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Torsional strengthening of steel circular hollow sections (CHS) using CFRP composites

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ABSTRACT

The use of carbon fibre reinforced polymer (CFRP) for strengthening of steel members has attracted increasing attentions in the structural engineering community. However, there is still a lack of understanding on the mechanisms of CFRP strengthening of steel tubular sections which are subjected to torsion. This paper presents a comprehensive experimental study on the effectiveness of the CFRP material for strengthening of steel circular hollow section (CHS) under pure torsion. Five different types of CHSs with various diameters and wall thicknesses were selected. Furthermore, five different types of CFRP strengthening schemes were used with the fibers aligned in different angles respect to the axial direction of the CHSs. In order to investigate the wrapping sequence, spiral (S) and reverse spiral (R), different mixed S/R schemes, such as SRRR vs. RRRS and etc., were applied to the CHSs. The abbreviations of the wrapping scheme, such as SRRR, refer to four strengthening layers with the spiral (S) and reverse spiral (R) wrapping directions. Various failure modes of the CFRP-strengthened specimens were observed including CFRP rupture, CFRP crushing and adhesive cracking without fiber failure. It was found that the CHS with larger diameter and thickness benefit the most from the CFRP strengthening scheme. In addition, S wrapping was found to be the most effective strengthening scheme. Finally, in order to achieve the best strengthening performance of the system for a mixed S/R CFRP strengthening scheme, it was recommended to apply the S wrapping inside. A theoretical model was proposed for the prediction of the torsional capacities of the CHS specimens. Reasonable agreement was achieved between the predictions and the experimental results.

1. Introduction

1.1. Carbon fiber reinforced polymer (CFRP) strengthening of steel members

CFRP has shown great potential for strengthening of steel structures due to their outstanding mechanical properties such as high strength to weight ratio, resistance to harsh environmental effects and superior fatigue behavior [1–6]. Previous studies have shown that application of the CFRP composites to steel structures can enhance their flexural capacity [7], buckling strength [8,9], stiffness [10–12] and fatigue behavior [13–15]. CFRP strengthening has resulted in a significant fatigue life extension [10,11,16–18] and even a complete fatigue crack arrest [19,20] in steel members with existing cracks [10,11,16–18]. CFRP strengthening has been also used to increase the stability of steel members subjected to dynamic and impact loading scenarios [21–23]. Furthermore, it has been proved that CFRP strengthening can significantly increase the flexural [24–26] and fatigue [27,28] behavior of steel beams [24–26].

The efficiency of CFRP composite to improve the web crippling behavior of thin-walled steel hollow sections, which are subjected to transverse concentrated loading, have been also shown in [29–31]. Such steel hollow sections are often used in bridges, buildings, cranes, offshore structures and etc. Despite of all these studies, steel hollow sections could also experience torsion loading when they are subjected to complex external loadings especially in connections. In particular, when a steel hollow section with a specific shape/pattern has to follow a special architectural design requirement, an unpredicted torsion, which has not been originally considered in its design, may become severe. Nevertheless, there exists very limited research on the torsional strengthening of steel structures using CFRP composites [32]. Therefore, there is a need for studies that fill this research gap and provide a better understanding on the problem.

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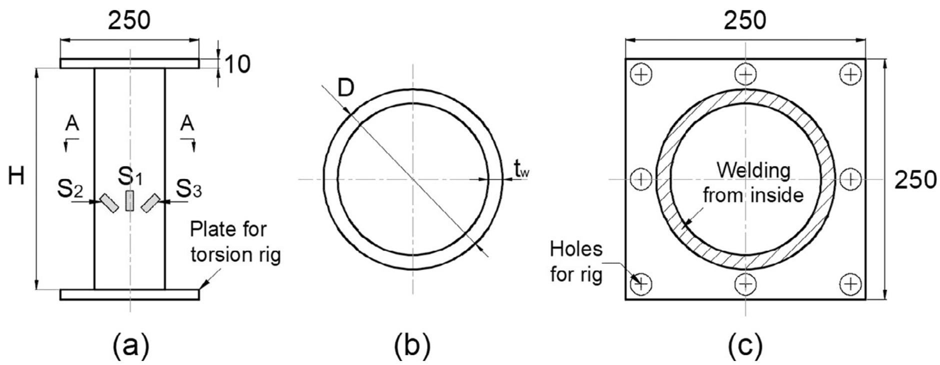

Fig. 1. Dimensions and symbols of (a) the specimen; (b) section A-A and (c) top view of the CHS (not to scale, dimensions in mm).

1.2. Torsional strengthening of concrete structures using CFRP

Despite of this background, extensive studies on the torsional strengthening of concrete structures using CFRP have been done since 2001 [33–35]. Therefore, the experiences gained in the concrete structures can be resorted to assist the understanding of CFRP torsional strengthening of steel structures. Matthys and Triantafillou [35] were among the first researchers discussing the potential application of CFRP composites for torsional strengthening of concrete beams. The torsional capacity of the beams was improved by CFRP strengthening and they proposed that the contribution of CFRP could be similar to the steel stirrups. Ghobarah et al. [36] have conducted experimental investigations on the torsional behavior of rectangular concrete beams with various CFRP strengthening schemes, e.g. full wrapping, vertical discrete strips at various distances and also inclined strips. Only one layer of CFRP was used for all the strengthening patterns. Their research has been then extended to concrete beams with T sections in [37], and, again, various CFRP strengthening patterns were investigated.

Different CFRP anchorage systems have been designed and developed for the CFRP torsional strengthening system. Hii and Al-Mahaidi [38–40] have conducted a series of torsional testing [38–40] on both solid and box-section concrete beams strengthened with CFRP composites. Discrete CFRP strips have been used with fibers aligned in vertical direction. Several other similar studies [41–43] exist in the literature that report the behavior of concrete beams strengthened with CFRP composites subjected to torsion [41–43]. After reviewing the works conducted on torsional strengthening of concrete structures using CFRP, it can be summarized that (1) continuous wrapping the whole surface of the member is more effective than wrapping with discrete CFRP strips, and (2) wrapping CFRP with the fibers aligned at 45° in the spiral direction is more effective than wrapping fibers aligned in the vertical direction.

1.3. Torsional strengthening of steel members using CFRP

There are very limited studies on the torsional strengthening of steel members using CFRP. The first work has been conducted by Chahkand et al. [32] in 2013. A steel square hollow section with a width of 50 mm and a thickness of 3 mm has been strengthened with four different CFRP wrapping schemes. Six specimens were tested under pure torsion with two control specimens (without CFRP strengthening) and four strengthened specimens. Theoretical model was developed using the equivalent thickness approach, which transferred the thickness of CFRP into equivalent steel thickness. The plastic torsional capacity of the strengthened steel tube was defined at the onset of yielding of the steel. It has been concluded that the effectiveness of the strengthening is dependent on the CFRP reinforcement ratio and wrapping scheme. This work has concluded that the best performance is achieved when the CFRP fibers are applied in the direction of the principle tensile stress. Although this work has provided valuable experience for torsional strengthening of steel members using CFRP, the experimental results are limited to only one steel rectangular section. In addition, yielding of the steel tube has been observed, which was the reason for using yielding capacity in their theoretical model. Nevertheless, thin-walled tubular sections may also experience local buckling under pure torsion. Therefore, it is necessary to extend the work to more common steel tubular sections so that some generalized observations and conclusions can be made.

This paper presents an experimental program on the torsional strengthening of steel circular hollow sections (CHS) with CFRP composites. Five CHSs were selected and strengthened with various CFRP schemes. A special testing rig was designed and fabricated which could apply a rotation angle of up to forty degrees to the CHS specimens. The variables in the experimental program include the CHS dimensions such as the diameter and wall thickness, the CFRP wrapping angle with respect to the axial direction of the specimen, and the CFRP strengthening schemes. The failure modes of CHS with and without CFRP strengthening were reported. The effects of CHS dimensions, CFRP wrapping direction, and CFRP wrapping sequence on the strengthening performance were discussed. Finally, a series of recommendations were provided for the design of CFRP-strengthened CHSs for an improved torsional performance.

2. Experimental program

2.1. Materials

The cross section and dimension symbols of the CHS are presented in Fig. 1. In the present study, five CHSs were used with three different diameters and three wall thicknesses. Their measured dimensions are listed in Table 1. In order to study the effect of the size of the specimens, the CHS1, CHS2 and CHS3 have the same nominal wall thickness of 3 mm but different nominal diameters of 88 mm, 100 mm and 114 mm. Similarly, the effect of the wall thickness was studied by comparing CHS3, CHS4 and CHS5 which have an identical nominal diameter of 114 mm but different nominal wall thicknesses of 3 mm, 4 mm and 5 mm. Each of the CHSs was cut into a length of four times of its diameter.

The CHSs were provided by the Orrcon Operations Pty Ltd,

Table 1
Measured dimensions and material properties of the CHSs.

Section ID	Diameter, D (mm)	Thickness, t_w (mm)	Length, L (mm)	Yielding strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
CHS1	88.91	3.04	360	399.66	461.48	212.05
CHS2	101.62	3.02	410	305.82	442.88	207.83
CHS3	114.34	3.63	460	316.50	426.23	203.85
CHS4	114.31	4.22	460	284.29	349.94	205.83
CHS5	114.30	5.11	460	371.83	459.51	208.68