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Advanced Stainless Steel Structural Materials for Bridge Constructions and Strengthening by Fibre Reinforced Polymer

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Abstract: Stainless steels are increasingly used as a structural member in buildings, bridges, stadiums, airport hangers, off-shore structure, industrial construction etc. Structural uses of stainless steel in bridge construction are presented in this study. This paper presents an extensive experimental and numerical investigation of FRP strengthening lean duplex stainless steel hollow sections subjected to web crippling. The investigation was focused on the effects of surface treatment, web slenderness, different adhesives and FRPs for the strengthening. A series of laboratory tests was performed on five different sizes of square and rectangular hollow sections that covered a wide range of web slenderness ratio from 8.2 to 56.2. The failure loads, failure modes, enhancement of load carrying capacity for FRP strengthening and the load-web deformation behaviour of lean duplex stainless steel sections are presented in this study. This study is also focused on the nonlinear finite element analysis using the program ABAQUS. The numerical results were verified against the test results. It is shown that the strengths of lean duplex stainless steel hollow sections may increase up to 76% due to the strengthening of FRP. Finally, a proposed design equation was developed for CFRP strengthened stainless steel tubular sections against web crippling loading.

Keywords: *Bridge construction, Experimental- fine element analysis, Design equation, Stainless steel structural materials, Web crippling- FRP strengthening*

Introduction: Cold-formed stainless steel tubular sections have been increasingly used in architectural and structural application due to its attractive features in terms of durability, superior corrosion resistance, easy maintenance, ease construction, aesthetic appearance and recyclability of the material. Stainless steels have excellent performance against corrosion. Therefore, stainless steels have tremendous potential for expanding applications in bridge structures. Their high strength, toughness and ductility coupled with excellent durability should lead to many future applications in sustainable bridges. The efficient and potential use of stainless steel in bridge construction has been described by Gedge [1-2] based on Arup experience on materials selection for bridges. There have been an increasing number of significant structural uses of stainless steels since the year 2000.

Tubular structures have well structural technological and constructive advantages that lead to optimized and economical solution for bridge construction. The practical applications of steel tubular structural members in bridge construction are shown in Fig. 1. The webs steel tubular members in bridge construction are often experienced web crippling failure due to concentrated bearing load. This web crippling failure could restrict the use of stainless steel tubular members in bridge construction. Furthermore, stainless steel tubular structures may found deficient from strength and/or serviceability due to ageing, corrosion, fatigue, insufficient design detailing, poor workmanship, increasing traffic volume, service load and upgrading design standard. Many existing steel bridges in the United States of America, Australia, Europe and Japan are found deficient due to ageing and corrosions. The deterioration factors

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may potentially lead to serious damage and in the worst case that caused collapse of bridge structures. Replacement part of the structure is not effective and economically feasible. Many steel bridges are needed of strengthening due to requirements to increase traffic volume, aging and rehabilitation due to corrosion degradation Schnerch and Rizkalla [3]. Miller et. al [4]. The webs of cold-formed stainless steel members in bridge construction may cripple due to concentrated bearing load in the absence of stiffeners. Externally adhesive bonded FRP strengthening can be considered as an alternately solution for such structural members. Therefore, the web crippling strength can be enhanced by FRP strengthening in the web of the sections.

The conventional method of repairing or strengthening steel bridge structures is to cut out and replace plating or to attach external steel plates Zhao and Zhang [5]. However, such strengthening has some drawbacks due to bulky, heavy, difficult to fix and prone to corrosion and fatigue of these steel plates. Fibre reinforced polymer (FRP) is an advanced material which is increasingly being used for strengthening and repair of existing metal structures. Therefore, externally bonded FRP strengthening can be considered as an alternately solution for the strengthening of stainless steel structural tubular members in the localise region subjected to load concentration. Recently, FPP were using in strengthening of in different form in steel and aluminum members and structures [6-10]. Many steel bridges have been strengthening FRP which is reported by Schnerch and Rizkalla, [3]; Miller et. al, [4]; Katsuyoshi et. al, [11]. However, little research on FRP strengthening of lean duplex stainless steel hollow sections up-to-date, in particular, investigation of web crippling. Hence, investigation on strengthening of lean duplex stainless steel tubular sections to localise region subjected to concentrated load is needed.

This paper presented structural uses of stainless steel in bridges and several recent examples of using stainless steels in bridge construction. This paper introduces importance of lean duplex stainless steel structural tubular member in terms of both costs and efficiency of design. The purpose of this paper is also to investigate the effects of surface treatment, different adhesives, different FRPs and web slenderness of lean duplex stainless steel hollow sections on the strengthening against web crippling. Both experimental and numerical investigations were conducted. Firstly, the effects of different surface treatment and adhesive on FRP strengthened lean duplex stainless steel tubular sections against web crippling failure were investigated. Secondly, the effects of different FRPs on the strengthening of lean duplex stainless steel hollow sections subjected to End-Two-Flange loading condition was also investigated. Thirdly, an extensive investigation was conducted on the effects of web slenderness of lean duplex stainless steel tubular sections on carbon fibre reinforced polymer (CFRP) strengthening against web crippling, and the tests were conducted under four loading conditions of End-Two-Flange (ETF), Interior-Two-Flange (ITF), End-One-Flange (EOF) and Interior-One-Flange (IOF). Then, finite element analysis and verification was performed and finally a proposed design equation was developed of specimens subjected to web crippling loading conditions.

Metro-Station Bridge, Washington D.C | Tubular Truss Bridge, UK | Tubular Bridge Oklahoma City | Bridge in Marina Bay, Singapore

Fig. 1. Tubular steel structural members in bridge construction (https://www.google.com.bd/tubular steel/stainless steel bridge)

Stainless Steel in Bridge Constructions: The structural use of stainless steel in bridge construction has been increased significantly since the year 2000. The stainless steel has been used in bridge for reasons of aesthetics, corrosion resistance, long term durability (freedom from maintenance) or a combination of these factors as well as the structural requirements. Table 1 is presented some examples of construction of bridge structures where stainless steels have been used for the main, if not entire, structure. Different grade stainless steel is used in bridge construction as shown in Table 1. Duplex (EN 1.4462) and lean duplex (EN 1.4162) stainless grade was used more than others types. Duplex stainless steels are increasingly used as structural materials in bridge construction because of their exceptional mechanical properties. Duplex stainless steel grade 1.4462 is combined austenitic and ferritic stainless steel composition. Its two phased microstructure combines the positive characteristics of austenitic and ferritic stainless steels. These characteristics result in a high corrosion resistance and high strength. Therefore, many bridges are constructed by duplex stainless steel. Duplex stainless steel is used for construction Cala Galdana Road Bridge, Menorca, Spain and the Stonecutters Bridge in Hong Kong, as shown in Figs. 2 and 3 respectively. The double Helix Bridge in Marina Bay, Singapore, is a landmark pedestrian bridge was constructed tubular stainless steel structural member. Lean duplex stainless steel sections feature low nickel ratio and very high strength, which enables lighter constructions. The optimized alloy gives better corrosion resistance, saves delivery costs and keeps material costs more stable compared to austenitic AISI 304/EN 1.4301. Lean Duplex is ideal for bridge construction, transportation and process industries and applications, where high strength, good corrosion resistance and low life cycle costs are needed. The price/cost advantage of lean duplex is its more suitable and stable than others types. The stable price is based on the low nickel content (1-2%) and lack and minor content of molybdenium whilst the material still retains competing corrosion resistance with the standard grades**.**

Fig. 2. Cala Galdana Road Bridge, Menorca, Spain 2005 [12]

Fig. 3. Stone cutter bridge, Hong Kong, 2010

The main advantage from a structural point of view is its improved stress corrosion cracking resistance in aggressive environments. Lean duplex stainless steel is chosen by bridge engineers due to cost effectiveness for demanding applications, high strength, good corrosion resistance, possibilities to reduce weight and costs. Over the last few years, lean duplex stainless steel is also playing an important role in the construction of bridges. Table 1 also lists some bridges which were constructed by lean duplex stainless steel incorporating main structural elements. Lean duplex stainless steel is used for construction Likholefossen Bridge, Norway; Viaduct Crni Kal road bridge, Slovenia; Siena Bridge, Ruffolo, Cable stayed pedestrian bridge Italy; Stockfjarden outlet in Flen, Sweden; Sant Fruitos Bridge, Spain; Second Gateway Bridge, Brisbane Australia. Stainless steel bridges obtain sustainability due of economical, meeting social properties and environmental impact.

Table 1. Bridges using stainless steel [12]

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SL.	Description (name and location)	Types of bridge	Date	Stainless steel grade
1.	Suransuns Bridge, Switzerland	Pedestrian bridge	1999	1.4462 (Duplex)
2.	Millennium Bridge, York, UK	Pedestrian bridge	2001	1.4462(Duplex)
3.	Apate Bridge, Stockholm, Sweden	Pedestrian bridge	2002	1.4462(Duplex)
4.	Kungalv, Sweden	Rail bridge,	2003	1.4462 (Duplex)
5.	Pedro Arrupe Bridge,Bilbao, Spain	Pedestrian bridge	2003	1.4362 (Duplex)
6.	Likholefossen Bridge, Norway	Pedestrian bridge,	2004	1.4162(Lean duplex)
7.	Viaduct Črni Kal, Slovenia	Road bridge	2004	1.4162(Lean duplex)
8.	Cala Galdana Bridge, Menorca	Road bridge	2005	1.4462(Duplex)
9.	Arco di Malizia, Siena, Italy	Single arch road suspension	2005	1.4362(Duplex)
10.	Siena Bridge, Ruffolo, Italy	Cable stayed pedestrian bridge	2006	1.4162(Lean duplex)
11.	Piove di Sacco Bridge, Padua, Italy	Dual arch road suspension	2006	1.4362(Duplex)
12.	Celtic Gateway Bridge, Holyhead, Wales	Arch pedestrian bridge	2006	1.4362(Duplex)
13.	Zumaia Bridge, Spain	Pedestrian bridge	2008	1.4462(Duplex)
14.	The Helix, Marina Bay, Singapore	Tubular pedestrian bridge	2009	1.4462(Duplex)
15.	Stockfjarden outlet in Flen, Sweden	Road bridge	2009	1.4162(Lean duplex)
16.	Meads Reach, Bristol, UK	Pedestrian bridge	2009	1.4462(Duplex)
17.	Sant Fruitos Bridge, Spain	Pedestrian arch bridge	2009	1.4162(Lean duplex)
18.	Stonecutters Bridge, Hong Kong	Cable-stayed road bridge	2010	1.4462(Duplex)
19.	Second Gateway Bridge, Brisbane Australia	Road bridge over river	2010	1.4162(Lean duplex)
20.	Harbor Drive Pedestrian Bridge, San Diego, US	Pedestrian bridge	2011	1.4462(Duplex)

Material Properties of Stainless Steel used in This Research: Some square and rectangular hollow stainless steel sections are shown in Fig. 4. The stress-strain behaviour of carbon steel and stainless steel is quite different. Typical stress-strain curves for stainless steel and carbon steel is presented in Fig. 5 [13]. For carbon and low-alloy steels, the proportional limit is assumed to be at least 70% of the yield point, but for stainless steel the proportional limit ranges from approximately 36 to 60% of the yield strength Yu and LaBoube[14]. The stainless steel materials have lower proportional limit than carbon steel which may affect the buckling and web crippling behaviour of tubular structural members.

Stainless steel is not a single alloy but rather the name applies to a group of iron based alloys containing a minimum of 10.5% chromium. Lean duplex stainless steel is a relatively new grade of material, which contains approximately 1.5% nickel. The lean duplex type EN 1.4162 material is much cheaper than the duplex type EN 1.4462 containing approximately 5.7% nickel. The material price of lean duplex (EN 1.4162) is approximately half of the duplex (EN 1.4462) material as shown in Table 2. Despite the low nickel content, lean duplex stainless steel display a good combination of strength, corrosion resistance and fatigue resistance together with adequate weldability Nilsson [15]. The chemical composition of the lean duplex stainless steel specimens given in the mill certificates is shown in Table 3.Tensile coupon tests were conducted by Islam and Young [16] to determine the material properties of the lean duplex stainless steel hollow section specimens. The tensile coupons were prepared and tested according to the American Society for Testing and Materials Standard [17] and the Australian Standard AS 1391 [18] for the tensile testing of metals using 12.5 mm wide coupons of gauge length 50 mm. The coupons were tested in a displacement controlled testing machine. The stress-strain behaviour of lean duplex stainless steel is shown in Fig. 6.

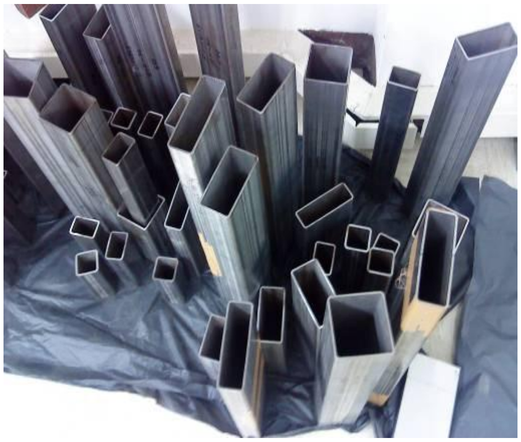


Fig. 4. Tubular stainless steel sections

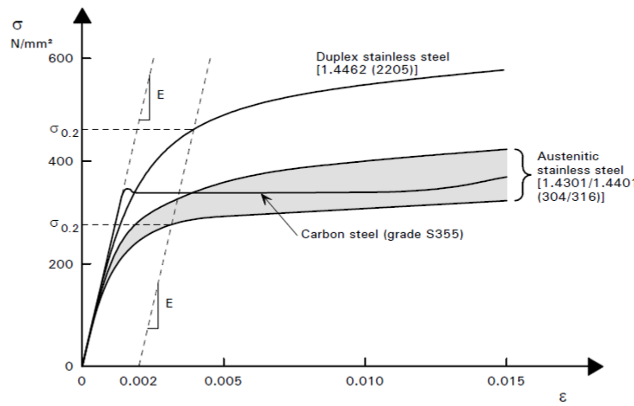


Fig. 5. Typical stress-strain curves for stainless steel and carbon steel [13]

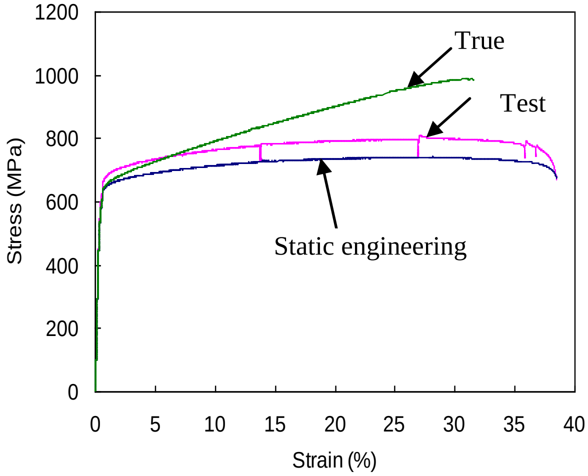
Table 2. Cost of different grade stainless steel sections [16]

Type (EN)	Type (ASTM)	Ni (%)	*f*0.2 (MPa)	USD*/ton
EN 1.4162 (Lean Duplex)	S32101	1.5	450	5,380
EN 1.4462 (Duplex)	S32205	5.7	460	11,340
EN 1.4301 (Austenitic)	304	8.3	210	4,680
EN 1.4404 (Austenitic)	316L	10.1	220	8,500
EN 1.4003 (Ferritic)	S40977	0.5	280	3,400

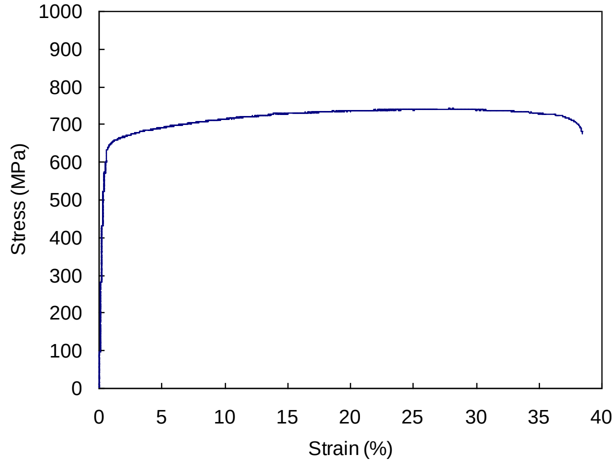
S355 Hot finished hollow section ~ USD 1,450/ton; 100x100x6 mm as a reference size.

Table 3. Chemical composition of lean duplex stainless steel test material [16]

Section	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	Mo (%)	Cu (%)	N (%)
D30×50×2.5	0.020	0.720	4.880	0.023	0.001	21.400	1.600	0.210	0.310	0.220
D50×50×2.5	0.032	0.650	5.010	0.020	0.001	21.500	1.600	0.210	0.210	0.220
D50×50×1.5	0.019	0.660	4.910	0.021	0.001	21.300	1.500	0.380	0.280	0.226
D100×50×2.5	0.022	0.690	4.930	0.022	0.001	21.400	1.600	0.300	0.300	0.221
D150×50×2.5	0.032	0.650	5.010	0.020	0.001	21.500	1.600	0.210	0.210	0.220



(b) Test, static engineering, and true stress-strain curves



(b) Static engineering curve

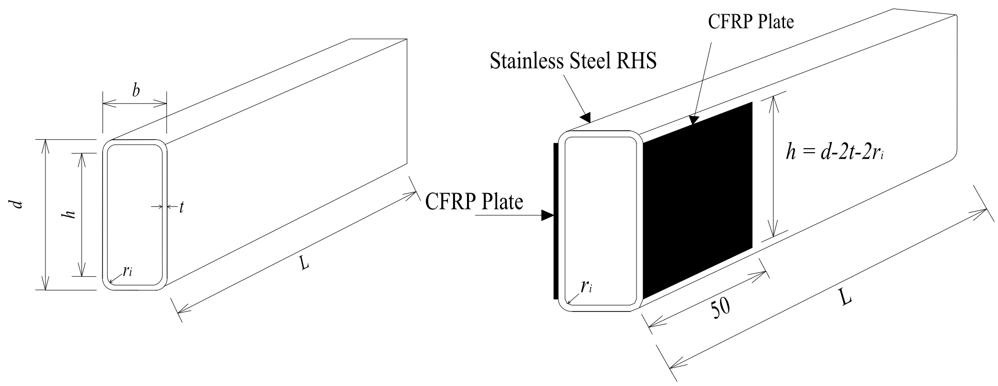
Fig. 6. Stress–strain curve of tensile coupon for D50x50x2.5 specimen [16]

Table 4. Measured material properties of lean duplex stainless steel sections obtained from tensile coupon tests [16]

Test Specimen	b_c (mm)	t_c (mm)	A_c (mm^2)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	E_o (GPa)	n	ε_f (%)
D30x50x2.5	12.47	2.601	32.4	774	861	200.4	4.9	17.7
D50x50x2.5	12.26	2.498	30.6	663	769	203.4	5.7	31.2
D50x50x1.5	12.49	1.550	19.4	595	742	191.1	7.6	38.5
D100x50x2.5	12.51	2.517	31.5	606	733	202.7	7.5	37.6
D150x50x2.5	12.57	2.495	31.4	620	735	202.8	6.7	38.7

Test Program for FRP Strengthening of Stainless Steel Tubular Sections: An extensive test program was conducted on strengthened lean duplex stainless steel tubular members using FRP to increase the web crippling capacity. A test program described by Islam [19], Islam and young [16, 20] provided experimental ultimate loads and failure modes for FRP strengthened stainless steel tubular sections subjected to web crippling. The cross-section geometry and symbol definition of the rectangular specimen is shown in Fig. 7(a). One layer of FRP plate of 50 mm is attached on the outer surface of both sides of the webs at one end of the specimens as shown in Fig. 7(b). The test specimens were labelled such that the type of material, nominal dimensions of the specimen, loading condition, type and number of FRP layer can be identified from the label. Details labelling procedures have been described in the Islam and Young [16] paper.

A series of web crippling laboratory tests were conducted by Islam and Young [16]. Firstly, two different surface treatments using electric sander (S) and electric grinder (G) were used in order to find out the effective surface treatment for FRP strengthened lean duplex stainless steel sections under the End-Two-Flange (ETF) loading condition. Three different adhesives, namely Tyfo TC, Araldite 2015 and Araldite 420 with high modulus CFRP Sika CarboDur H514 laminate plate were used to investigate the effective surface treatment. Tensile coupon tests were conducted to obtain the material properties of these three types of adhesive. Secondly, six different FRPs were investigated to find out the best performance of FRP for lean duplex cold-formed stainless steel hollow sections using a suitable surface treatment. The specified material properties of each FRP provided in the specifications are also shown in Islam and Young [16] research. The grinding surface treatment and adhesive Araldite 420 were used to find the best FRP for strengthening of lean duplex stainless steel sections. Thirdly, the influence of slenderness of lean duplex hollow sections on CFRP strengthening against web crippling has been investigated. The surface treatment by grinding seems more suitable for lean duplex stainless steel hollow sections in this study. Furthermore, adhesive Araldite 420 **(**symbolized by 'F'**)** and CFRP Sika CarboDur S1214 laminated plate **(**symbolized by 'd'**)** were used in the third phase of the investigation.



(a) Lean duplex stainless steel RHS section

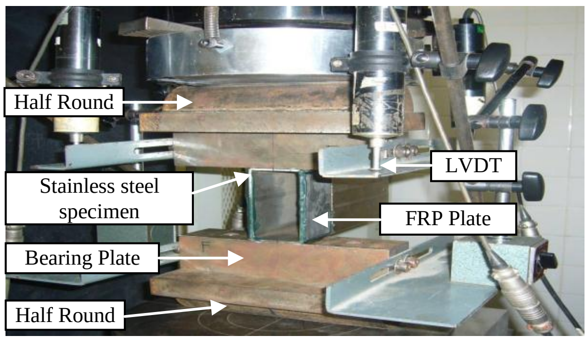
(b) FRP plate strengthened lean duplex stainless steel section

Fig. 7. Definition of symbols and FRP strengthened lean duplex stainless steel hollow section [16]

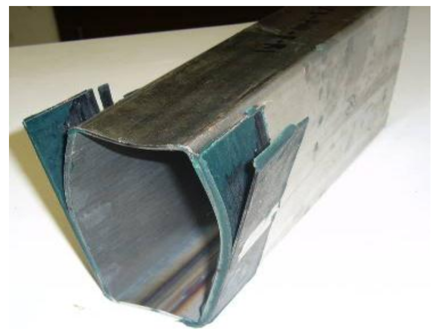
The web crippling tests were carried out under the four loading conditions specified in American Society of Civil Engineers Specification [21]. The specimens were tested under the End-Two-Flange (ETF), Interior-Two-Flange (ITF), End-One-Flange (EOF) and Interior-One-Flange (IOF) loading conditions. Test setup of End-Two-Flange loading condition is shown in Figure 8(a). The load was applied by means of bearing plates. A servo-controlled hydraulic testing machine was used to apply a concentrated compressive force to the test specimens. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.3 mm/min for all tests.

Results and Discussions: The failure modes of lean duplex section strengthened with CFRP Sika CarboDur H514 laminate plate subjected to End-Two-Flange loading condition is shown in Fig. 8(b). The experimental ultimate web crippling loads per web with FRP (P_u) and without FRP (P_{u0}) are presented in Table 5. The specimens without strengthening of FRP were tested as reference tests and these specimens are labeled using a suffix of "-0" as shown in Table 5 and as well as labeled as "F0" in Fig. 9. In the first stage of the tests, two different surface treatments using electric sander (S) and electric grinder (G) were investigated on section D150x50x2.5 to find a suitable surface treatment and adhesive for the FRP strengthened lean duplex stainless steel sections. Three different adhesives of Tyfo TC (C), Araldite 2015 (E) and Araldite 420 (F) as well as high modulus CFRP Sika CarboDur H514 laminate plate (f) were considered in the investigation. It is shown that the grinding surface treatment and adhesive Araldite 420 provided better performance (P_u/P_{u0}=1.12) compared to other lean duplex stainless steel sections in terms of the peak load enhancement [15].

In the second stage of the tests, grinding surface treatment was used. Six different FRPs were investigated using adhesive Araldite 420 on the section D150x50x2.5. It is shown FRP Sika CarboDur S1214 delivered the best performance (P_u/P_{u0}=1.22) for the tested lean duplex stainless steel hollow sections. It is shown that grinding surface treatment, the adhesive Araldite 420 and the high strength and strain with lower modulus CFRP CarboDur S1214 laminate plate provided the best performance subjected to web crippling [16]. Physical bonding, chemical bonding, and mechanical interlocking bonding mechanisms between adhesive and steel surface as well as FRP surface have significant influence on strengthening performance. In the CFRP-strengthened, the load-carrying capacity depends on depends on the interfacial stress transfer function of the adhesive layer. The effect of adhesive mechanical properties, debonding of interface between the CFRP and stainless steel surface and the bonded area of the CFRP has great influence on strengthen enhancement.



(a) Test setup of End-Two-Flange loading condition



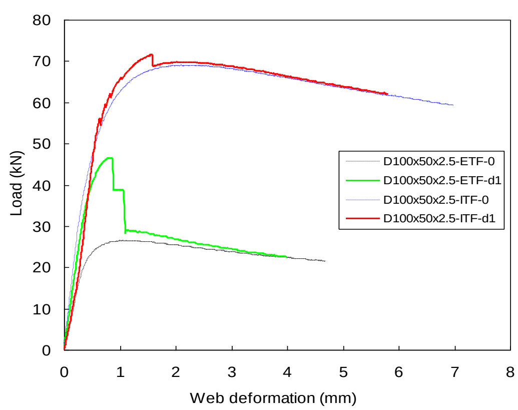
(b) Failure mode

Fig. 8. Test setup and failure mode of End-Two-Flange loading condition

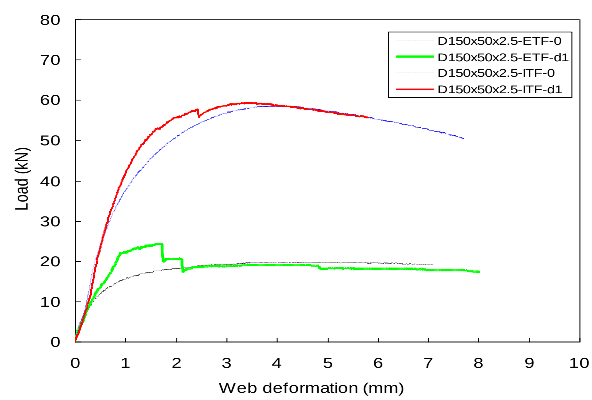
Following the first and second phases of the tests, the third phase of the experiments was conducted to investigate the behaviour of specimens having different web slenderness. A series of tests was conducted under the four loading conditions of ETF, ITF, EOF and IOF. The experimental ultimate web crippling loads per web with CFRP (P_u) and without CFRP (P_{u0}) for ETF loading condition is shown in Tables 5 and Fig. 9 by Islam and Young [16]. It is shown that as the web slenderness (*h/t*) ratio increases, the web crippling load enhancement generally increases for the four loading conditions, except for D150x50x2.5 section [16]. For stainless steel sections D30x50x2.5, D50x50x2.5, D50x50x1.5, D100x50x2.5 and D150x50x2.5 of measured web slenderness values of 8.2, 17.0, 29.7, 36.9 and 56.2, the web crippling load enhancement was found to be 4%, 4%, 13%, 76% and 22%, respectively, subjected to End-Two-Flange loading as shown in Table 5. Elastic local buckling of stainless steel was reduced and web stiffness as well as load carrying capacity was increased due to FRP strengthening. Moreover, slenderness ratio increases strengthening performance also increases. In the ITF loading, the aforementioned sections had the maximum enhancement of web crippling loads per web (P_u) of 1%, 2%, 4%, 4% and 1%, respectively [16]. Fig. 9(a) and ((b) show the load-web deformation behaviour of D100x50x2.5 and D150x50x2.5 specimen subjected to ETF and ITF loading. It was observed that considerable increase in load carrying capacity due to CFRP strengthening.

Table 5. Test results of CFRP strengthened lean duplex stainless steel specimens under End-Two-Flange loading [16]

Specimen	h/t	P_u	P_u/P_{u0}	Failure mode
		kN		
D30x50x2.5-ETF-0	8.2	41.8	1.00	Web buckling failure
D30x50x2.5-ETF-d1	8.2	43.6	1.04	Adhesion failure
D50x50x2.5-ETF-0	17.1	41.3	1.00	Web buckling failure
D50x50x2.5-ETF-d1	17.0	42.8	1.04	Adhesion failure
D50x50x1.5-ETF-0	29.3	11.4	1.00	Web buckling failure
D50x50x1.5-ETF-d1	29.7	12.8	1.12	Adhesion failure
D50x50x1.5-ETF-d1-R	29.7	12.9	1.13	Adhesion failure
D100x50x2.5-ETF-0	36.6	26.5	1.00	Web buckling failure
D100x50x2.5-ETF-d1	36.9	46.6	1.76	Interlaminar FRP failure
D100x50x2.5-ETF-d1-R	36.9	45.5	1.72	Interlaminar FRP failure
D100x50x2.5-ETF-d1-R2	36.8	45.1	1.70	Interlaminar FRP failure
D150x50x2.5-ETF-0	55.9	19.9	1.00	Web buckling failure
D150x50x2.5-ETF-d1	56.2	24.2	1.22	Interlaminar FRP failure



(a) Lean duplex specimen D100x50x2.5 section

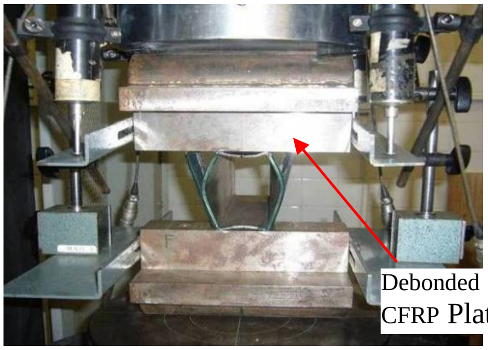


(b) Lean duplex specimen D150x50x2.5 section

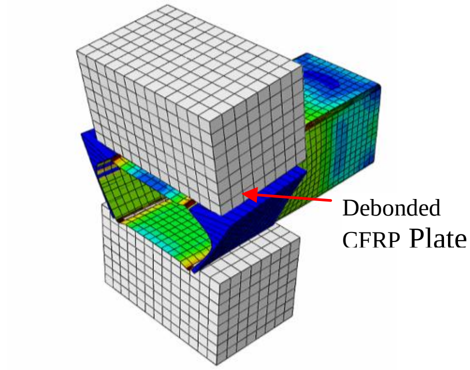
Fig. 9. Load-web deformation behaviour of lean duplex section subjected to ETF and ITF loading conditions

Finite Element Analysis and Verification: The finite element software ABAQUS [22] was used to develop finite element models for CFRP strengthened lean duplex stainless steel tubular sections subjected to web crippling for two-flange loading conditions, such as the ETF and ITF. The bearing plates were modeled using discrete rigid 3D solid elements and the stainless section was modeled using the S4R shell elements. ABAQUS [22] has a special cohesive element to model the adhesive response for CFRP strengthened stainless steel tubular sections. The adhesive layer was modeled using 3D cohesive elements COH3D8. The cohesive elements provided by ABAQUS were adopted and their constitutive behaviour was defined by the mixed-mode cohesive law. Details FEM modeling has been described by Islam and Young [21]. A comparison of experimental and FEA failure modes for specimens with no strengthening and CFRP-strengthened stainless steel sections of D100x50x2.5-ETF-0 are shown in Fig 10. Fig. 11

shows the comparison of experimental and finite element analysis load-web deflection curves for specimen D100x50x2.5-ITF-d1 and D100x50x2.5-EOF-d1under ITF EOF loading condition, respectively. The FEA results agreed well with the experimental curve.

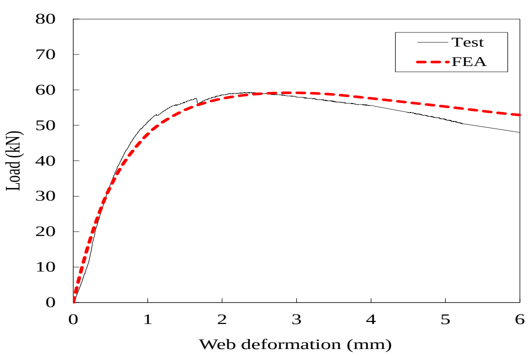


(a) Experimental

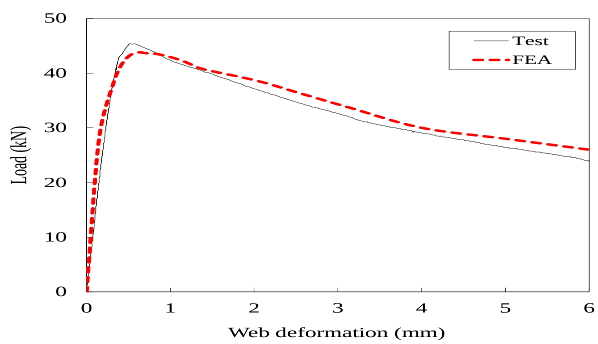


(a) FEA

Fig. 10. Comparison of experimental and FEA failure modes for specimen D100x50x2.5-ETF-d1



(a) Lean duplex specimen D150x50x2.5-ITF-d1and



(b) Lean duplex specimen D100x50x2.5-EOF-d1

Fig. 11. Comparison of experimental and FEA load–web deformation curves

Proposed Design Equation (P_P): Current design rules are not able to compute the performance of CFRP strengthened stainless steel hollow sections against web crippling. The web crippling design equation for CFRP strengthened stainless steel tubular sections under the ETF, ITF, EOF and IOF loading conditions is proposed in this study. The proposed equation uses the same technique as the NAS Specification [23] for the unified web crippling equation for sections without CFRP strengthening. The web crippling behaviour of the sections without strengthening are influenced by the primary parameters t, f_y, r_i/t N/t and h/t [24-27]. For CFRP strengthened stainless steel tubular members, bonded area, ultimate stress of adhesive and co-efficient of adhesive-CFRP have been incorporate in modified proposed equations in order to produce better prediction as shown in Eq 1. Therefore, the proposed design equation is used new coefficients of C, C_N, C_h and $C_{ad\text{-}CFRP}$ as well as using the resistance factor lean duplex stainless steel tubular sections. The design equation is proposed based on test data and the FEA results obtained from the parametric study. The proposed design equation is as follows:

$$P_p = Ct^2 f_y \sin\theta\left(1 - C_R\sqrt{\frac{r_i}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) + [\sigma_{u-ad}.A_{bonding}].C_{ad-FRP} \qquad \text{eq 1.}$$

where C is the coefficient, t is the thickness of the web, f_y is the yield stress, θ is the angle, N is the length of the bearing, h is the depth of the flat portion of the web, C_R is the inside corner radius coefficient, C_N is the bearing length coefficient and C_h is the web slenderness coefficient, σ_{u-ad} = ultimate tensile stress of adhesives, $A_{bonding}$ is FRP bonded area, C_{ad-FRP} is coefficient of adhesive-FRP. The web crippling strengths predicted by test and finite-element analysis are compared with the design strengths calculated using proposed equations. Reliability analysis was carried out and it was demonstrated that web crippling strengths calculated using the proposed design equation provide an accepted safety margin.

Conclusions: Stainless steels have tremendous potential for expanding future applications in bridge structures. In this study, the grinding surface treatment generally provides better performance than the sanding surface treatment. Furthermore, the use of adhesive Araldite 420 and the high strength with lower modulus CFRP CarboDur S1214 laminate plate for the tested lean duplex stainless steel specimens also showed better performance compared to other adhesives and FRPs. The web crippling strengths of CFRP strengthened lean duplex stainless steel hollow sections were increased up to 76%, 4%, 24% and 4% for specimens subjected to ETF, ITF, EOF and IOF loading conditions, respectively. Furthermore, non-linear finite element analysis was also performed and it is shown that the numerical results closely predicted the web crippling behaviour of the CFRP strengthening. Finally, a proposed design equation was developed for CFRP strengthened stainless steel tubular sections against web crippling loading. It was concluded that the web crippling strengths calculated using the proposed design equations provide a safe and reliable design for CFRP-strengthened stainless steel sections.

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