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Structural Evaluation of Stainless Steel as a Strengthening Material: A State of a Review

Minakshi Vaghani [1], Dr. S.A. Vasanwala [2], Dr. A.K. Desai [3]
[1](Civil Engineering Department, Sarvajanik College of Engineering & Technology, Surat – 1, India)
[2,3.] (Applied Mechanics Department, SVNIT, Surat- 1, India)

Abstract: *Stainless steels have not traditionally been widely used as structural materials in architectural and civil engineering. Where the steels have been used for this purpose there has been some other imperative driving the design, usually corrosion resistance or architectural requirements rather than the inherent structural properties of the steel. The primary reason for this low use in structural applications is usually the perceived and actual cost of stainless steel as a material. Developments over the last 10 years, both in available materials and attitudes to durability, are now offering a new opportunity for stainless steels to be considered as primary structural materials. The paper also considers recent developments, particularly with respect to available alloys and considers obstacles to the wider use of stainless steels in structural engineering that is related to both supply chain costs and efficiency of design. This paper introduces testing of Stainless steel tubular sections with using different FRPs and adhesives.*

Keywords – *Austenitic, Corrosion, Plasticity, Stress-strain, adhesives, crippling load, coupon test.*

I. Introduction

Stainless steels have not traditionally been widely used as structural materials in building and civil engineering because of their superior corrosion resistance, ease of maintenance and pleasing appearance. The mechanical properties of stainless steel are quite different from those of carbon steel. 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 % - 60 % of the yield strength [1]. Therefore the lower proportional limits would affect the buckling behaviour of stainless steel structural members. Stainless steel structural members are more expensive than carbon steel. Therefore, more economic design and the use of high strength stainless steel could offset some of the costs.

Fig. 1 (left)Column of Bus Terminal Shelter (left) and Appearance of forging office plant at Aichi Steel Works Ltd. (right)

(Source: Hirofumi Aoki (2000))

Stainless steel can be a confusing material to those unfamiliar with the alloys as the term stainless steel refers to a large family of material types and alloys. The commonest grades of SSs utilized for structural applications include austenitic (ASS), ferritic (FSS), and austenitic–ferritic (AFSS) or duplex. This classification is based on the amount of chromium (Cr) present in the alloy considered. Several applications already exist worldwide for structural and non-structural components made of SSs, All these steels are alloys of iron, chromium, nickel and to varying degrees molybdenum. The characteristic corrosion resistance of stainless steel is dependent on the chromium content and is enhanced by additions of molybdenum and nitrogen. Nickel is added, primarily, to ensure the mechanical properties and the correct microstructure of the steel. Other alloying elements may be added to improve particular aspects of the stainless steel such as high temperature properties, enhanced strength or to facilitate particular processing routes [2].

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Austenitic stainless steels are the steels most architects, engineers and lay people think of stainless steels. The term austenitic refers to the microstructure of the steel. Designation and compositions are given in TABLE 1. Recent developments in alloy technology relevant, to structural engineering, have seen the introduction of newer low alloy duplex steels, often referred as duplex steels. Designation and compositions of the same are given in TABLE 2.

Table 1 Major Alloy Element Compositions of Austenitic Stainless Steels

Steel designation		Alloy composition (Min%) from EN 10088		
EN10088	ASTM International	Chromium	Nickel	Molybdenum
1.4301	304	17	8	-
1.4404	316 L	16.5	10	2
1.4435	316 L	17	12.5	2.5

(Source: Graham Gedge et. al.(2008))

Table 2 Major Alloy Element Compositions of Duplex Stainless Steels

Steel designation (EN10088)	Alloy composition (Min%) from EN 10088			
	Chromium	Nickel	Molybdenum	Nitrogen
1.4462	21	4.5	2.5	0.22
1.4410	24	6	3	0.35
1.4362	22	3.5	0.1	0.05
1.4162 (LDX2101)	21.5	1.5	0.3	0.22

(Source: Graham Gedge et. al.(2008))

These steels are characterized by comparable strength to established duplex grades but lesser resistance to localized corrosion although comparable to established austenitic steels [2].

1.1 Mechanical Properties of Stainless Steels

The stress-strain behaviour of duplex and austenitic steels in a tensile test differs from that of carbon steels. Stainless steels are also characterized by:

- A high degree of plasticity between the proof stress and the ultimate tensile stress.
- Very good low temperature toughness.
- A degree of anisotropy

Given the relatively recent emergence of stainless steel as a structural material, efforts have been made to maintain consistency with Carbon steel design guidance. However, unlike carbon steel, stainless steel exhibits a rounded non-linear stress-strain relationship with no strictly defined yield point (**Fig. 2**). Hence, no sharp behavioral transition occurs at any specified stress [3]. This complexity is overcome by defining the yield point as the stress level corresponding to 0.2 % permanent strain $\square_{0.2}$, and assuming bilinear stress-strain behavior for stainless steel as for carbon steel. The substantial differences in the structural response between the two materials are neglected in favour of simplicity, generally resulting in conservative slenderness limits for stainless steel cross-sections. Stainless steel exhibits a rounded stress-strain relationship with no sharply defined yield point as illustrated in **Fig. 2**. Traditionally its stress-strain relationship has been described by Ramberg-Osgood model. Ramberg and Osgood proposed the expression given in (1) for the description of material stress-strain behavior, where E_o is Young's modulus and K and n are constants.

$$\varepsilon = \frac{\sigma}{E_o} + K\left(\frac{\sigma}{E_o}\right)^n \qquad (1)$$

This basic expression was later modified by Hill to give (2) where R_p is a proof stress and c is the corresponding plastic strain.

$$\varepsilon = \frac{\sigma}{E_o} + c\left(\frac{\sigma}{R_p}\right)^n \qquad (2)$$

In both expressions, the total strain is expressed as the summation of elastic and plastic strains which are treated separately. The power function is applied only to the plastic strain. The Ramberg-Osgood expression is a popular material model for non-linear materials since its constants have physical significance and it also provides a smooth curve for all values of strain with no discontinuities [4].

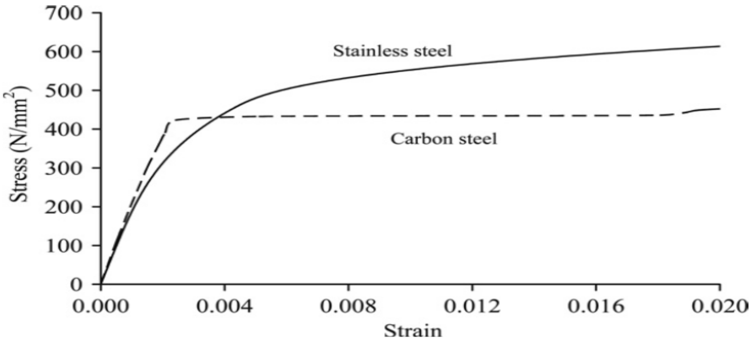


Fig. 2 Indicative Stainless Steel and Carbon Steel Stress-Strain Behavior
(Source: Mahmud Ashraf et. al.(2006))

The proof stress was taken as the value corresponding to the 0.2% plastic strain giving the most familiar form of the Ramberg-Osgood expression as given by (3).

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \qquad (3)$$

This equation has been found to give excellent predictions of stainless steel material stress-strain behaviour up to 0.2 % proof stress 0.02 but greatly over-predicts the stress beyond that level. **Fig. 3** shows a typical comparison between a measured stainless steel stress-strain curve and the Ramberg-Osgood equation (3).

1.2 Behaviour at Elevated Temperature

At both room temperature and elevated temperature, the material characteristics of stainless steel differ from those of carbon steel due to the high alloy content. At room temperature, stainless steel displays a more rounded stress-strain response than carbon steel and no sharply defined yield point, together with a higher ratio of ultimate to yield stress and greater ductility (**Fig. 4**). At elevated temperatures, stainless steel generally exhibits better retention of strength and stiffness in comparison to carbon steel [5].

1.3 Corrosion Resistance of Stainless Steels

There are two broad categories of corrosion that need to be considered:

- General or uniform corrosion which refers to a general corrosion and loss of section over the entire surface of the metal. All austenitic and duplex stainless steel are resistant to this type of corrosion in atmospheric conditions and water (sea or fresh) immersion.
- Localized corrosion which refers to surface straining, pitting, crevice corrosion and stress corrosion cracking (SCC). Stainless steel has varying resistance to these forms of corrosion and in broad terms, the resistance can be related to the alloy content for a given environment.

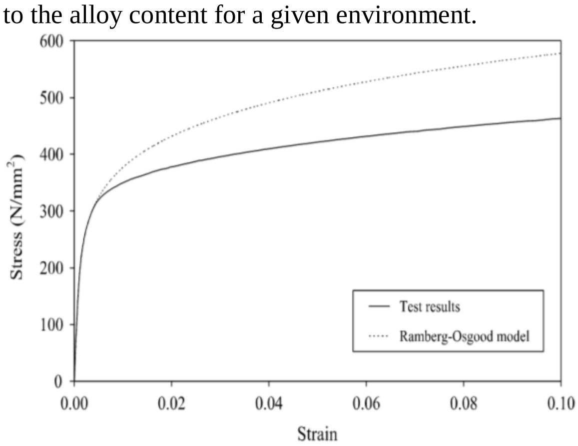


Fig. 3 Comparison between the Measured Stress- Strain Curve and the Ramberg-Osgood Material Model for an Austenitic Grade 1.4301

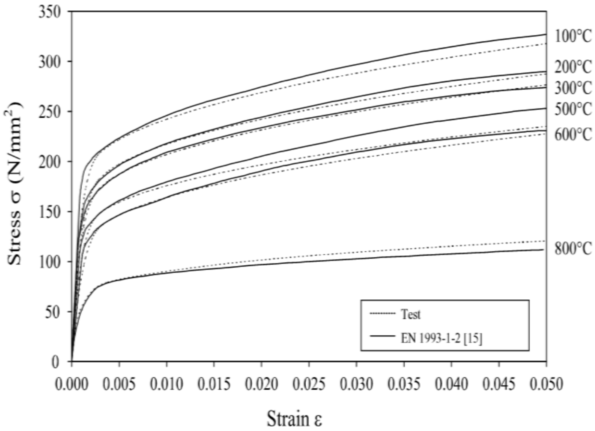


Fig. 4 Stress-Strain Curve using EN 1993-1-2 guidelines for an Austenitic Grade 1.4301 at Elevated Temperatures

(Source: L. Gardner et. al. (2010))

Designers should also be aware that factors other than simply the alloy content have an effect on corrosion performance [2]. These include:

- The quality of surface finish
- The presence of welds and heat tint around welds
- Contamination of the surface with debris from other materials, most notably carbon steel swarf.

Iii Stainless Steel Costs

The mill price of stainless steels is comprised of two parts:

- The base production cost that is set by the steel maker
- The Alloy Adjustment Factor (AAF) that relates to the current price of the alloy elements. The AAF is not directly controlled by the steelmaker.

The actual cost of stainless steel fabrication is clearly not related solely to the ex mill price of base material, the final cost will be dependent on other factors and parts of the supply chain [2]. These include:

- The procurement route – mill, mill service centre, stockiest or trader.
- The supply condition – base plate, cut and prepared plate, specified surface finish quality etc.
- The cost of fabrication – fabrication costs are likely to be somewhat higher than carbon steel due to higher consumable costs and lower production rates.
- The requirement for a finish- architectural finishes add significant cost.
- The workmanship standard specified for the work.

Iv Outline Of Research Activities

In order to accumulate the basic data for applying stainless steel to buildings as a structural material, research papers from various reputed journals were studied.

L. Di Sarno et. al. [3] assess the feasibility of the application of SSs for seismic retrofitting of framed structures, either braced (CBFs) or moment resisting (MRFs) frames. Number of experimental tests carried out primarily in Europe [5,6] and Japan [3] on austenitic (304 and 316) and austenitic–ferritic grades of SSs have demonstrated that:

- Experimental tests on SS beams, columns and beam to- column connections have shown large plastic deformation capacity and energy redistribution at section and member levels.
- The ultimate elongation (ε_u) and the ultimate-to-proof tensile strength ratios (f_u/ f_y) are on average higher than for Carbon Steel. For austenitic plates with thicknesses less than 3 mm the values of ε_u range between 35% and 40% (S220), while a value of 45–55% was found for greater thicknesses;
- SS generally exhibits rather greater increases in strengths at fast rates of loading [1,7]. The initial stress state of the material has an effect on the strain rate.
- Austenitic SSs possess greater toughness than mild steels. The former are less susceptible to brittle fracture than the later for service temperatures down to −40 ˚C.

The above properties render SS an attractive metal for applications in plastic and seismic design, particularly for seismic retrofitting of steel, concrete and composite structures. The suitability of the application of SSs for seismic retrofitting is analyzed herein with regard to multi-storey framed structures, either MRFs or CBFs.

Eunsoo Choi et. al. [7] have studied the bond behavior between steel reinforcing bars and concrete confined via steel wrapping Jackets. Lateral bending tests are conducted for the reinforced concrete columns with continuous longitudinal reinforcement or lap-spliced longitudinal bars confined by the steel wrapping jackets.

In this study, the specimens of concrete cylinders prepared were expected to induce splitting bond failure in an unconfined state; concrete cylinders with dimensions of 100 mm x 200 mm were used. Stainless steel jackets with the dimensions of 324 mm x 200 mm were prepared in order to confine the concrete cylinders; the width was 10 mm larger than the perimeter of the cylinder in order to create the welding overlap. Steel jacket thicknesses of 1.0 mm and 1.5 mm were chosen to assess how the amount of confinement has an effect on the bond behavior. There were three types of specimens for the splitting failure mode: (1) unconfined, (2) confined by a 1 mm jacket, and (3) confined by a 1.5 mm jacket. Each type had two specimens, and a total of six specimens were prepared for the bonding tests.

It is found that the jackets increase the bond strength and ductile behavior due to the transfer of splitting bonding failure to pull-out bonding failure. In the column tests, the steel wrapping jackets increase the flexural strength and ultimate drift for the lap-spliced column. The bond strength of the lap-spliced bar in the jacketed column was estimated as 6.5 MPa that was 1.52 times as large as that of the lap-spliced bar in the unjacketed column. The flexural strength of the jacketed lap-spliced column was 1.32 times as large as that of the unjacketed column. Consequently, it was reasoned that the increment of the flexural strength of the lap-spliced column was due to the increment of the bond stress in the lap-spliced bars providing lateral confining pressure of the steel jacket. Steel and fiber reinforced polymer (FRP) jacketing methods possess critical drawbacks such as grouting for steel jackets or bonding for FRP jackets. The grouting of the steel jackets increases the cross-sectional area and creates the discontinuity in the column surface. Also, the grouting bonds the steel jacket to the concrete surface. The bonding of the FRP jackets with an adhesive such as epoxy causes a problem of wrinkles in the FRP sheet surface. These wrinkles inhibit the confining action on the concrete and reduce the effectiveness of the FRP jacket.

V Testing Of Stainless Steel Specimen

The material properties of the ferritic stainless steel tube specimens were determined by tensile coupon tests (TABLE 3). 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 [8].

Table 3 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	$\square_f$ (%)
F 50 x 50 x 4	504	514	202.0	6.4	11.9
F120 x 40 x 3	426	459	203.5	6.2	21.5

Six different types of FRP were used in this study, the main characteristics of the fibres were their strength and Young's modulus. The six different types of FRP comprise of two wrap sheets namely (a) Sika Wrap-300C/60 carbon fibre, (b) Sika Wrap- 430 G/25 glass fibre, and four laminate plates namely (c) Tyfo UC laminate, (d) Sika CarboDur S1214, (e) Sika CarboDur M614, (f) Sika CarboDur H514 that symbolized as 'a' to 'f' in alphabetical order in **TABLE 4**.

Table 4 Material properties of FRPs given in specification

Types of FRP	Symbol	t_F MPa	σ_u MPa	E_o GPa	$\square_f$ (%)
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

The six different types of adhesive comprise of Sika330, Sika30, Tyfo TC, Araldite 2011, Araldite2015 and Araldite420, which are symbolized as 'A' to 'F' in alphabetical order as shown in **TABLE 5**. Tensile coupon tests were also conducted to obtain the material properties of these six different types of adhesive.

Table 5 Material properties of adhesives obtained from tensile coupon tests

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

The web crippling tests of ferritic stainless steel sections were carried out under the two loading conditions specified in the ASCE Specification [9]. The specimens were tested under the End- Two-Flange (ETF) and Interior-Two-Flange (ITF) loading conditions. A servo-controlled hydraulic testing machine was used to apply a concentrated compressive force to the test specimen. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.3 mm/min.

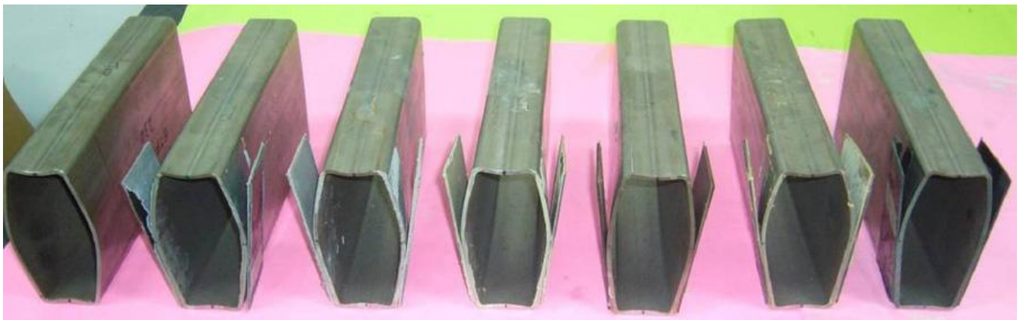
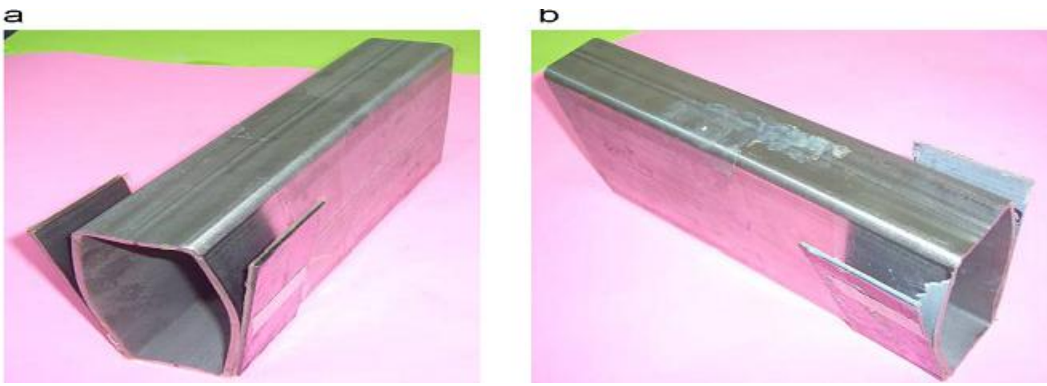


Fig. 5 Failure modes of stainless steel section F120 x 40 x 3 using different adhesives.

Fig. 6 Failure modes of stainless steel section F120 x 40 x 3 using different FRPs

The failed specimens using different adhesives and FRPs for strengthening are shown in **Figs. 5** and **6**, respectively. It was shown that debonding failure was a critical issue for FRP strengthening of ferritic stainless steel tubular members.



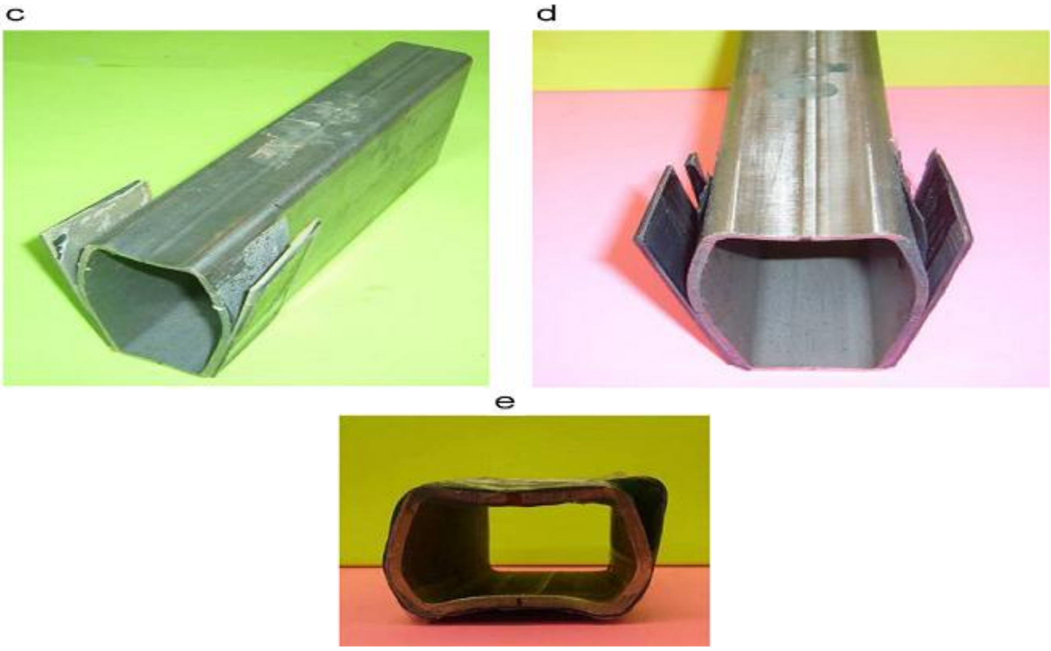


Fig. 7 Different failure modes of FRP strengthened ferritic stainless steel specimens. (a) Adhesion failure, (b) Cohesion failure, (c) Combination of adhesion and cohesion failure, (d) Inter laminar FRP failure and (e) FRP delaminating failure.

The main different failure modes such as adhesion, cohesion, combination of adhesion and cohesion, inter laminar failure of FRP plate and FRP delaminating failure were observed in this study as shown in **Fig. 7**. The strengthened specimens were experienced adhesion failure using Tyfo UC laminate CFRP plate. The adhesion failure was found at physical interface between the adhesive and the adherents; it depends on the surface characteristics of adherent such as the roughness and other factors. The cohesion failure is fully controlled by the adhesive properties. The cohesion failure was observed for specimens using Sika330 adhesive (A). A more flexible and less stiff adhesive of Araldite 2015 provided better performance for such strengthening against web crippling by relieving stress concentrations in the FRP. The combination of adhesion and cohesion failure was observed for some of the specimens using Araldite2015 adhesive by transmitting stresses adequately between the FRP and ferritic stainless steel surface. The effects of adhesive and FRP on the failure modes of strengthened aluminum tubular members are detailed in Islam and Young [8]. The initial cracking is normally started at the end of the FRP plate that experienced high interfacial stresses developed in the region.

II. CONCLUSION

From the past research work, suitability and material properties of stainless steel as a structural material is studied with reference to mechanical properties like stress-strain behavior, thermal resistance, corrosion resistance and cost. A test program on fibre-reinforced polymer (FRP) strengthening of ferritic stainless steel tubular structural members subjected to web crippling has been presented. A series of tests was performed to investigate the effects of different surface treatment, different adhesive and FRP for the strengthening of stainless steel tubular sections against web crippling failure. The failure loads, failure modes and the load-web deformation behaviour of the ferritic stainless steel sections have been reported. The test results showed that the adhesive and FRP properties influence on the performance of FRP strengthened ferritic stainless steel tubular structural members. It was shown that the adhesive Araldite2015 and the high modulus CFRP Sika CarboDur H514 laminate plate revealed the best performance for the tested ferritic stainless steel tubular sections subjected to web crippling. The ferritic stainless steel sections F50 x 50 x 4 and F120 x 40 x 3 have the web crippling load enhancement of 11% and 51%, respectively. Furthermore, the influence of different widths of FRP plate strengthening against web crippling subject to End- Two-Flange and Interior-Two-Flange loading conditions was also investigated. It was shown that the increases of FRP width did not provide much improvement on the strengthening of ferritic stainless steel sections.

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