and Packer [24], where LLH were used in the combination of CFRP composites, and tested under the four-point loading conditions. It can be seen that, in the current study, the strength increment for strengthened beams having three layers of CFRP configuration (LLH) is by 6 % greater compared to previous studies. This higher strength capacity may have appeared due to bond enhancement which may be attributed to uniform pressure exerted by the masking tape wrapped during the curing stage, and by the MBrace primer adhesion promoter. In addition, the difference in strength increment between three (HHL) and four (HHLL) layers oriented strengthened compact sections was 42 % in [23], while this difference was only 12.0 % in the current study for the beam with three LHL layers compared to four HHLL layers oriented beams tested in a previous study, although the application of four layers is time consuming and costly.

3.1.2. Effects of fibres orientation on ultimate strength of untreated strengthened beams

The effects of layer orientation on an average ultimate strength of untreated strengthened beams are clearly depicted in Figure 9. The LLH oriented untreated beam S6A-2 displays a higher ultimate load compared to other two beams S4B-1 and S6A-1, with LHL and HHL orientation of CFRP fibres. It can be observed that the beam S6A-1 shows a slightly higher ultimate load than the beam S4B-1, although it contains a higher number of longitudinal fibre sheets. This may be due to poor bonding, which may lead to the initiation of early debonding when tested under a gradual loading increment. On the other hand, the load exhibited by the beam S6A-1 is by about 2.85 % lesser than that of the beam S6A-2 having higher number of longitudinal layers with different orientation of layers (LLH).

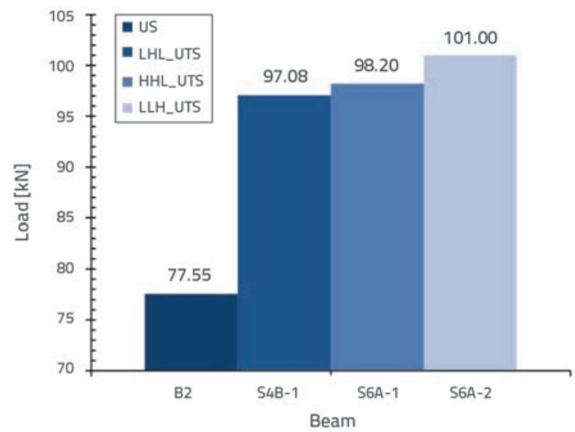


Figure 9. Ultimate load for unstrengthened and strengthened untreated beams

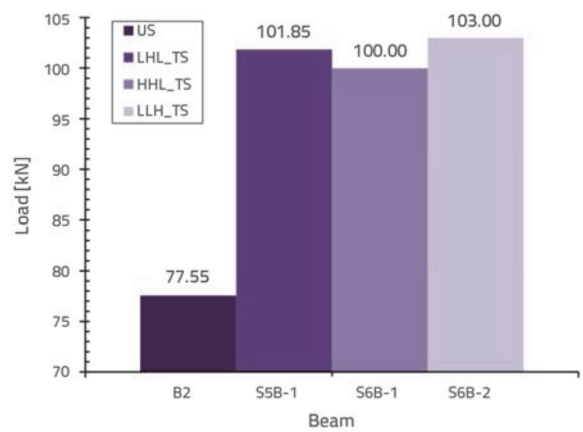


Figure 10. Ultimate load for unstrengthened and strengthened treated beams

3.1.3. Effects of fibre orientation on ultimate strength of treated strengthened beams

In case of strengthened beams with treated surface shown in Figure 10, the variation of the average ultimate load improvement among them appears minimal. However, it can be seen that at failure the beams S5B-1 and S6B-2 having LHL and LLH fibres orientation, with the same number of longitudinal fibres, were little bit stronger than the beam S6B-1 with a smaller number of longitudinal fibres. It is interesting to see that the LHL and LLH oriented surface treated beams S5B-1 and S6B-2, with two longitudinal layers of fabrics, exhibit almost a similar load increment although the position of the longitudinal and hoop layers is different. The experimental results show that the load increment trends for the surface untreated and treated beams are not consistent. It may be due to variation of effectiveness of bond between the steel and adhesive, or between CFRP layers.

3.1.4. Effects of surface pre-treatment on ultimate strength of strengthened beams

The surface of six beams including identical beams, with different fibres layer orientations, was pre-treated using the MBrace primer adhesion prompter to enhance the bond, while other four beams, including identical beam, were kept untreated. The measured average ultimate capacities for all strengthened beams of various layer orientations (Figure 11) show that the surface treated beams S5B-1, S6B-1, and S6B-2 perform slightly better than the corresponding untreated beams S4B-1, S6A-1, and S6A-2. It can therefore be said that the adhesion promoter such as the epoxy based MBrace primer is able to enhance the bond between the steel and CFRP for various combinations of longitudinal and hoop layers, although this enhancement is not significant. However, when the durability in wet environment is considered, this thin adhesion layer is cost effective because it creates a passivation layer and acts as a galvanic corrosion barrier by protecting ion infiltration which usually reduces the bond between the steel and adhesive [25].

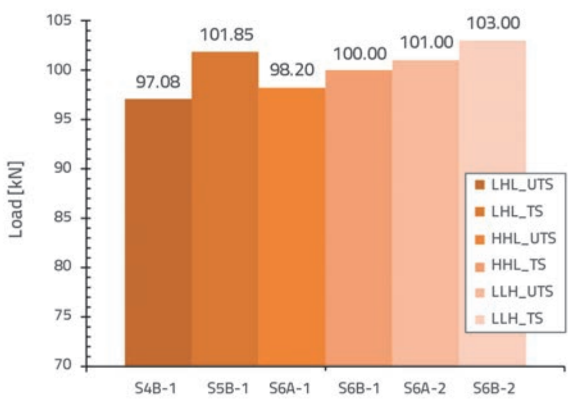


Figure 11. Ultimate load for strengthened untreated and treated beams

3.2. Mid-span deflection

The load-deflection responses of unstrengthened and strengthened beams with various fibre layer orientations are shown in Figures 12 to 15, where the effects of the CFRP layer, fibres layer orientation, and surface pre-treatment, on the stiffness of strengthened beams, can be drawn.

3.2.1. Contribution of CFRP on stiffness of strengthened beams

Figure 12 shows that the CFRP strengthened beams with LHL, HHL and LLH fibres orientation display higher stiffness than the unstrengthened beam B2 starting from around 40 kN load till the end of the test. It can therefore be said that the additional stiffness was contributed by the bonded CFRP layers on steel members. This stiffness increment agrees well with that measured experimentally by Seica and Packer [24] for CFRP strengthened HHL fibres oriented compact tubular members tested under bending.

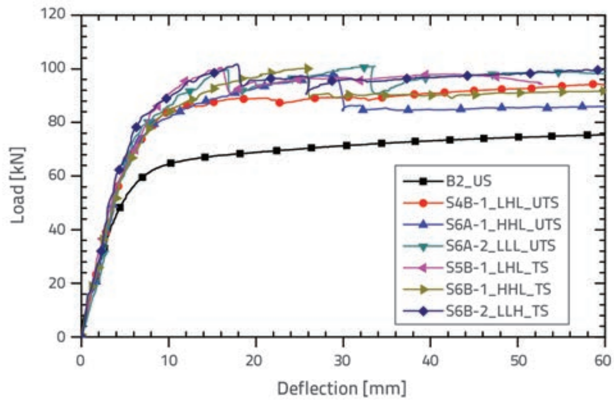


Figure 12. Load-deflection curves for unstrengthened and strengthened beams

3.2.2. Effects of fibres orientation on stiffness of untreated strengthened beams

The effects of fibres layer orientation on stiffness of the untreated strengthened beams S4B-1, S6A-1 and S6A-2, are shown in Figure 13.

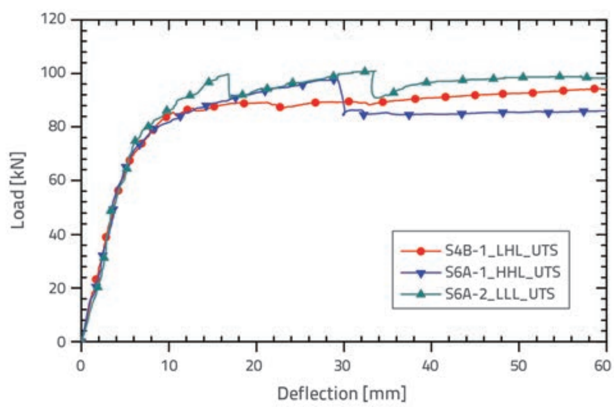


Figure 13. Load-deflection curves for strengthened untreated beams

It can be seen that all specimens exhibit a very similar deflection trend and linear-elastic behaviour until around the 72 kN load, and then the deflection trend changes to inelastic behaviour and falls in the plastic zone. It can be observed that, in the plastic zone, the LLH fibres oriented untreated beam S6A-2 displays stiffer behaviour than others. The LHL oriented untreated beam S4B-1 shows an intermediate level of stiffness behaviour without showing any sudden drop of load. It can be seen that the debonding starts at an early stage of loading when the deflection of about 10 mm is attained, and it continues gradually throughout the loading period. This poor performance of the beam S4B-1 might be due to a less efficient bonding surface.

3.2.3. Effects of fibres orientation on stiffness of treated strengthened beams

Similarly, the effects of fibres layer orientation on the stiffness of the treated strengthened beams S5B-1, S6B-1 and S6B-2, are shown in Figure 14. It can be seen that the beams with LHL, HHL, and LLH fibres layer orientation show similar deflection trend and linear-elastic behaviour until around the 78 kN load, and then the deflection trend changes to inelastic behaviour. In the plastic zone, the identical deflection further continues up to the 100 kN load for LHL and LLH layer oriented beams S5B-1 and S6B-2, respectively. The LHL and LLH layers oriented beams S5B-1 and S6B-2 show stiffer behaviour than the HHL layers oriented beam S6B-1 in the plastic zone until the first sudden drops of stiffness, where the sudden debonding or rupture of CFRP composites is assumed to occur. However, in case of the beam S6B-1, the first sudden drop of stiffness is delayed and then it exhibits a higher deflection than the LHL and LLH layers oriented beams. In addition, the LHL and LLH layers oriented treated beams having similar number of longitudinal layers of fibres composites show negligible difference in stiffness after the final noticeable drop of stiffness till to the recorded values of deflection.

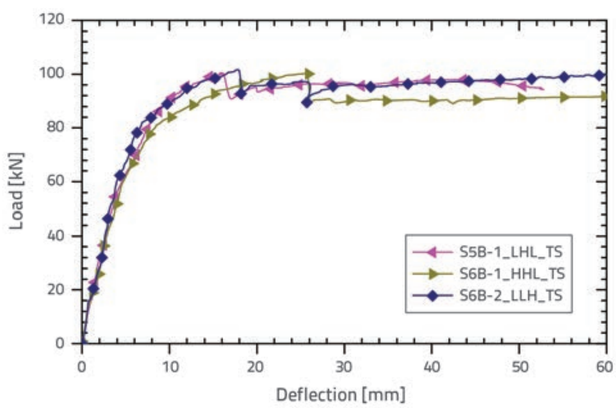


Figure 14. Load-deflection curves for strengthened treated beams

3.2.4. Effects of surface pre-treatment on stiffness of strengthened beams

Figure 15 shows the stiffness of the surface untreated and treated strengthened beams with LHL, HHL and LLH layers orientation at the serviceability limit state (L_e/250) for members not supporting articulated brittle partitions. It can be seen that the LHL and HHL layers oriented beams S5B-1 and S6B-1 with the treated surface show a slightly higher stiffness than the untreated beams S4B-1 and S6A-1. However, in case of LLH layers oriented beams, the stiffness increment is noticeable for the treated beam compared to the untreated beam. Hence, it can be said that the adhesion promoter has increased the bond between the steel substrate and conventional adhesives by increasing the stiffness of the surface treated beams at maximum service load.

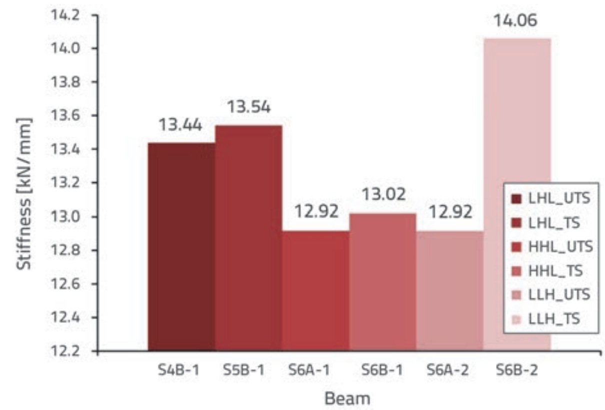


Figure 15. Stiffness of strengthened beams at serviceability limit state (Le/250)

3.3. Composite beam action

Four electrical resistance strain gauges were attached to each of the CFRP-wrapped beams to monitor the overall composite action on both tension and compression sides of the beam. Figure 16 presents the uniform tensile strain increment of both steel

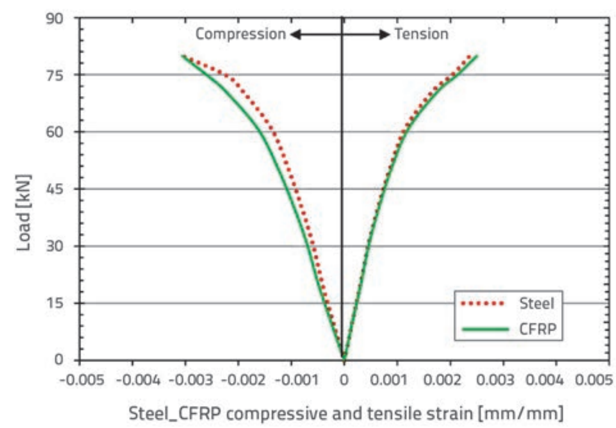


Figure 16. Typical load-strain curves of steel and CFRP for treated beam

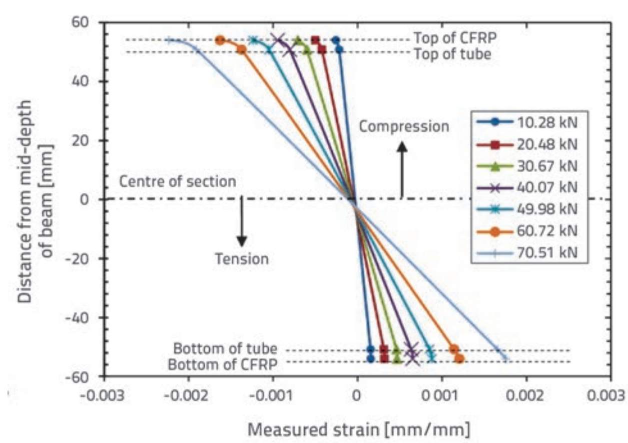


Figure 17. Measured strain variation along depth of treated beam during increased loading

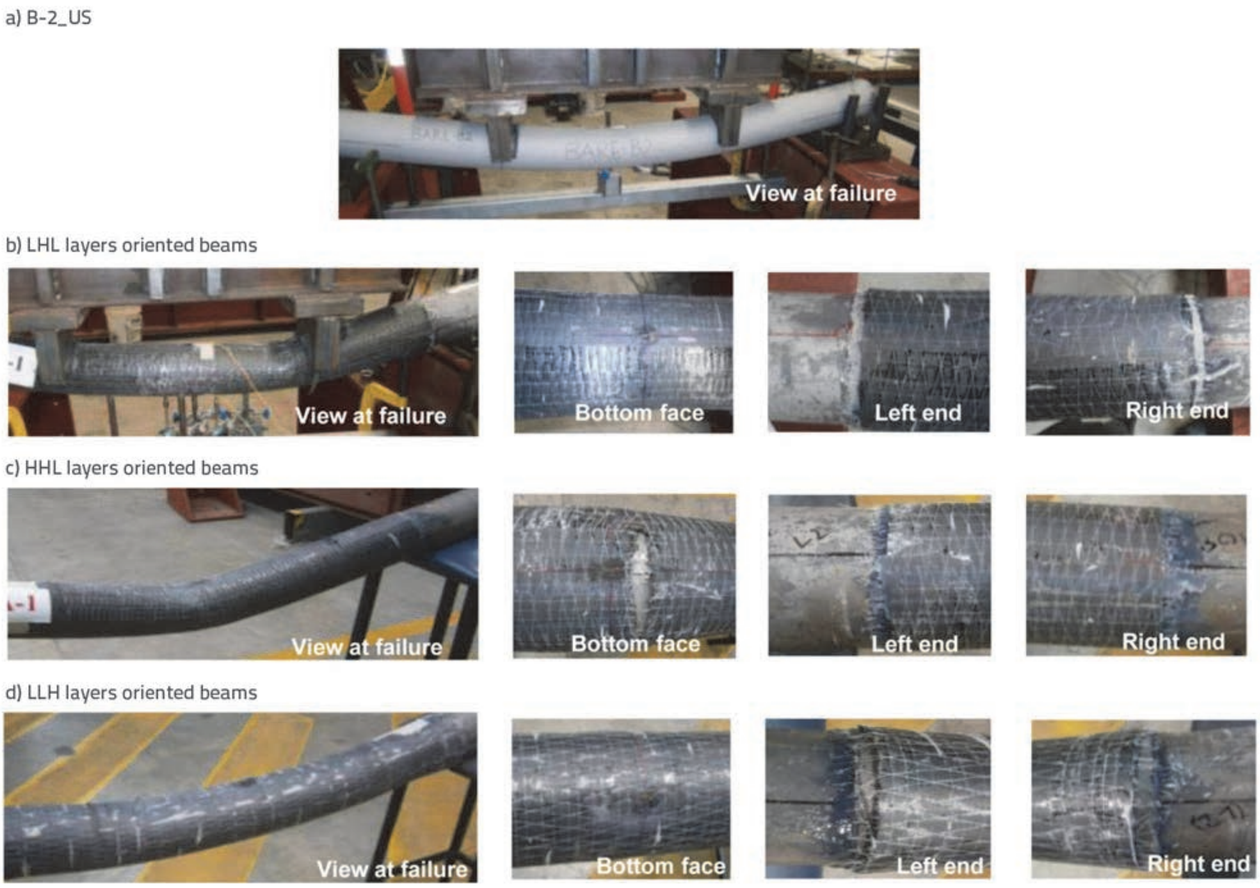


Figure 18. Failure mode of tested beams

and CFRP materials for strengthened treated beams until the recorded 75 kN load. It implies that the composite beam action continues to this point, which is fairly higher than the yield point. The strains from the bottom to top of the strengthened beam section during the increased loading steps are presented in Figure 17. It shows that strains of the CFRP and steel on the tension side of the beam remained linear during the loading period and continued until the recorded load value of 70.51 kN. Hence, it can be said that the sections remained plane and that the composite action was achieved. However, the curving lines in the extreme compression face indicate that the section behaved in a non-linear manner starting at lower strains, and that this behaviour became more evident at higher load. This phenomenon may happen due to gradual de-bonding and micro-buckling of fibres on the compression side of the beam. Based on this observed fact, it can be said that the composite action at the compression side was partially active, and thus the neutral axis of the beam shifted slightly towards the tension zone. The observation for composite beam action presented here is in good agreement with the findings of Seica and Packer [24].

3.4. Failure modes of tested beams

Failure modes of the tested unstrengthened and strengthened beams with various layers orientation are shown in Figure 18. Typical ductile modes of failure were displayed by all specimens during the testing. It can be seen that the failure occurred at both LHL and LLH layers oriented beams due to local buckling of the tubular hollow section in the compression zone near the loading points where the crushing of fibre layers was also observed. This type of failure indicates that the reinforced beam failed before reaching its full flexural capacity, and that the local buckling of the tube wall in compression zone was initiated before the CFRP composite rupturing at the tension face of the beam. It can also be noticed that a minor debonding occurred at the tension face of both beam ends and that it continued up to the loading points. It may be due to huge stress concentration at ends**.** The CFRP composites at the tension face remained intact. On the other hand, the failure modes of strengthened beams S6A-1and S6B-1 having HHL layers orientation were totally different. It was observed that the HHL layers oriented beams failed by the complete CFRP rupturing and by steel yield at the tension face. The fibres at the compression face also crushed, and the steel also yielded. This type of failure mode is usually found in under-reinforced beams subjected to bending. No end de-bonding was found for HHL layers oriented beams until failure. This change of failure mode is interesting. However, it can be said that the full capacity of the section was utilized in that case, and that it may be due to the replacement of one longitudinal layer with one hoop layer of CFRP composites.

4. Conclusions

The effects of fibres layer orientation on structural behaviour of CFRP strengthened tubular steel members were investigated in this paper. The LHL and LLH layers oriented epoxy treated beams performed very similarly in terms of resistance to ultimate load. In addition, the adhesion promoter such as the MBrace primer was found to enhance the strength and stiffness of various layer oriented beams. The following conclusions can be drawn based on the study presented in this paper:

1. The strengthened tubular steel members with three layers of CFRP configuration and various layer orientations presented the maximum service and ultimate load that is by about 43 % and 33 % higher than the load observed for the unstrengthened beam. The strength variations among untreated beams and treated beams were marginal, and LHL and LLH layers oriented treated beams performed slightly better than HHL layers oriented treated beams. Moreover, the treated beams with LHL, HHL and LLH layers orientation showed a slightly higher ultimate load than the corresponding untreated beams.
2. The unstrengthened and all strengthened beams with various fibre orientations showed similar stiffness behaviour when the applied load was relatively low. But at higher load, a significant increase in stiffness was observed for all strengthened beams compared to unstrengthened beams. In the elastic region, the stiffness behaviour was also identical for all strengthened beams with various layer orientations. Treated beams showed a slightly higher stiffness than untreated beams at maximum service load. The stiffness differences among untreated beams with various layer orientations were significant in the plastic region. However, these differences were marginal for treated beams with an exception of the HHL layers oriented beam.
3. The composite beam action of CFRP strengthened beams was present until a certain load. Two different types of failure modes were observed for strengthened beams with various layer orientations. The LHL and LLH layers oriented untreated and treated beams failed by showing local buckling of the tube wall and crushing of fibre layers in the compression zone near loading points. However, the HHL layers oriented untreated and treated beams failed by complete CFRP rupturing and steel yield at the tension face. The fibres at the compression face also crushed and steel also yielded.
4. Although the difference in performance between LHL and LLH layers oriented treated beams was found to be very marginal, both layer orientations can be adopted for strengthening steel CHS members subjected to bending. However, from the theoretical point of view. it is advisable to use LHL layers orientation to minimise moisture infiltration in wet environments.

Acknowledgement

The authors would like to thank Queensland University of Technology (QUT) for providing support to the realization of the work reported in this paper. The authors would also like to express their gratitude to all persons that contributed to their work either directly or indirectly.

LITERATURA

[1] Wardenier, J.: Hollow Sections in Structural Applications, Comité International pour le Développement et l'Etude de la Construction Tubulaire, The Netherlands, 2001.

[2] Tavakkolizadeh, M., Saadatmanesh, H.: Strengthening of Steel-Concrete Composite Girders using Carbon Fiber Reinforced Polymers Sheets, Journal Of Structural Engineering-ASCE, 129, pp. 30-40, 2003., http://dx.doi.org/10.1061/(ASCE)0733-9445(2003)129:1(30)

[3] Teng, J.G., Chen, J.F., Smith, S.T., Lam, L.: FRP-Strengthened RC Structures, West Sussex, United Kingdom, John Wiley and Sons Ltd, 2002.

[4] Zhao, X.-L.: FRP-strengthened metallic structures, CRC Press, 2014.

[5] Alsayed, S., Al-Salloum, Y., Almusallam, T.: Fibre-Reinforced Polymer Repair Materials - Some Facts, Proceedings of the Institution of Civil Engineers-Civil Engineering. London, Thomas Telford Services Ltd, pp. 131-134, 2000., http://dx.doi.org/10.1680/cien.2000.138.3.131

[6] Cromwell, J., Harries, K., Shahrooz, B.: Environmental Durability of Externally Bonded FRP Materials Intended for Repair of Concrete Structures, Construction and Building Materials, 25, pp. 2528-2539, 2011., http://dx.doi.org/10.1016/j.conbuildmat.2010.11.096

[7] López, C., Firmo, J., Correia, J., Tiago, C.: Fire Protection Systems for Reinforced Concrete Slabs Strengthened with CFRP Laminates, Construction and Building Materials, 47, pp. 324-333, 2013., http://dx.doi.org/10.1016/j.conbuildmat.2013.05.019

[8] Firmo, J., Arruda, M., Correia, J.: Contribution to the Understanding of the Mechanical Behaviour of CFRP-Strengthened RC Beams Subjected to Fire: Experimental and Numerical Assessment, Composites Part B: Engineering, 66, pp. 15-24, 2014., http://dx.doi.org/10.1016/j.compositesb.2014.04.007

[9] Haritos, N., Hira, A.: Repair and Strengthening of RC Flat Slab Bridges using CFRPs, Composite Structures, 66, pp.555-562, 2004., http://dx.doi.org/10.1016/j.compstruct.2004.05.003

[10] Haritos, N., Hira, A., Mendis, P., Perera, U.: Repair and Strengthening of Reinforced Concrete Structures Using CFRPs, Advances in Structural Engineering, 9, pp.1-9, 2006. http://dx.doi.org/10.1260/136943306776232882

[11] Fawzia, S., Al-Mahaidi, R., Zhao, X.: Experimental and Finite Element Analysis of a Double Strap Joint between Steel Plates and Normal Modulus CFRP, Composite Structures, 75, pp.156-162, 2006., http://dx.doi.org/10.1016/j.compstruct.2006.04.038

[12] Fawzia, S., Zhao, X., Al-Mahaidi, R.: Bond-Slip Models for Double Strap Joints Strengthened by CFRP, Composite Structures, 92, pp. 2137-2145, 2010., http://dx.doi.org/10.1016/j.compstruct.2009.09.042

[13] Narmashiri, K., Jumaat, M., Sulong, N.H.R.: Strengthening of Steel I-Beams Using CFRP Strips: An Investigation on CFRP Bond Length, Advances in Structural Engineering, 15, pp. 2191-2204, 2012., http://dx.doi.org/10.1260/1369-4332.15.12.2191

[14] Fawzia, S.: Evaluation of Shear Stress and Slip Relationship of Composite Lap Joints, Composite Structures, 100, pp. 548-553, 2013., http://dx.doi.org/10.1016/j.compstruct.2012.12.027

[15] Mertz, D.R., Gillespie, Jr. J.W.: Rehabilitation of Steel Bridge Girders through the Application of Advanced Composite Materials, 1996.

[16] Linghoff, D., Haghani, R., Al-Emrani, M.: Carbon-Fibre Composites for Strengthening Steel Structures, Thin-Walled Structures, 47, pp. 1048-1058, 2009., http://dx.doi.org/10.1016/j.tws.2008.10.019

[17] Colombi, P., Poggi, C.: An Experimental, Analytical and Numerical Study of the Static Behavior of Steel Beams Reinforced by Pultruded CFRP Strips, Composites Part B, 37, pp. 64-73, 2006., http://dx.doi.org/10.1016/j.compositesb.2005.03.002

[18] Shaat, A., Fam, A.: Axial Loading Tests on Short and Long Hollow Structural Steel Columns Retrofitted using Carbon Fibre Reinforced Polymers, Canadian Journal of Civil Engineering, 33. pp. 458-470, 2006., http://dx.doi.org/10.1139/l05-042

[19] Bambach, M.R., Jama, H.H., Elchalakani, M.: Axial Capacity and Design of Thin-Walled Steel SHS Strengthened with CFRP,Thin-Walled Structures, 47, pp. 1112-21, 2009. http://dx.doi.org/10.1016/j.tws.2008.10.006

[20] Teng, J.G., Hu, Y.M.: Behaviour of FRP-Jacketed Circular Steel Tubes and Cylindrical Shells under Axial Compression, Construction and Building Materials, 21, pp. 827-838, 2007., http://dx.doi.org/10.1016/j.conbuildmat.2006.06.016

[21] Jiao, H., Zhao, X.L.: CFRP Strengthened Butt-Welded Very High Strength (VHS) Circular Steel Tubes, Thin-Walled Structures, 42, pp. 963-978, 2004., http://dx.doi.org/10.1016/j.tws.2004.03.003

[22] Fawzia, S., Al-Mahaidi, R., Zhao, XL., Rizkalla, S.: Strengthening of Circular Hollow Steel Tubular Sections using High Modulus CFRP Sheets. Construction and Building Materials, 21, pp. 839-845, 2007., http://dx.doi.org/10.1016/j.conbuildmat.2006.06.014

[23] Haedir, J., Bambach, M.R., Zhao, X.L., Grzebieta, R.H.: Strength of Circular Hollow Sections (CHS) Tubular Beams Externally Reinforced by Carbon FRP Sheets in Pure Bending, Thin-Walled Structures, 47, pp. 1136-1147, 2009., http://dx.doi.org/10.1016/j.tws.2008.10.017

[24] Seica, M.V., Packer, J.A.: FRP Materials for the Rehabilitation of Tubular Steel Structures, for Underwater Applications, Composite Structures, 80, pp. 440-450, 2007., http://dx.doi.org/10.1016/j.compstruct.2006.05.029

[25] Dawood, M., Rizkalla, S.: Environmental Durability of A CFRP System for Strengthening Steel Structures, Construction and Building Materials, 24, pp. 1682-1689, 2010., http://dx.doi.org/10.1016/j.conbuildmat.2010.02.023

[26] BASF Construction Chemicals Australia Pty Ltd,: MBrace Application Guidelines (MBrace Fabric), 11 Stanton road seven hills, NSW 2147, Australia, 2009.