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CFRP strengthening of steel I-beam against local web buckling: A numerical analysis

M.A. Ghareeb
Bemco Steel Industries, Saudi Arabia

M.A. Khedr
Faculty of Engineering, Benha University, Egypt

E.Y. Sayed-Ahmed
The American University in Cairo and Professor (on leave), Ain Shams University, Egypt

ABSTRACT: The use of Carbon Fibre Reinforced Polymers (CFRP) in strengthening of steel structural elements is growing every year. CFRP laminates offer an economic strengthening alternative for steel I-beams. The common method of using CFRP laminates in strengthening steel beams is by bonding the laminates (usually high modules type) to the lower flange of the beam to increase its flexural strength. However, for thin walled "slender" I-section steel beams, the risk of local buckling failure is also a major concern. Recently, it was found that bonding CFRP laminates to steel slender I-section web can enhance the local buckling of the steel section. Here, a numerical investigation is performed to investigate the effect of bonding CFRP laminates to the webs of I-section steel beams on the beam's flexural strength. The main advantage of this technique is delaying the onset of local buck-ling of the beam's web thus allowing the slender I-section to reach its yield flexural capacity. The study reveals that bonding the CFRP laminates to the web of I-sections significantly increases the critical load and may allow the beam to reach its yield capacity.

1 INTRODUCTION

Traditional strengthening techniques of steel beams involve an expensive process of welding/bolting steel plates to the beams' cross section. These plates are heavy, impractical and face many difficulties in site-installation. Fibre Reinforced Polymers (FRP) which are characterized by their high strength to weight ratio may offer an attractive strengthening alternative. FRP laminates/strips are currently adopted as one of the most successful strengthening techniques for different reinforced and prestressed concrete elements. On the other hand, investigations on strengthening steel structures using FRP are still limited, in most cases, to applying the laminates/strips to the tension flange of the beam in order to increase its flexural strength (Miller et al. 2001; Liu et al. 2001; Teng and Podolny 1998; Chajes and Swinehart 2002; Miller 2000; Moy 2001; West 2001; Cadei et al. 2004).

Furthermore, for thin walled I-section beams the risk of buckling failure is also a major concern. Steel I-sections subject to flexure are classified into compact, non-compact and slender sections. Compact sections of can develop the cross-section full plastic moment while non-compact sections are guaranteed only to develop the cross-section yield moment, then the section would fail by local buckling of its component plate elements before reaching the plastic moment. Slender sections suffer local buckling of the component plate elements before reaching the yield moment. FRP laminates may offer a good strengthening technique for slender section by delaying its local buckling and as such, changing the section class.

On another front, steel plate girders are widely used in buildings and bridges. They have good flexure capacity and serviceability performance due their deep webs. Environmental effects and substandard maintenance of plate girders can cause their main strength element to rust. Rehabilitation of such damaged sections could be very tricky. The traditional rehabilitation techniques are based on welding steel plates and stiffeners to the damaged web. However, one of the many disadvantages of this technique is the resulting elevated temperature due to the welding process which may cause more damage to the steel section. So FRP laminates may offer an attractive alternative in such cases.

Failure modes of CFRP strengthened steel I-section beams may take place via steel yielding, flange and/or web local buckling, rupture of the CFRP laminates, and/or de-bonding of CFRP laminates from the section (Buyukozturk et al. 2004). In most cases, an interactive failure mode between more than one of the previously mentioned modes may govern failure of the FRP strengthened steel I-beam. An experimental investigation conducted by Lam and Clark, 2003 showed that bonding CFRP laminates to the tension flange of a compact I-section is not as effective as it is thought to be: only 9% increment on the strength of the compact section were achieved. The final and sudden failure occurred by shattering of the epoxy layer after the steel had reached its yield strength. The strength of the CFRP laminates was not fully utilized. The investigation also pointed-out that bonding CFRP laminates to the web of non-compact I-section beam increased the ultimate load by about 23% and also improved the buckling behaviour. Similar numerical investigation was conducted by Sayed-Ahmed (2004, 2006) which yielded the same previously mentioned conclusions.

More interestingly, the non-compact sections with web-bonded CFRP laminates in some cases were able to achieve steel yielding followed by formation of plastic hinge, and then the CFRP laminates debonded from the steel sections. It was found that bonding CFRP strips in such configuration may increase the critical load by a ratio ranging between 20% and 60% (Sayed-Ahmed 2004, 2006).

Here, a numerical model is developed based on the finite element technique and solved using a commercially available FE package. The model is used to analyse the effect of bonding Carbon Fibre Reinforced (CFRP) laminates to webs of slender steel I-beams. The numerical analysis is also used to investigate web buckling of these strengthened I-beams. The main objective of this work is to investigate the benefit of using high modules CFRP laminates in strengthening steel I-beams. The study also investigated the effect of increasing the thickness of the adhesive layer on the web stability of the CFRP strengthened I-beams.

2 FINITE ELEMENT MODEL

Steel beam composed of a built-up section (Figure 1) with a total length of 12.0 m is numerically modeled. The beam's web depth is 573 mm with a thickness varying between 2 mm and 12 mm which corresponding to compact, non-compact and slender sections. The two flanges of the beams are composed of 229 mm × 20 mm plates. Sections proprieties for the analyzed beams are listed in Table 1.

The beam is subjected to four points loading with points of applications shown in Figure 1. CFRP laminates are bonded to the beam's web with the configuration shown in Figure 1.

To prevent lateral torsional buckling, the beam is laterally supported every 3.0 m. The beam is simply supported at both ends. It is restrained against rotation around its longitudinal (weak) axis.

As shown in Figures 1 and 2, horizontal CFRP laminates are bonded to the web at mid height (mimicking plate girder's horizontal stiffeners). Other vertical CFRP laminates mimicking plate girder's vertical stiffeners are welded to the web in the configuration shown in Figures 1 and 2. All the CFRP strips are 100 mm wide by 1.4 mm thick. To study the effect of increasing the thickness of the adhesive layer which bonds the laminates to the steel web, two thicknesses are assumed, 1.0 mm and 1.4 mm.

Layered shell element (Figure 3) is adopted for modelling the steel and both the adhesive and the CFRP laminates. The element has 8 nodes with 6 degrees of freedom per node. For the web parts with the bonded CFRP laminates, five layers are used: central steel layer modelling the steel web, two layers modelling the epoxy adhesive and two outer layers modelling the CFRP laminates.

The constitutive model of steel beam follows a bilinear elastic-plastic stress-strain curve which has identical behaviour in tension and compression. The strain hardening modulus was assumed to be 5% of Young's modulus. The assumed initial yield stress of the steel material is 300 MPa and the Young's modulus was taken as 200 GPa. Poisson's ratio of 0.3 was adopted.

Two types of CFRP laminates are modelled: normal modulus laminates (S), and high modulus laminates

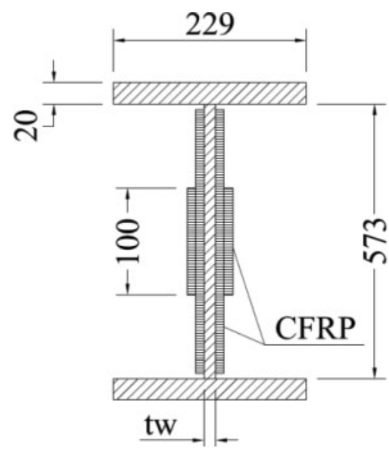

Figure 1. Strengthened steel beam's cross-section.

Table 1. Mechanical properties of the analysed beams.

Beam	t_w (mm)	h_w/t_w	Sec Class	A ($\times 10^3$) mm^2	I_x ($\times 10^6$) mm^4	I_y ($\times 10^6$) mm^4
B1	12	47.75	1	16.04	993.2	40.1
B2	6	95.50	2	12.60	899.0	40.0
B3	4	143.25	3	11.50	567.7	40.0
B4	2	286.50	4	10.30	836.3	40.0

Beam	r_x mm	r_y mm	S_x ($\times 10^3$) mm^3	S_y ($\times 10^3$) mm^3	Z_x ($\times 10^6$) mm^3	Z_y ($\times 10^6$) mm^3
B1	249	50.0	3241	350	3699	545
B2	267	56.4	2934	349	3207	529
B3	275	59.1	2832	349	3043	527
B4	285	62.3	2730	349	2961	526

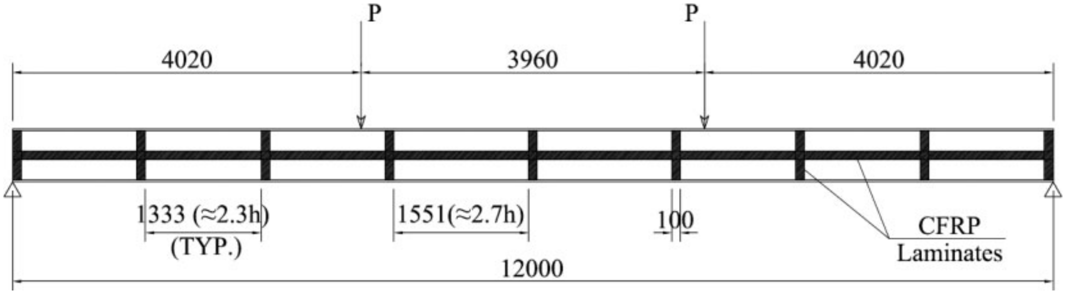

Figure 2. Strengthened steel beam: loading, boundary conditions and CFRP laminates configuration.

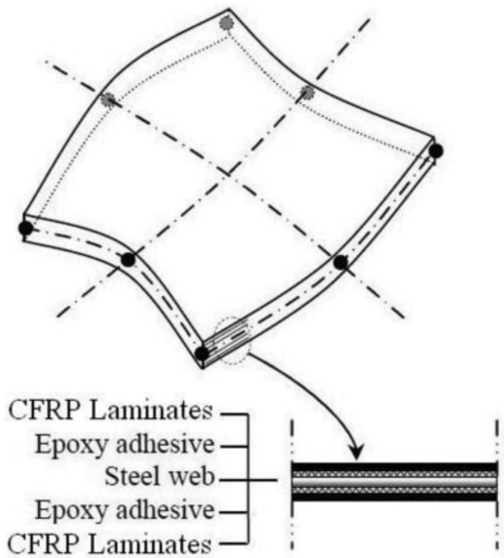

Figure 3. Layered shell element adopted in the analyses.

Table 2. Properties of the CFRP laminates.

Mechanical properties	St. Modulus Laminates (S) MPa	High Modulus Laminates (H) MPa
Tensile Modulus	167,000	300,000
Tensile Strength	2,800	1,500

(H). The mechanical proper-ties of the CFRP laminates and the epoxy are shown in Table 2. Table 3 shows the mechanical properties of the adhesive material.

The layered shell element requires linear isotropic and multi-linear isotropic material properties to properly model the adhesive. The multi-linear isotropic material uses the von-Mises failure criterion (Willam and Warnke 1974). The modulus of elasticity of the adhesive and Poisson's ratio are obtained from the manufacturer's datasheet. Implementation of the material material model requires 9 constants to be defined. Only 4 constants are affecting the behaviour of the adhesive layer: shear transfer coefficients for an open crack, shear transfer coefficients for a closed crack, uni-axial tensile cracking stress, (assumed to be 5.9), and uni-axial crushing stress (assumed to be 1.0). Typical shear transfer coefficients range from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). The shear transfer coefficients for open and closed cracks are assumed to be 0.2 and 1.0, respectively. The adopted finite element mesh, boundary conditions and loading are shown in Figure 4.

Table 3. Properties of the epoxy adhesive.

Mechanical properties	Value MPa
Tensile Strength	26
Compressive Strength	85
Shear Strength	18
Bond Strength	21
Tensile Modulus	11,200

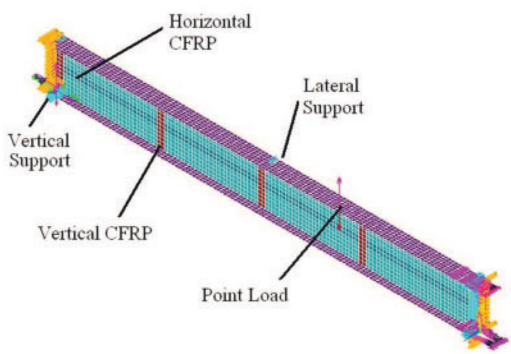

Figure 4. Finite element model (because of symmetry, only half the beam is shown and modelled.

3 RESULTS AND DISCUSSION

A linear elastic buckling analysis on each steel beam is performed to evaluate the critical loads which initiate web buckling.

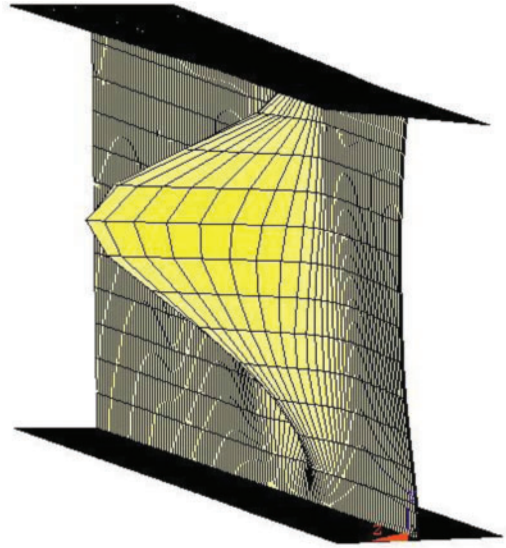

Figure 5. Modelled steel beam deformed shape at web buckling.

For each class of beams, five types of beams are analyzed. The first type (D1) is the control beam with no CFRP laminates bonded to it. The second type (D2-S-1) is strengthened with normal modulus CFRP laminates with the CFRP arrangement shown in Figures 1 and 2: the thickness of the adhesive layer is 1.0 mm. The third type (D2-S-1.4) has the same CFRP laminates arrangements and the same laminates type but the thickness of the adhesive layer is 1.4 mm. The forth type (D2-H-1) has the same CFRP laminates arrangements as the third beam but the type of laminates is high modulus CFRP: the thickness of the adhesive layer is 1.0 mm. The fifth type (D2-H-1.4) has the same CFRP laminates arrangements and the same type of laminates but the thickness of the adhesive layer used is 1.4 mm.

Eigen buck-ling analysis was performed for all the beams: Figure 5 shows the deformed shape of the one of the analyzed beams. The full results of these analyses are shown in Table 4. The Table reveals that bonding the CFRP strips to web of slender sections significantly delayed web buckling and increased the critical load by about 31%. For non-compact section, the enhancement in the critical load is in the order of 16%.

Table 4. Results of Eigen buckling analyses.

			D1	D2-S-1		D2-S-1.4		D2-H-1		D2-H-1.4	
Beam No.	h_w/t_w	Section Classification	P_{cr} kN	P_{cr} kN	% of Incr.	P_{cr} kN	% of Incr.	P_{cr} kN	% of Incr.	P_{cr} kN	% of Incr.
B1	47.75	Compact	1342.0	1380.0	3.0%	1395.0	4.0%	1384.0	3%	1400.0	4.3%
B2	95.50	Compact	292.0	316.0	8.0%	322.0	10.0%	319.0	9%	325.0	11.0%
B3	143.25	Non-compact	102.6	115.0	12.0%	117.1	14.1%	116.9	14%	118.9	15.8%
B4	286.50	Slender	15.2	18.9	24.3%	19.2	26.3%	19.6	29%	19.9	31.0%

Table 5. Failure moment to plastic moment and yield moment.

Beam No.	h_w/t_w	Section Classification	M_y kN·m	M_P kN·m	M_f kN·m	M_f/M_y	M_f/M_p
B1-D1	47.75	Compact	972.3	1109.7	5394.8	5.55	4.86
B1-D2-S1	47.75	Compact	972.3	1109.7	5547.6	5.71	5.00
B1-D2-S14	47.75	Compact	972.3	1109.7	5607.9	5.77	5.05
B1-D2-H1	47.75	Compact	972.3	1109.7	5563.7	5.72	5.01
B1-D2-H14	47.75	Compact	972.3	1109.7	5628.0	5.79	5.07
B2-D1	95.50	Compact	880.2	962.1	1173.8	1.33	1.22
B2-D2-S1	95.50	Compact	880.2	962.1	1270.3	1.44	1.32
B2-D2-S14	95.50	Compact	880.2	962.1	1294.4	1.47	1.35
B2-D2-H1	95.50	Compact	880.2	962.1	1282.4	1.46	1.33
B2-D2-H14	95.50	Compact	880.2	962.1	1306.5	1.48	1.36
B3-D1	143.25	Non-compact	849.6	912.9	412.5	0.49	0.45
B3-D2-S1	143.25	Non-compact	849.6	912.9	462.3	0.54	0.51
B3-D2-S14	143.25	Non-compact	849.6	912.9	470.7	0.55	0.52
B3-D2-H1	143.25	Non-compact	849.6	912.9	469.9	0.55	0.51
B3-D2-H14	143.25	Non-compact	849.6	912.9	478.0	0.56	0.52
B4-D1	286.50	Slender	819.0	888.3	61.1	0.07	0.07
B4-D2-S1	286.50	Slender	819.0	888.3	76.0	0.09	0.09
B4-D2-S14	286.50	Slender	819.0	888.3	77.2	0.09	0.09
B4-D2-H1	286.50	Slender	819.0	888.3	78.8	0.10	0.09
B4-D2-H14	286.50	Slender	819.0	888.3	80.0	0.10	0.09

Using high modules CFRP laminates in the configurations shown in Figures 1 and 2 increased the critical load from 24% to 29% for slender sections. Increasing the adhesive layer thickness from 1.0 mm to 1.4 mm had no significant effect on the critical load: only a 2% strength enhancement is achieved. Table 5 shows a comparison between the calculated yield moment M_y and the calculated plastic moment M_p to the failure moment obtained from the finite element analyses. The results show that for beam no. 3, the use of the suggested strengthening technique increased the ratio of the failure moment to the yield moment from 0.49 to 0.56. For beam no. 4, the ratio is increased from 0.07 to 0.10.

4 CONCLUSIONS

The effect of bonding CFRP strips to the webs of thin-walled I-section steel beams on the beam's flexural strength is numerically investigated. The main advantage of this detail is delaying the local buckling of the beam's web. Nonlinear finite element analyses were performed on steel I-section beams with different web height-to-thickness ratios. The effect of bonding 100 mm × 1.4 mm CFRP strips on the critical load initiating web buckling is evaluated. It is found that bonding CFRP strips in such configuration may increase the critical load by a ratio of 24%. Increasing the tensile modules of CFRP strips will enhance the performance of the configurations by additional 5%. The effect of increasing the adhesive layer thickness is also studied and was found to be negligible.

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