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The influence of strengthening the hollow steel tube and CFST beams using U-shaped CFRP wrapping scheme

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Abstract. This study investigated the behaviour of the simply supported hollow steel tube (HST) beams, either concrete filled or unfilled when strengthened with carbon fibre reinforced polymer (CFRP) sheets. Eight specimens with varied tubes thickness (sections classification 1 and 3) were all tested experimentally under static flexural loading, four out of eight were filled with normal concrete (CFST beams). Particularly, the partial CFRP strengthening scheme was used, which wrapped the bottom-half of the beams cross-section (U-shaped wrapping), in order to use the efficiency of high tensile strength of CFRP sheets at the tension stress only of simply supported beams. In general, the results showed that the CFRP sheets significantly improved the ultimate strength and energy absorption capacities of the CFST beams with very limited improvement on the related HST beams. For example, the load and energy absorption capacities for the CFST beams (tube section class 1) were increased about 20% and 32.6%, respectively, when partially strengthened with two CFRP layers, and these improvements had increased more (62% and 38%) for the same CFST beams using tube class 3. However, these capacities recorded no much improvement on the related unfilled HST beams when the same CFRP strengthening scheme was adopted.

Keywords: partial wrapping; CFRP strengthening; CFST beams; HST beams; energy absorption

1. Introduction

Recently, the hollow steel tube (HST) and the concrete-filled steel tube (CFST) flexural members are widely used in the modern structural projects. These flexural members may need to be strengthened for different reasons: to carry extra loads and/or need to repair due to degradation attributed to aging, corrosion, environment, fire, and fatigue problems. However, the conventional strengthening methods of the steel members by adding and/or replacing new steel parts often need special tools and long time for repairing works, because of that, it usually leads to an increase in the project cost. Therefore, the engineers have employed the carbon fibre-reinforced polymer (CFRP) sheets as an alternative solution to strengthen and repair the steel and CFST structural members. The CFRP sheets have high tensile strength and elastic modulus values compared to their weight ratio; additionally, these sheets are flexible that can form any structural member shape (Zhao *et al.* 2007).

To date, several researchers have studied the performance of the CFRP composite materials (sheets/plates) when used for strengthening the steel members, including those presented in (Zhao *et al.* 2007, Tashan and Al-mahaidi 2012, Wu *et al.* 2012, Al-Zubaidy *et al.* 2013, Fawzia 2013, Nguyen *et al.* 2013, Yang *et al.* 2013, Al-Mosawe *et al.* 2015, Ou and Nguyen 2016). They have extensively examined the use of different applications of loads (static, cyclic, impact, and thermal loads), strengthening techniques, and the CFRP-steel bonding behaviour. In the last few years, the strengthening and repairing behaviours of simply supported HST beams fully wrapped with CFRP sheets (wrapped the entire beam's cross-section) have been investigated theoretically and experimentally in different studies (Haedir *et al.* 2010, Haedir *et al.* 2011, Elchalakani 2014, Elchalakani 2016), for example. In addition, the influence of using the fully CFRP wrapping scheme for strengthening the CFST beams was investigated (Tao *et al.* 2008, Wang *et al.* 2015, Wang and Shao 2015).

However, in case of simply supported beams, usually the loads were applied onto their top flanges; thus, it could be difficult to full wrap the HST/CFST beams' cross-sections by the CFRP sheets. Up to now, a few studies have experimentally investigated the influence of using a partial CFRP wrapping scheme for strengthening and/or repairing the behaviour of CFST beams (Sundarraja and Prabhu 2013, Al Zand *et al.* 2016, Al Zand *et al.* 2017). In these studies, the bottom-half of CFST beams' cross-sections were strengthened with unidirectional CFRP sheets (U-shaped wrapping scheme), where their fibres laid parallel to the beam's direction. For example, Al Zand *et al.* (2017) experimentally and numerically investigated the strengthening behaviour of the high-strength rectangular CFST beams that were partially wrapped with multiple CFRP layers (U-shaped scheme) under three-point bending. The results showed that the strength capacity of the tested beams increased significantly with increasing the CFRP layers by approximately 40% and 55% for those with compact and slender tubes' sections, respectively, when used four CFRP layers. Moreover, the partially-wrapped CFST beams along 75% and 100% of their lengths with the

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same number of CFRP layers achieved almost similar enhancement ratios since no delamination failure was occurred along the CFRP-steel surface. Generally, unlike the fully CFRP wrapping scheme of HST beams (Elchalakani 2014, Elchalakani 2016), the influence of using partial wrapping scheme (U-shaped scheme) on the behaviour of HST beams has not been investigated yet.

Generally, the design specifications of steel members classify the tubular cross-sections into several groups to identify whether the sections are susceptible to local buckling. Several steel design standards, such as the American Institute of Steel Construction-Load and Resistance Factor Design specification (AISC-1999) and Australian Standard (AS 4100-1998) have classified the tubular sections as Compact, Non-compact or Slender. British Standards (BS 5950-2000) classified the same tubular sections as Plastic, Compact, Semi-compact and Slender. Meanwhile, the Eurocode 3 for the Design of Steel Structures (EC3-2002) classified them as Class 1, 2, 3 or 4. Accordingly, the main aims of this paper is to further investigate the strengthening performance of the rectangular HST simply supported beams using U-shaped CFRP wrapping scheme, and comparing with performance of the CFST beams, particularly when they have the same tube's properties. Eight downscale specimens of rectangular HST beams with two different sections classification (Class 1 and 3), including four specimens were filled with normal concrete (CFST beams), all tested experimentally under four-point bending in the structural laboratory of Universiti Kebangsaan Malaysia (UKM). The study discussed in detail the failure modes, flexural strength capacities, and energy absorption capacities of the tested specimens.

2. Experimental program

2.1 General description

A total of eight specimens of simply supported rectangular HST beams, including 4 specimens filled with normal concrete (CFST beams), were tested under static four-point bending. All steel tubes were with 1,100 mm in length, 75 mm in depth and 50 mm in width, but with different thickness (3.0 mm and 1.5 mm), which were classified as sections Class 1 and 3, respectively. For each tube's section (Class 1 and 3), two specimens were tested as an HST beam, and another two as CFST beams, where one of these HST and CFST specimens was partially strengthened with two CFRP layers, the fibres of these sheets laid parallel along the full beam's length, as shown in Fig. 1. Table 1 presents the details of designations and configurations of the tested specimens, where the numbering system for the tested specimens indicated their type, tube's section class, and the CFRP layers. 'HT' and 'FT' represent the HST and CFST specimens, respectively, and 'C1' and 'C3' stand for the specimens with tube's section of Class 1 and Class 3, respectively. Additionally, '2L' indicates the two CFRP layers that used for the strengthening purpose. In general, the limitations of this research are to investigate the down scale HST beams with rectangular cross-section, L/D equal to 13.6, filled with normal concrete (low strength), and tubes with sections classification of Class 1 and 3 only.

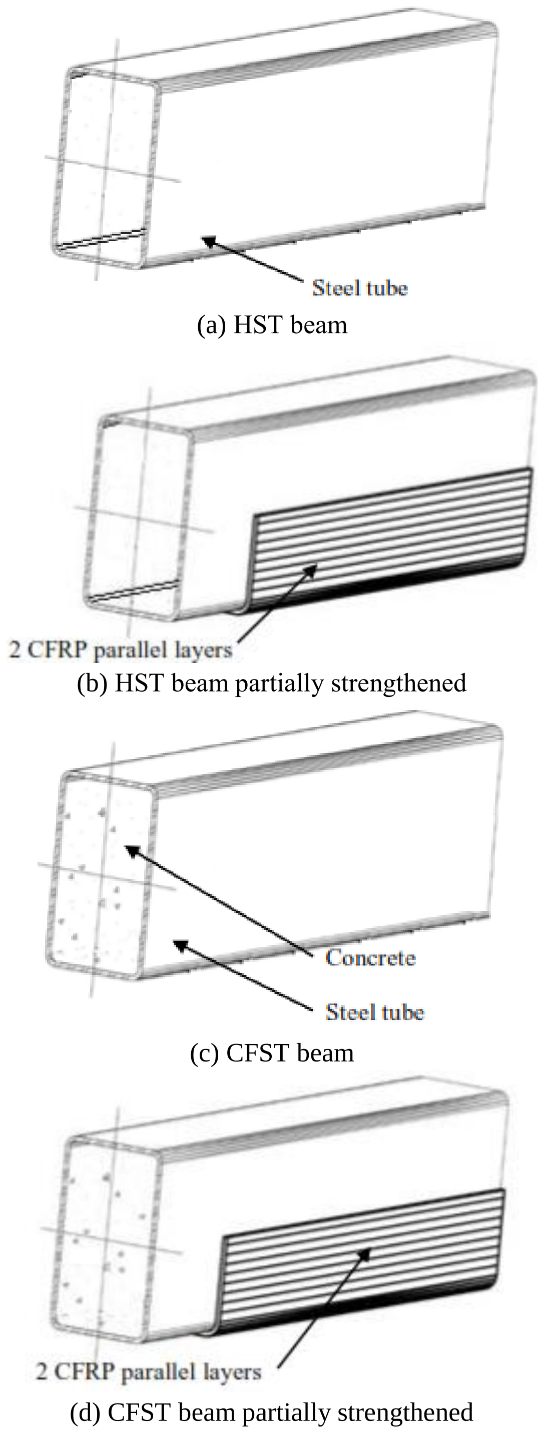
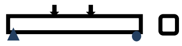
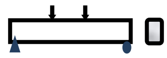
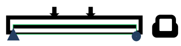
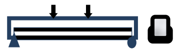


Fig. 1 Specimens with/without U-shaped CFRP wrapping scheme

2.2 Specimens preparations

The steel tubes were placed upright to pour the concrete from top side. During the casting time, the bottom side of each tube was covered temporarily with a plastic sheet to prevent the water of the concrete from leaking out. After 20 days from the concrete casting, the tubes' surfaces were

Table 1 Rectangular HST and CFST specimens' designations and CFRP strengthening schemes

No.	Specimens designation	Beam's type	Tube section classification	CFRP layers (L)	Specimens configuration
1	HT-C1	Hollow tube (HST)	Class1	-	
2	HT-C3	Hollow tube (HST)	Class3	-	
3	FT-C1	Concrete filled tube (CFST)	Class1	-	
4	FT-C3	Concrete filled tube (CFST	Class3	-	
5	HT-C1-2L	Hollow tube (HST)	Class1	2	
6	HT-C3-2L	Hollow tube (HST)	Class3	2	
7	FT-C1-2L	Concrete filled tube (CFST)	Class1	2	
8	FT-C3-2L	Concrete filled tube (CFST)	Class3	2	

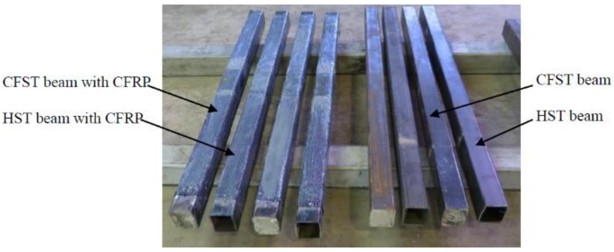
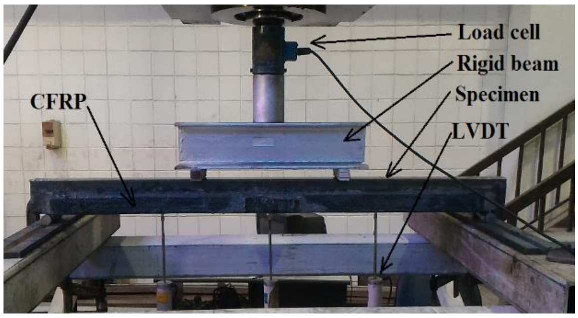
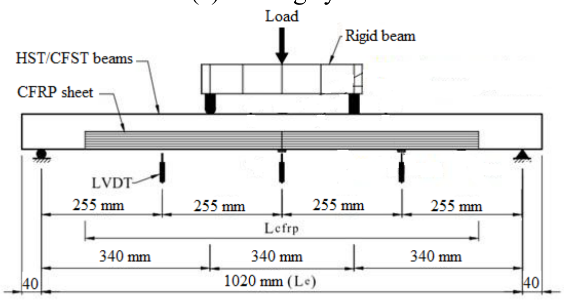


Fig. 2 HST and CFST specimens strengthened/unstrengthened with CFRP sheets



(a) Test rig system



(b) Specimens test arrangement

Fig. 3 Test setup of HST and CFST specimens

cleaned totally by wet fabric. For the specimens selected to strengthen with CFRP sheets, an electrical grinder with a sandpaper of grit #24 was used to clean their surface and improve the bond interlocking with the epoxy (see Fig. 2). Acetone liquid was used to clean the grinded surface before the application of the epoxy material and CFRP sheets. The epoxy was mixed in accordance with the manufacturer's instructions. Then, the layers of CFRP sheets were applied in parallel to the beam's direction. A special ribbed roller was used after the application of each CFRP layer in order to remove the air void between the layers. All specimens were cured at room temperature. The HST and CFST specimens are presented in Fig. 2.

2.3 Material properties

Eight cold-formed hollow steel tubes with rectangular cross-section were used (75×50×1.5 mm and 75×50×3.0 mm). For the tensile test, three coupons were cut and prepared based on ASTM E8-2009. The values of steel yielding strength and modulus of elasticity, which were obtained from the coupons tests, were equal to 352.3 MPa and 203.8 GPa, respectively. In the current study, the Eurocode 3 (EC3 2002) was used to classify the tubes' cross-sections based on their width-to-thickness ratio. Normal concrete with mixing ratio equal to 1:3:6 by weight and a 0.47 water/cement ratio was used as a filler material for the CFST beams. The average compressive strength obtained during 28 days from the cubes test was 20.5 MPa. The SikaWrap-231C was the brand type of the unidirectional CFRP fabric sheet used for strengthening purpose, and Sikadur-330 was the adhesive material (epoxy). The properties of CFRP sheets are 0.13 mm, 3224 MPa, 1.8% and 228.8 Gpa for the sheet's thickness, tensile strength, ultimate strain and Modulus of elasticity, respectively, and for epoxy material the tensile strength, ultimate strain and modulus of elasticity are equal to 80 MPa, 0.9% and 4.5 GPa, respectively, which are the same properties given in (Al Zand *et al.* 2016; Al Zand *et al.* 2017).

2.3 Test setup

In order to achieve the four-point bending, a manual hydraulic jack with a capacity of 300 kN was used. The load gradually increased with average rate approximately 4-5 kN/min. Three linear variable displacement transducers (LVDTs) were placed equally under the specimens to measure and record the changing in deflection values during the loading stages. The test rig system and the specimen's test arrangement are shown in Fig. 3. The data obtained from the LVDTs and load cell at each loading step of the tested specimens was recorded in a computerised data acquisition system.

3. Test results and discussion

3.1 Failure modes

In general, the failure modes of hollow tube beams are different from those of CFST beams. Before the HST beams achieved their ultimate capacity, for both of specimens HT-C1 and HT-C3, inward buckling occurred at the top flange (at the loading points), which was immediately followed by outward web buckling. However, the same tube sections with concrete infill (FT-C1 and FT-C3 beams) showed limited outward buckling at the top flange and web once these beams reached their ultimate capacity. Because of the infill concrete, it significantly prevented/delayed the inward

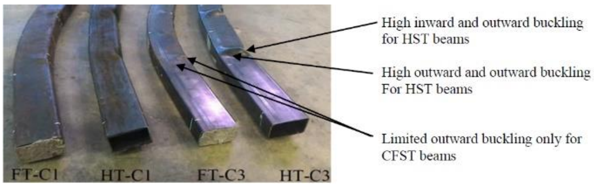


Fig. 4 Typical buckling failure of HST and CFST specimens

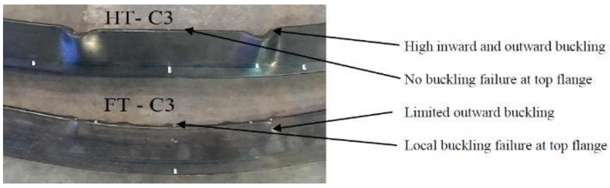


Fig. 5 Comparison between the failure modes of HST and CFST specimens-Class 3

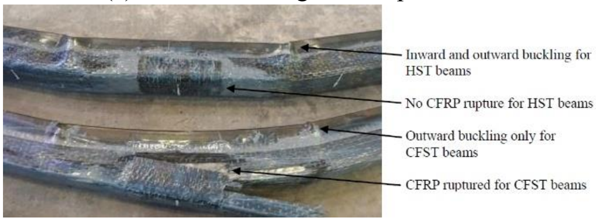
local buckling of tubes at the compression zones. The difference in tube buckling failure for the HST and CFST beams are shown in Fig.4. Furthermore, the HST specimen with Class 1 (HT-C1) showed less buckling failure than that with Class 3 (HT-C3), which was a logic behaviour since it had a thicker tube's thickness. Unlike the hollow specimens HT-C3 (tube section Class 3), multi outward local buckling were observed at the top flange (the distance between the two loading points) have been observed for the concrete filled specimen FT-C3 (see Fig. 5).

When the CFST specimens strengthened with CFRP sheets almost reached their ultimate capacity (90-95% of M_u), a typical outward buckling failure was recorded near the loading point. At this loading limit, the CFRP sheets started to crack from the bottom mid-span, after that, these sheets were ruptured totally once achieved its ultimate tensile strength (see Fig. 6). For any of the strengthened CFST specimens, no CFRP debonding failure was observed/recorded. However, for all of HST specimens strengthened with CFRP sheets (HT-C1-2L and HT-C3-2L specimens), a typical inward and outward buckling failure occurred at the loading points, just similar to that occurred for the unstrengthened hollow specimens (HT-C1 and HT-C3). Generally, the failure modes of the HST and CFST specimens strengthened partially with CFRP sheets shown in Fig. 6. No concrete-tube slip failure was observed at ends of CFST beams during the tests.

3.1 Moment-deflection relationships

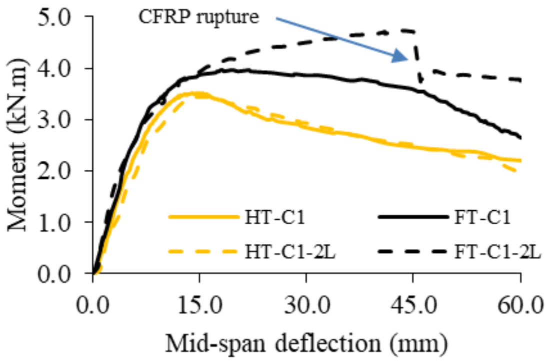
The moment vs. mid-span deflection relationships of the tested specimens are presented in Fig. 7. Generally, all beams showed an elastic behaviour at the initial loading stage, then their flexural stiffness decreased gradually at the inelastic stage until reached the ultimate moment capacity (Mu). Specifically, the strengthened CFST beams exhibited a sudden drop in their curves due to the CFRP patch rupture failure that occurred once achieved its tensile strength, where at this point, the Mu value was recorded for the strengthened beams. After the effects of CFRP absence, the CFST specimen's behaviour returned back similar to that of its unstrengthened specimen (the control specimen). Furthermore, regardless of the class level of steel tubes' sections (Class 1 or Class 3), the HST beams partially strengthened with CFRP sheets achieved no loads enhancements, see the behaviour of specimens HST-C-2L and HST-C3-2L presented in Fig. 7(a) and (b), respectively. This was because the CFRP sheets could only improve the tensile capacity at the bottom flange (tension flange) of

(a) all CFRP strengthened specimens

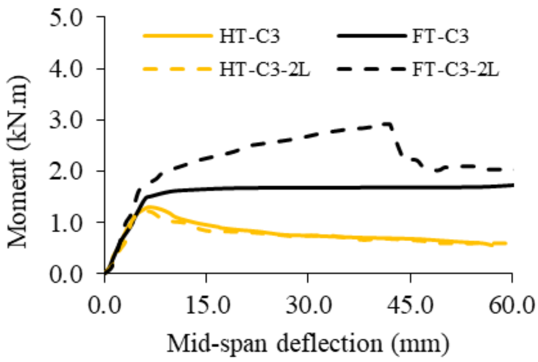


(b) Comparison of CFRP failure (HST and CFST beams-tube class 3)

Fig. 6 Typical failure modes of HST and CFST specimens partially strengthened with CFRP

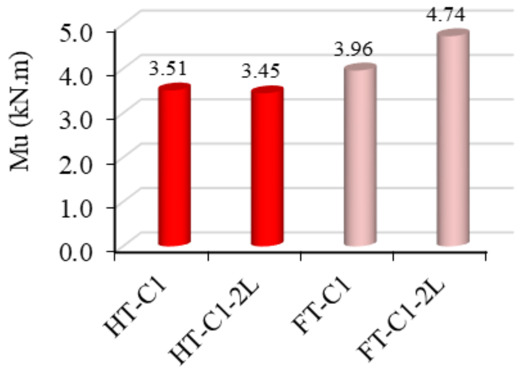


(a) Specimens with tube Class 1

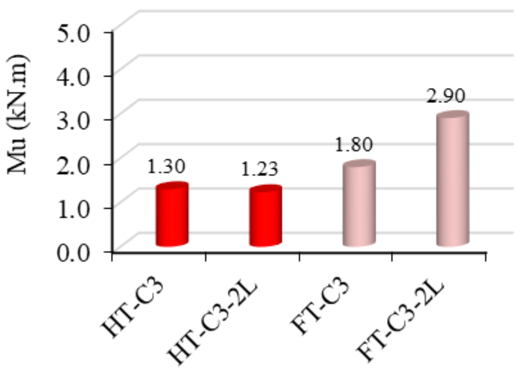


(b) Specimens with tube Class 3

Fig. 7 Moment-deflection relationships of the tested specimens

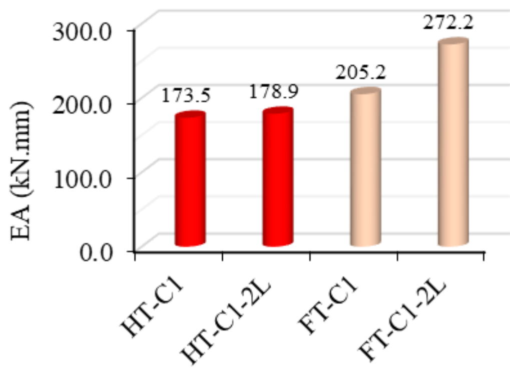


(a) Specimens with tube Class 1

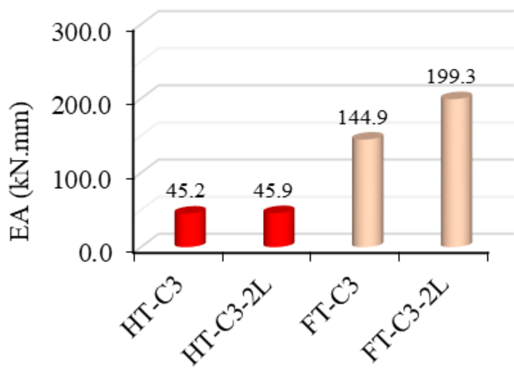


(b) Specimens with tube Class 3

Fig. 8 Moment capacity (M_u) of the tested specimens



(a) Specimens with tube Class 1



(b) Specimens with tube Class 3

Fig. 9 Energy absorption (EA) capacity

Table 2 Summary of the test results of rectangular HST and CFST specimens

No.	Specimens designation	M_u (kN.m)	FIR	SIR	EA (kN.mm)
1	HT-C1	3.51	-	-	173.5
2	HT-C1-2L	3.45		0.98	178.9
3	FT-C1	3.96	1.13	-	205.2
4	FT-C1-2L	4.74		1.20	272.2
5	HT-C3	1.30	-	-	45.2
6	HT-C3-2L	1.23		0.96	45.9
7	FT-C3	1.80	1.38	-	144.9
8	FT-C3-2L	2.90		1.62	199.3

hollow tube beam, and the top flange alone could not delay/prevent the inward buckling that occurred underneath the point loads, unlike the CFST beams (the inward buckling prevented by providing the concrete infill). Thus, using partial CFRP wrapping scheme (U-shaped scheme) was found much significant for strengthening the CFST beams than the HST beams.

3.3 Moment carrying capacity

This section presents and discusses the ultimate moment capacities (M_u) of the tested specimens. As discussed earlier, the moment capacity of the HST specimens was not improved when partially strengthened with CFRP sheets, unlike the CFST specimens, as shown in Fig. 8. Again, this was because the CFRP sheets strengthened the bottom flange (tension flange) of the beams with no influence on the top flange; since these sheets can resist the tensile stress only. For example, the M_u value of HT-C1 was equal to 3.51 kN.m, this value remained almost the same (3.46 kN/m) when strengthened with two CFRP layers (HT-C1-2L). Meanwhile, the M_u value for the same tube section filled with concrete (FT-C1) was equal to 3.96 kN.m, and this value increased about 20% when the same CFRP strengthening scheme was used (FT-C1-2L), which achieved approximately 3.96 kN.m (see Fig. 8(a)). Similar behaviour was recorded for the strengthened HST and CFST specimens with Class 3 (see Fig. 8(b)) but with different values.

Furthermore, Table 2 presents the filled improvement ratio (FIR) estimated from the ratios of M_u value of the concrete-filled specimens-to-the value of related hollow tube specimens, also shows the strengthened improvement ratios (SIR) that estimated from the ratios of M_u values of the strengthened specimen-to-the value of related unstrengthened specimen. In general, the infill concrete significantly improved the load's capacity of the hollow tube beams with Class3, much more than those with Class 1, where the specimen FT-C3 achieved FIR equal to 1.38 (+38%) compared to the capacity of its reference specimen (HT-C3), while the specimen FT-C1 achieved only 1.13

(+13%) compared to its reference specimen HT-C1. Moreover, this load's improvement of the filled tube beams led to improvement of the response of CFST beams when partially strengthened with CFRP sheets, much more than those for the HST beams. For example, both of specimens HT-C1 and HT-C3 achieved SIR equal to 0.98 and 0.96, respectively, when strengthened with two CFRP sheets (HT-C1-2L and HT-C3-2L). Meanwhile, the specimens FT-C1 and FT-C3 achieved SIR equal to 1.20 (+20%) and 1.62 (+62%), respectively, when used the same strengthening scheme (specimens FT-C1-2L and FT-C3-2L).

3.4 Energy absorption

The capacity of HST and CFST beams for absorbing the energy before and after being strengthened with CFRP sheets are discussed in this section, where it was estimated by calculating the areas under the curves of load-deflection (Al Zand *et al*. 2016). The values of energy absorption (EA) capacities for the tested specimens are presented in Table 2 and Fig. 9. The CFRP sheets significantly improved the EA capacities of the CFST beams more than that of HST beams, since they achieved higher load enhancements compared to their control specimens. For example, the HST specimens partially strengthened with 2 CFRP sheets (i.e., HT-C1-2L and HT-C3-2L) achieved EA capacities equal to 178.9 kN.mm and 45.9 kN.mm, respectively, where these values were almost remained the same as the unstrengthened specimens HT-C1 and HT-C3 (173.5 kN.mm and 45.2 kN.mm, respectively). Meanwhile, the EA capacities of the specimens FT-C1 and FT-C3 were of about 205.2 kN.mm and 144.9 kN.mm, respectively; these values were improved by approximately +32.6% and +37.5% when these beams partially strengthened with two CFRP sheets (FT-C1-2L and FT-C3-2L, respectively).

5. Conclusions

The flexural behaviour of the simply supported hollow steel tube (HST) and concrete-filled steel tube (CFST) beams that partially strengthened with CFRP sheets were investigated under static flexural loading. The conclusions drawn of the study are summarised as follow:

• Generally, the CFST beam showed limited local buckling failure once achieved its ultimate capacity compared to the related HST beams. The inward local buckling failure of tubes of the CFST beams was significantly delayed due to the influence infill concrete. The concrete filled improvement ratio (FIR) for the specimens with tube's Class 1 achieved 1.13, while for specimens with tube's Class 3 achieved 1.38.

• Unlike the HST beam, using partial CFRP strengthening scheme (U-shaped scheme) significantly improved the load's capacity of the CFST beam, where the load's improvement ratio of the strengthened beams mainly depended on the tube's thickness (section Class 1 or 3). For example, both of CFST specimens with Class 1 and 3 achieved load's improvement ratio of about 1.2 and 1.62, respectively, when strengthened with two CFRP sheets, compared to their control specimens (unstrengthened specimens). Meanwhile, the load's capacity ratios of the related HST beams were not improved much when the same strengthening scheme was used, which remained of about 0.98 compared to their unstrengthened specimens.

• Due to the influence of the infill concrete, the CFST beams could absorb more energy than the HST beams, which are equal to 205.2 kN.mm and 173.5 kN.mm, respectively, for specimens with tube Class 1 as example. Therefore, the CFRP strengthened CFST beam achieved higher energy absorption (EA) capacity compared to the related strengthened HST beam. For tubes with Class 1, the EA capacity of the CFST and HST specimens increased about +32.6% and +3.1%, respectively, when strengthened with two CFRP layers.

• In order to investigate further the strengthening performance of the HST beams (filled/unfilled with concrete material) when partially strengthened with CFRP sheets/plate, more testes are recommended to be done on large beams' scale, varied beams' cross-sections, using different types of concrete filler and different types of loading (impact, cyclic and long term of static loads).

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