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Strengthening of ferritic stainless steel tubular structural members using FRP subjected to Two-Flange-Loading

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ABSTRACT

Cold-formed stainless steel tubular structural members which may experience web crippling failure due to localise concentrated loads or reactions are investigated. A series of tests on fibre-reinforced polymer (FRP) strengthening of cold-formed stainless steel tubular structural members subjected to End-Two-Flange and Interior-Two-Flange loading conditions is presented. The strengthening only applied to a localise area of the members under concentrated load. A total of 58 web crippling tests were conducted. The investigation mainly focused on the effects of different surface treatment, different adhesive, and FRP for strengthening of stainless steel tubular sections against web crippling. The behaviour of stainless steel members strengthened by different widths of FRP plate against web crippling has been also investigated in this study. The test specimens consisted of ferritic stainless steel EN 1.4003 square and rectangular hollow sections. Two different surface treatments were considered. Furthermore, six different adhesives and six different FRPs were also considered in this study. The properties of adhesive and FRP as well as the bonding between the FRP and stainless steel tube have significant influence on the effectiveness of the strengthening. Most of the strengthened specimens were failed by debonding of FRP plates form the stainless steel tubes. Six different failure modes were observed in the tests, namely the adhesion, cohesion, combination of adhesion and cohesion, interlaminar failure of FRP plate, FRP delaminating failure and web crippling failure. The failure loads, failure modes, and the load-web deformation behaviour of the ferritic stainless steel sections are presented in this study. It was found that the web crippling capacity of ferritic stainless steel tubular sections may increase up to 51% using FRP strengthening.

1. Introduction

Cold-formed stainless steel tubular structural members are being increasingly used in architectural and structural application because of the desirable features on corrosion resistance, durability, easy maintenance, fire resistance, pleasing appearance and recyclability of the material. Cold-formed stainless steel tubular structural members may experience web crippling failure due to the high local intensity of concentrated loads or reactions. Fibre-reinforced polymer (FRP) is an advanced material which is increasingly being used for strengthening and repair of existing metal structures. Externally bonded FRP can be used to strengthen the web crippling capacity of stainless steel tubular structural members.

Previous research on strengthening of metal structures was mainly focused on carbon steel members as summarised by Zhao and Zhang [1]. Experimental investigation on web crippling strengthening of rectangular carbon steel tubes and light steel beam using FRP have been conducted by Zhao et al. [2], Fernando et al. [3], and Zhao and Al-Mahaidi [4]. However, stress-strain behaviour of carbon steel and stainless steel is quite different. Stainless steel materials have lower proportional limits than carbon steel which may affect the buckling and web crippling behaviour of structural tubular members. Zhou and Young [5–6] conducted a series of tests on cold-formed stainless steel tubes subjected to web crippling. The test specimens were not strengthened by FRP. Therefore, it is novel to strengthen stainless steel tubular structural members using FRP subjected to web crippling, and the strengthening only applied to a localised area under the concentrated load.

The effectiveness of strengthening directly depends on the properties of adhesive and FRP. Debonding failure is a critical issue for the strengthening of stainless steel tubular members. The cohesion, adhesion and combined of these two failure modes generally occur in FRP strengthening of carbon steel tubular members [3]. The properties of the adhesive fully control the cohesion failure, while adhesion failure depends on the surface characteristics of the adherents including the texture, roughness,

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Nomenclature

b	flange width;
CFRP	Carbon Fibre-Reinforced Polymer;
d	overall depth of web;
E_o	initial Young's modulus;
ETF	End-Two-Flange;
FRP	Fibre-Reinforced Polymer;
h	depth of flat portion of web measured along the plane of web;
ITF	Interior-Two-Flange;
L	actual length of test specimen;
N	length of bearing plate;
n	exponent in Ramberg-Osgood expression;
P_u	experimental ultimate web crippling loads per web with CFRP;
P_{u0}	experimental ultimate web crippling loads per web without CFRP;
RHS	Rectangular Hollow Section;
SHS	Square Hollow Section;
t	thickness of stainless steel tube;
t_F	thickness of FRP;
ε_f	ultimate tensile strain after fracture based on gauge length of 50 mm;
$\sigma_{0.2}$	static 0.2% tensile proof stress; and
σ_u	static tensile strength;

and chemical composition of the surface [7]. Different failure modes for FRP strengthened steel structures have been reported [1–3,7–8]. The investigations on the bonding behaviour of FRP to steel joints have been also conducted [9–12]. However, little research has been reported on FRP to stainless steel bonding.

Up-to-date, extensive research has been conducted on FRP-Strengthened concrete structures and carbon steel structures, but little research on FRP-strengthened stainless steel structures. It should be noted that interaction of shear stress and normal stress was experienced in FRP strengthening of members failed by web crippling [3]. It is not easy to find an analytical model for strengthening of tubular members subjected to web crippling. Therefore, experimental investigation is needed for a better understanding on such structural behaviour.

The purpose of this paper is to investigate the effects of different surface treatment, different adhesive and FRP on the strengthening of stainless steel tubular sections against web crippling failure. The influence of different width of FRP plate strengthening against web crippling is also investigated in this study. A series of tests on FRP strengthening of stainless steel tubular structural members subjected to End-Two-Flange and Interior-Two-Flange loading conditions is conducted. The load-web deformation behaviour of the stainless steel sections is presented. The failure loads and different failure modes are also presented in this study.

Table 1
Measured material properties of ferritic stainless steel sections obtained from tensile coupon tests.

Test specimen	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	E_o (GPa)	n	ε_f (%)
F50 × 50 × 4	504	514	202.0	6.4	11.9
F120 × 40 × 3	426	459	203.5	6.2	21.5

Table 2
Material properties of FRP given in specifications.

Types of FRP	Symbol	t_F (MPa)	σ_u (MPa)	E_o (GPa)	ε_f (%)
Sika Wrap-300C/60 (CFRP)	a	0.166	3900	230	1.50
Sika Wrap 430 G/25 (GFRP)	b	0.172	2300	76	2.80
Tyfo UC laminate (Laminate Plate)	c	1.400	2790	155	1.80
Sika CarboDur S1214 (Laminate Plate)	d	1.400	3100	165	1.70
Sika CarboDur M614 (Laminate Plate)	e	1.400	3200	210	1.35
Sika CarboDur H514 (Laminate Plate)	f	1.400	1500	300	0.45

2. Material properties

2.1. Ferritic stainless steel tubes

The material properties of the ferritic stainless steel tube specimens were determined by tensile coupon tests. The flat tensile coupons were taken from the centre of the face at 90° angle from the weld for all ferritic stainless steel tubes in the longitudinal direction. The tensile coupons were prepared and tested according to the American [13] and Australian [14] standards for the tensile testing of metals using 12.5 mm wide coupons of gauge length 50 mm. The coupons were tested in a MTS displacement controlled testing machine. Two strain gauges

Table 3
Measured material properties of adhesives obtained from tensile coupon tests [16].

Types of adhesive	Symbol	σ_u (MPa)	E_o (GPa)	ε_f (%)
Sika 330	A	31.8	4.6	0.8
Sika 30	B	22.0	11.6	0.4
Tyfo TC	C	19.6	2.3	1.3
Araldite 2011	D	23.1	1.6	4.5
Araldite 2015	E	19.7	1.8	3.3
Araldite 420	F	24.3	1.6	3.2

Fig. 1. Six different adhesives tensile coupon test specimens.