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Flexural behaviour of concrete-filled stainless steel SHS and RHS tubes strengthened by CFRP

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ABSTRACT

This paper presents the experimental and numerical investigations on concrete-filled stainless steel square and rectangular hollow section (SHS and RHS) tubes subjected to in-plane bending. A total of 32 specimens were tested, in which one fourth of test specimens were unstrengthened for comparison. The ultimate strengths, failure modes, flexural stiffness, ductility and longitudinal strains of test specimens are reported. The corresponding finite element analysis (FEA) was also performed and calibrated against the test results. An extensive parametric study was carried out by using the verified finite element model to investigate the strengthening effect of CFRP on the flexural behaviour of concrete-filled stainless steel SHS and RHS tubes. It is shown from the comparison that the strengthening effect of CFRP was improved with the increase of the β value. Whereas, the ductility ratio was greatly deteriorated. Furthermore, the secant stiffness at $0.6M_u$ was recommended to be the flexural stiffness of concrete-filled stainless steel SHS and RHS tubes strengthened by CFRP in the practical applications. On the other hand, the flexural strength and flexural stiffness of concrete-filled stainless steel SHS and RHS tubes were increased with the increase of interface friction coefficient between stainless steel tube and concrete up to 0.6. The design formulae are also proposed for the flexural strengths and flexural stiffness of concrete-filled stainless steel SHS and RHS tubes strengthened by CFRP based on the current design rules for concrete-filled steel tubes by further considering the flexural strengths and flexural stiffness of the CFRP, which were verified to be accurate by the finite element analysis results.

1. Introduction

Concrete-filled stainless steel tube was developed by combining the advantages of both stainless steel and concrete-filled steel tube, which has aesthetic appearance, good corrosion resistance, high load-carrying capacity, excellent ductility property, good aseismic and fireproof behaviour, and ease of construction as well as maintenance. A lot of researches have been conducted on concrete-filled stainless steel tube, which was first investigated by Roe [1].

Owing to the inconsiderate design or construction and the change of function of buildings, repair and reinforcement of concrete-filled composite members are normally required. Carbon fiber-reinforced polymer (CFRP) was commonly used for structure rehabilitation due to its excellent corrosion resistance, high durability, and good heat resistance and rust-proof behaviour. A considerable amount of researches were previously conducted on the flexural behaviour of steel and concrete-filled composite members reinforced by CFRP. The externally bonded CFRP strengthened steel C channel beams were tested by Selvaraj and Madhavan [2]. Feng et al. [3] proposed fatigue design guides and programs for CFRP strengthened steel structures. CFRP strengthened and rehabilitated pipes and RHS beams under various loading were experimentally investigated by Elchalakani et al. [4–6]. Four full scale beams were conducted in order to investigate the ability of CFRP to recover the strength and stiffness of beams with web openings by Altaee et al. [7]. A total of 20 structural steel channel sections with various retrofitting configurations were tested by Selvaraj and Madhavan [8]. Effect of electrochemical reactions on the physical and chemical responses of steel beams strengthened with CFRP sheets was experimentally investigated by Kim and Bumadian [9]. Effects of prolonged cold weather exposure on CFRP strengthened CHS member subjected bending were experimentally and numerically studied by Kabir et al. [10,11]. Fatigue crack growth of steel beams strengthened by using CFRP was experimentally and analytical investigated by Colombi and Fava [12]. Notch damaged steel beams strengthened with a CFRP plate were experimentally and numerically investigated by Deng et al. [13]. High

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Nomenclature

A_c	Cross-section area of inner concrete
A_p	Cross-section area of CFRP
A_s	Cross-section area of stainless steel tube
b	Outer width of stainless steel SHS and RHS tube
E_c	Elastic modulus of concrete
E_p	Elastic modulus of CFRP
E_s	Elastic modulus of stainless steel
f_{ck}	Characteristic strength of concrete
f_p	Ultimate tensile stress of CFRP
f_u	Ultimate tensile stress of stainless steel
f_y	Tensile yield stress of stainless steel
h	Outer depth of stainless steel SHS and RHS tube
I_c	Moment of inertia of inner concrete
I_p	Moment of inertia of CFRP
I_s	Moment of inertia of stainless steel tube
j	Coefficient accounting for the contribution of stainless steel tube
K_c	Flexural stiffness obtained from design formulae
K_{se}	Flexural stiffness obtained from finite element analysis
L	Overall length of specimen
L_e	Effective span of specimen
m	Coefficient accounting for the contribution of inner concrete
M	Bending moment
M_{FEA}	Ultimate bending moment obtained from finite element analysis
M_{Test}	Ultimate bending moment obtained from tests
M_u	Ultimate bending moment
M_{u0}	Ultimate bending moment of concrete-filled stainless steel SHS and RHS tube
M_{u1}	Ultimate bending moment of concrete-filled stainless steel SHS and RHS tube strengthened by one layer of CFRP
M_{u2}	Ultimate bending moment of concrete-filled stainless steel SHS and RHS tube strengthened by two layers of CFRP
M_{u3}	Ultimate bending moment of concrete-filled stainless steel SHS and RHS tube strengthened by three layers of CFRP
M_{u0}^{r}	Flexural strength of concrete-filled stainless steel SHS and RHS tube obtained from proposed design formulae
M_u^{m}	Flexural strength of concrete-filled stainless steel SHS and RHS tube strengthened by CFRP obtained from proposed design formulae
M_y	Bending moment at yielding
p	Binding stress
t	Thickness of stainless steel tube
u	Vertical deflection
u_m	Mid-span vertical deflection
u_y	Mid-span vertical deflection at yielding
α	Area ratio of stainless steel tube (A_s/A_c)
β	Strength ratio of CFRP (A_pf_p/A_sf_y)
δ_u	Mid-span vertical deflection at ultimate load
δ_y	Mid-span vertical deflection at yield load
ε	Longitudinal strain
ε_f	Ultimate limit strain of CFRP
ξ	Strength ratio of stainless steel tube (A_sf_y/A_cf_{ck})
σ	Stress
σ_f	Ultimate limit stress of CFRP
$\sigma_{0.2}$	0.2% proof stress
φ	Ductility ratio (δ_u/δ_y)
ω_i	Enhancement of ultimate bending moment
ω_1	Enhancement of ultimate bending moment obtained from one layer of CFRP
ω_2	Enhancement of ultimate bending moment obtained from two layers of CFRP
ω_3	Enhancement of ultimate bending moment obtained from three layers of CFRP
ϕ_y	Curvature at yielding

strength galvanized steel tubular structural members using externally bonded CFRP sheets were investigated by Chen et al. [14]. Effect of CFRP bond length was investigated under transverse impact loading by Alam et al. [15]. Behaviour of CFRP-strengthened steel beams was examined by Teng et al. [16]. Crack-tip behaviour of wide-flange steel beams strengthened with CFRP sheets was investigated by Hmidan et al. [17]. Structural behaviour of the CFRP flexural strengthened steel I-beams was experimentally and numerically investigated by Narmashiri et al. [18]. A design method for evaluating the capacity of CFRP-strengthened steel CHS subjected to bending was proposed by Haedir and Zhao [19,20]. Performance of steel beams strengthened with CFRP laminate was experimentally and numerically investigated by Linghoff and Al-Emrani [21,22]. A large number of studies were conducted by the group led by Ozbakkaloglu on various kinds of specimens combining with steel tube, concrete and FRP [23–27]. FRP structure in FRP-concrete-steel double-skin tubular members is aramid fiber tube, while FRP structure reinforcing concrete-filled stainless steel SHS and RHS tubes is composed of carbon fiber reinforced plastics sheets.

It is worth noting that few studies were performed on CFRP reinforced concrete-filled stainless steel tubes, which was investigated in this paper on the flexural behaviour of concrete-filled stainless steel square and rectangular hollow section (SHS and RHS) tubes strengthened by CFRP.

2. Experimental investigation

2.1. Test specimens

A total of 32 concrete-filled stainless steel SHS and RHS tubes were tested under in-plane bending, in which one fourth of test specimens were strengthened by bonding a layer of CFRP at the bottom flange, one fourth of test specimens were strengthened by bonding a layer of CFRP at the bottom flange and both sides of the web, another one fourth of test specimens were strengthened by bonding a layer of CFRP at all four sides including top flange, bottom flange and both sides of the web, and the remaining one fourth of test specimens were unstrengthened for comparison. All specimens were manufactured from the same batch of SUS 304 stainless steel SHS and RHS tubes. The SHS and RHS tubes consist of a large range of section sizes, which have nominal outer width (b) ranged from 50 to 100 mm, nominal outer depth (h) ranged from 60 to 100 mm and nominal thickness (t) ranged from 1.1 to 1.5 mm. The overall length (L) of all specimens was taken to be a constant value of 1000 mm for comparison, with the effective span (L_e) between the end supports of 900 mm. The cross-section dimensions of all specimens with the critical geometric parameters are summarized in Table 1, using the nomenclature defined in Fig. 1 and the test photo shown in Fig. 2.

The specimens are labelled according to their cross-section shape, cross-section dimensions and arrangement of CFRP bonded at the exterior of concrete-filled stainless steel tubes. For example, the label 'R50 × 100 × 1.1B0' defines concrete-filled stainless steel RHS tubes denoted by 'R'. The following expression '50 × 100 × 1.1' indicates the cross-section dimensions of the RHS, which have the nominal outer width (b) of 50 mm, the nominal outer depth (h) of 100 mm and the wall thicknesses (t) of 1.1 mm. The last notation 'B0' indicates that there is no CFRP bonded at the exterior of concrete-filled stainless steel tubes. If the notation is 'B1', it indicates a layer of CFRP bonded at the bottom flange. If the notation is 'B2', it indicates a layer of CFRP bonded