Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Toronto, Canada, March 25-28, 2014

Experimental investigation on shear strength of elastic end-web panels strengthened with CFRP strips

S.S. Safar[1], M.N. Abou-Zeid[2]

Abstract
An experimental program was conducted to investigate the shear strength of elastic end-web panels of steel plate girders strengthened with intermediate-modulus carbon fiber-reinforced polymers, CFRP, strips. Test parameters included; number of strips, aspect ratio of end-web panel and width-to-thickness ratio of web plate. Twelve plate girder specimens composed of mild-steel were loaded in a four-point bending test till failure. The girders were proportioned so that the load capacity was governed by elastic web buckling. Four specimens were not strengthened to serve as reference girders whereas the remaining specimens were strengthened by applying CFRP strips in the diagonal tension direction on one or both sides of the web. Test results indicated that the buckling strength of strengthened specimens was not improved, however, the ultimate shear strength increased by 6% to up to 120% due to significant increase in post-buckling strength. The increment in post-buckling strength due to pasting CFRP strips on web plate was several multiples of that of reference girders and was reduced when slender web plates or long end-web panels were utilized. In addition to higher ultimate shear capacity, it was observed that vertical deflections, out-of-plane displacements of the web and bending curvature of transverse stiffeners of strengthened girders were reduced at ultimate load. It was concluded that the ultimate shear strength of elastic end-web panels was successfully improved using intermediate-modulus CFRP strips. On the other hand, current design rules adopted by current AISC specifications need to be revised to account for post-buckling strength of elastic end-web panels.

1. Introduction
Due to corrosion and continuous demand to increase traffic loads, there was a need for an efficient, cost-effective system that could be used to strengthen and repair steel high-way bridge girders. Recent research work was conducted to assess the use of carbon fiber-reinforced polymers, CFRP, to address such need. Miller 2001 and Tavakkolizadeh 2003a revealed that the moment capacity of steel-concrete composite beams increased by 30% to 70% when CFRP strips were bonded to the tension flange. Although the effect of using CFRP strips on the elastic behavior of strengthened beams was insignificant, it was shown that tensile strains were

[1] Associate Professor, American University in Cairo, <ssafar@aucegypt.edu>
[2] Professor and Chair of Const & Arch End Dept, American University in Cairo, <mnagiba@aucegypt.edu>

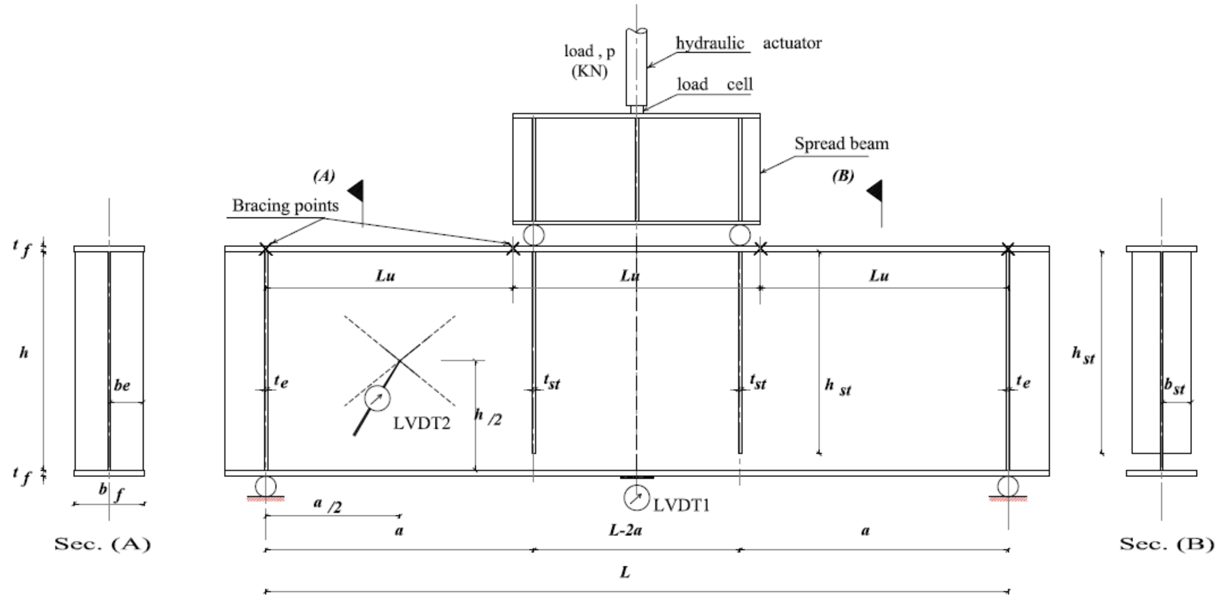
dramatically reduced in the inelastic region compared to bare girders. Dawood 2005 and Peiris 2011 demonstrated that the application of high and intermediate modulus CFRP strips to tension flange of composite girders increased the elastic stiffness, yield load and ultimate moment capacity, reduced crack propagation rates and enhanced the fatigue durability of strengthened girders (Tavakkolizadeh 2003c). Al-Saidy 2004 and Tavakkolizadeh 2003b successfully used CFRP strips to repair naturally deteriorated and/or overloaded girders. It was shown that the application of CFRP strips increased the yield load and ultimate capacity of deteriorated beams by up to 67% and 52%; respectively. The bonding strength and behavior of the material used to past CFRP strips to steel beams was known to vital to the behavior of strengthened girders, Tabar 2010 and Narmashiri 2012 conducted experimental work to improve bonding methods and describe adequate bond length of CFRP strips pasted on steel beams.

The majority of previous research work was focused on upgrading or retrofitting moment strength of steel girders whereas shear strengthening of steel girders using CFRP materials was rarely addressed. Narmashiri 2010 conducted an experimental program on five steel beams strengthened with different areas of CFRP strips on end web panels. Vertical CFRP strips were pasted on one or both sides of the web in the shear zone. It was concluded that the use of CFRP strips with area ratio of 0.48 from that of the web in the shear zone improved the shear capacity of steel beams by up to 51%. However, it was noted that increasing the area ratio of CFRP from 0.48 to 0.72 did not enhance the load capacity of the tested beams.

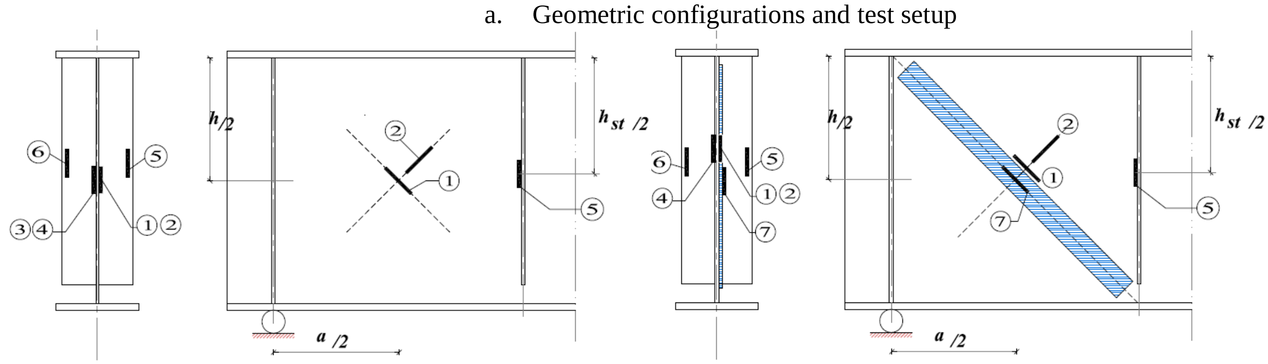
In this work an experimental program was conducted to assess the shear strength of elastic end-web panels strengthened with intermediate-modulus CFRP strips. Unlike previous research work, the CFRP strips were pasted on the web in the diagonal tension direction. Twelve plate girders composed of mild steel were proportioned as per AISC specifications 2005 so that the load capacity was governed by elastic web buckling. Test parameters included; number of CFRP strips, aspect ratio of end-web panels and width-to-thickness ratio of web plate. Among the twelve girders, four girders were not strengthened to serve as reference girders. All girders were loaded in a four-point bending test till failure and test results including; buckling load, post-buckling load, ultimate load, mode of failure, strains in girders and CFRP strips, and vertical deflections were recorded. Current design rules (AISC 2005) for shear strength of end-web panels were assessed by comparison to the ultimate load of un-strengthened girders obtained by test.

2. Experimental Program

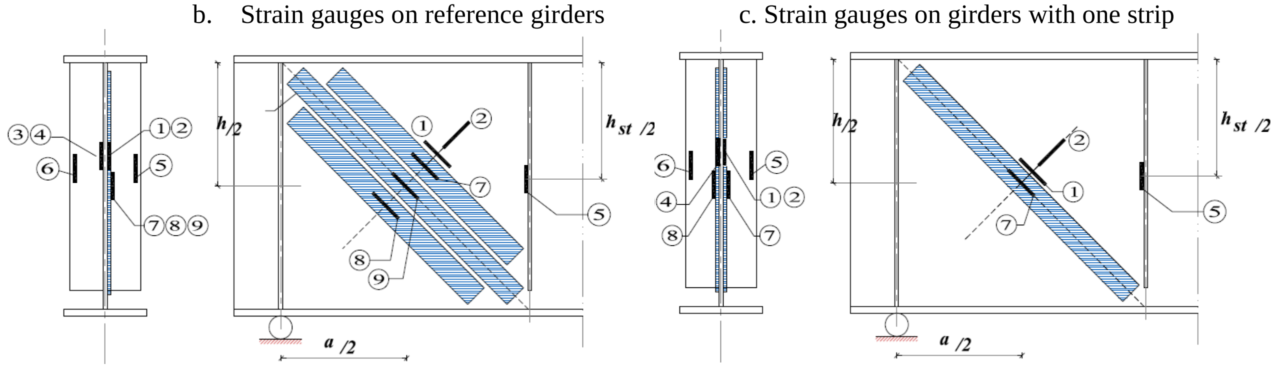
Fig. 1 illustrates the geometric configurations and test setup of plate girders specimens examined herein. All specimens were composed of mild steel with yield stress, F_y, of 240 MPa, tensile strength, F_u, of 360 MPa, Young's modulus, E, of 200 GPa and Poisson's ratio, μ, of 0.3. Table 1 lists section dimensions, width-to-thickness ratio of web plate, h/t_w, aspect ratio of end-web panel, a/h, and span, L. In order to evaluate the shear strengthening effect of CFRP strips on plate girders, the selected specimens were divided into four groups according to a/h and h/t_w ratios. In order to exclude the fixation effect of flanges to web plate (Machaly 2007, Machaly 2008 and Safar 2013), the ratio of t_f/t_w was kept constant in all specimens. Double-sided transverse stiffeners and end stiffeners were used at loading points and at supports; respectively (see Fig. 1) to exclude web crippling and local web yielding failure modes at concentrated loads (AISC 2005). Dimensions of transverse and end stiffeners were listed in Table 2.



a. Geometric configurations and test setup



b. Strain gauges on reference girders   c. Strain gauges on girders with one strip



d. Strain gauges on girders with three strips   e. Strain gauges on girders with two strips

Figure 1: Test set-up and geometric configurations of tested girders

One specimen in each group was not strengthened to serve as reference girder whereas the other two specimens were strengthened with different number, *n*, and/or location of CFRP strips (see Table 1). The CFRP strips were made by SIKA® Co. pultruded Sika® Carbo Plate type S512/80, 50 mm in width and 1.2 mm in thickness. Material properties of the CFRP strips were listed in Table 3 (SIKA® product information, 2008). The strips were bonded to webs of plate girders using 1 mm thick adhesive SIKA®DUR30. Material properties of adhesive were listed in Table 4.

Table 1: Dimensions and strengthening details of specimens

GR	Designation	Section Dimensions (mm)					a	a/h	L	L_u	CFRP strips	
		b_f	t_f	h	t_w	h/t_w	(mm)		(mm)	(mm)	n	Location
1	CG-1-135	165	12	540	4	135	540	1	1620	810	0	--
	SG-1-135-1										1	One side
	SG-1-135-3										3	
2	CG-1-180	165	10	540	3	180	540	1	1620	810	0	--
	SG-1-180-1										1	One side
	SG-1-180-3										3	
3	CG-2-135	165	12	540	4	135	1080	2	3240	1080	0	--
	SG-2-135-1										1	One side
	SG-2-135-2										2	Two sides
4	CG-3.5-135	165	12	540	4	135	1890	3.5	4320	1080	0	--
	SG-3.5-135-1										1	One side
	SG-3.5-135-2										2	Two sides

Table 2: Dimensions of double-sided end and transverse stiffeners

GR	Designation	End Stiffeners (mm)				Transverse Stiffeners (mm)			
		b_e	t_e	h_e	b_e/t_e	b_{st}	t_{st}	h_{st}	b_{st}/t_{st}
1	CG-1-135 SG-1-135-1 SG-1-135-3	80	10	540	8	70	8	520	8.75
2	CG-1-180 SG-1-180-1 SG-1-180-3	70	10	540	7	65	6	520	10.8
3	CG-2-135 SG-2-135-1 SG-2-135-2	70	10	540	7	60	6	520	10
4	CG-3.5-135 SG-3.5-135-1 SG-3.5-135-2	60	10	540	6	55	5	520	11

Table 3: Dimensions and material properties of CFRP strips

Sika® CarboDur® S512/80											
Dimensions. (mm)		E-Modulus (GPa)				Tensile Strength (MPa)				Strain (%)	
Width	Thickness	Mean	Min	5% Fracture	95% Fracture	Mean	Min	5% Fracture	95% Fracture	Break	Design
50	1.2	165	>162	160	180	3100	>2800	3000	3600	1.7	0.85

Table 4: Dimensions and material properties of adhesive material

SikaDur®-30								
Dimensions (mm)		Compression		Tension		Shear (Mpa)	Bond to steel (MPa)	
Width	Thickness	E (GPa)	Strength 7 days	E (GPa)	Strength 7 days		Mean	Min
50	1.0	9.6	70-95	11.2	24-31	14-19	30	21

The test setup was composed of a four-point bending test (see Figs 1 and 2). The load was applied on a spread beam by means of a hydraulic actuator with capacity 2000 KN. To avoid failure by lateral-torsion buckling, the compression flange of the specimens was braced at intervals of L_u (see Fig 3 and Table 1).

Figure 2: Setup of experimental test

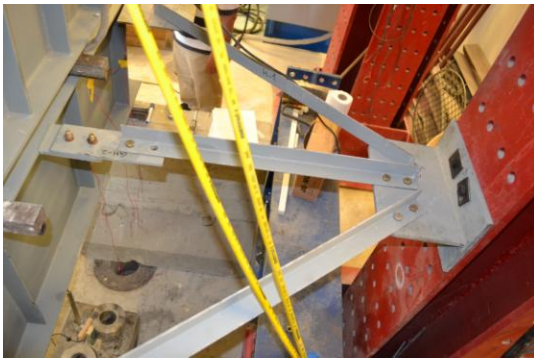


Figure 3: Bracing of compression flange at intervals of L_u

Vertical deflection at mid-span, δ_v, and lateral displacement at center of end-web panel, δ_u, was measured by Linear Variable Deformation Transducers, LVDT-1 and LVDT-2; respectively (see Figs 1 and 2). Six strain gauges were pasted on the end-panel web and transverse stiffeners are shown in Fig. 1. Strain gauges (1) and (2) were pasted at the center of on one side of the web in the direction of principal tension and principal compression; respectively. Strain gauges (3) and (4) were located as strain gauges (1) and (2) but pasted on the other side of the web to facilitate computing middle surface strains by averaging surface strains as follows:

$$\varepsilon_t = 0.5\ (\varepsilon_1 + \varepsilon_3) \tag{1}$$

$$\varepsilon_c = 0.5\ (\varepsilon_2 + \varepsilon_4) \tag{2}$$

where ε_1 to ε_4 are strains measured by strain gauges (1) to (4); respectively. The objective of computing middle surface strains was to determine the amount of tensile and compressive stress resultants supported by the web excluding the effect of through-thickness stresses that appear after buckling and formation of tension folds in the web (Machaly 2007 and 2008). Strain gauges (5) and (6) were pasted on edges of transverse stiffeners as shown in Fig. 1 to compute bending curvature at mid-depth of stiffeners, Φ_{stiff}, as follows:

$$\emptyset_{stiff} = \frac{\varepsilon_5 - \varepsilon_6}{2b_{st} + t_w - 10} \tag{3}$$

where ε_5 and ε_6 are strains measured by strain gauges (5) to (6); respectively, and the term in the denominator of Eq (3) represents the horizontal center-to-center spacing in millimeters between strain gauges (5) and (6) (see Fig. 1). Strain gauges (7) to (9) were pasted at the center of CFRP strips as shown in Fig. 1 to measure growth of tensile strains in CFRP strips during loading.

Geometric imperfections, δ_o, of the web in left and right end-panels were measured using three LVDT's leveled at $h/4$, $h/2$ and $3h/4$ from the top flange and mounted on a beam parallel to the plane of the web. Inward imperfections were designated by negative sign whereas outward imperfections were designated by a positive sign. The beam carrying the three LVDT's was translated parallel to the longitudinal axis of the specimens to measure imperfections every 135 mm. Table 5 lists the imperfections measured at mid-width of left and right end-web panels at levels; $h/4$, $h/2$ and $3h/4$ from top flange. It was observed that most of specimens contained large geometric imperfections exceeding the permissible limit of $h/120$ stipulated by the AISC specifications except specimens SG-1-135-1, SG-1-180-1, and SG-2-135-1 (see Table 5).

Table 5: Measured geometric imperfections in end-web panels

GR	Designation	δ_o in left panel (mm)			δ_o in right panel (mm)			$\frac{\delta_{o\,max}}{h}$
		h/4	*h/2*	*3h/4*	*h/4*	*h/2*	*3h/4*	
1	CG-1-135	0.42	1.40	0.49	3.22	4.97	2.01	1/108
	SG-1-135-1	1.32	2.01	-1.69	-0.16	0.84	-0.35	1/268
	SG-1-135-3	-0.05	-1.71	-3.02	-3.48	-6.7	-6.22	1/80
2	CG-1-180	4.25	5.08	-1.33	4.82	8.23	2.95	1/65
	SG-1-180-1	1.32	2.01	-1.69	-0.11	-3.09	-1.08	1/174
	SG-1-180-3	3.92	5.13	3.16	3.28	6.35	5.39	1/83
3	CG-2-135	-3.02	-4.11	-4.63	-2.59	-1.76	-1.03	1/116
	SG-2-135-1	3.17	4.41	4.13	-0.47	-1.40	0.37	1/122
	SG-2-135-2	4.86	8.18	5.13	5.65	8.69	5.77	1/62
4	CG-3.5-135	5.60	7.11	6.3	4.99	3.95	4.34	1/76
	SG-3.5-135-1	-3.44	-4.98	-2.91	-2.70	-2.63	-3.16	1/108
	SG-3.5-135-2	2.80	5.38	4.53	-0.96	2.78	1.85	1/100

3. Results and Discussions

3.1 Shear Strength and mode of failure

In this section the shear strength and mode of failure of tested girders were discussed. Since girders were loaded in a four-point bending test, the load supported by the girder, P, at any stage corresponded to twice the shear capacity of end-web panel, V. The maximum load supported by the girder was designated as ultimate load, $P_u = 2V_u$, whereas the load at which tension folds started to develop and principal compressive strains ε_c in the web started to decline was designated as buckling load, $P_{cr} = 2V_{cr}$. The difference between P_u and P_{cr} is the post-buckling strength, $P_{pb} = 2V_{pb}$. Table 6 lists V_{cr}, V_{pb} and V_u obtained by test. Results were compared to V_u stipulated by the AISC specifications for bare girders. Although all tested girders were symmetric, the amount of lateral displacement of the web, δ_u, was not symmetric in the left and right end-web panels due to the effect of geometric imperfections (see Table 5). Table 6 identifies the end-web panel at which buckling was started and larger δ_u were observed at ultimate load. It was observed that the web panel with larger δ_u at ultimate load was not necessary containing the larger geometric imperfection. Due to complex effect of imperfection shape and configuration of CFRP strips, the direction of lateral displacements at the center of end-web panel was sometimes opposite to the direction of geometric imperfections.

Table 6: Shear strength of tested specimens

GR	Designation	Test				AISC	$\frac{V_{u\,AISC}}{V_{u\,Test}}$	$\frac{V_{u\,SG}}{V_{u\,CG}}$	Web panel with larger δ_u
		V_{cr} (KN)	V_{pb} (KN)	V_u (KN)	$\frac{V_{pb}}{V_y - V_{cr}}$	V_u (KN)			
1	CG-1-135	203.5	29.1	232.6	0.30	193.3	0.83	--	Right
	SG-1-135-1	195.4	56.3	251.6	0.53	--	--	1.08	Left
	SG-1-135-3	207.0	188.1	395.1	2.00	--	--	1.70	Right
2	CG-1-180	139.3	32.4	171.8	0.38	81.5	0.47	--	Left
	SG-1-180-1	128.4	65.9	194.3	0.68	--	--	1.13	Right
	SG-1-180-3	129.7	79.8	209.5	0.83	--	--	1.22	Right
3	CG-2-135	131.1	20.7	151.8	0.12	120.8	0.80	--	Left
	SG-2-135-1	131.7	40.4	172.1	0.24	--	--	1.13	Left
	SG-2-135-2	132.7	201.3	333.9	1.20	--	--	2.20	Left
4	CG-3.5-135	172.2	85.3	257.5	0.66	104.5	0.41	--	Right
	SG-3.5-135-1	171.7	100.8	272.5	0.78	--	--	1.06	Left
	SG-3.5-135-2	172.9	104.9	277.8	0.82	--	--	1.08	Right

Based on test results listed in Table 6, it was noticed that pasting intermediate-modulus CFRP strips on the web did not improve the buckling load since all webs were proportioned to buckle in the elastic range (i.e. h/t_w > 1.37 $\sqrt{K_v E/F_y}$ where K_v is the web plate buckling coefficient (AISC 2005)). Similar to previous numerical research work (Safar 2013) and unlike current codes, it was revealed that end-web panels of un-strengthened girders possessed post-buckling strength despite of relatively large geometric imperfections. The value of V_{pb} of reference girders increased from 0.30 to 0.66 of V_y - V_{cr} (where $V_y = 0.6F_y h t_w$ is the shear yield capacity of the web) when the aspect ratio, a/h, increased from 1 to 3.5 at $h/t_w = 135$. On the other hand, the post-buckling strength of reference girders increased from 0.30 to 0.38 of V_y-V_{cr} when the web slenderness ratio h/t_w increased from 135 to 180 at $a/h = 1$. Comparison of the design ultimate strength stipulated by AISC specifications to that obtained by testing reference girders revealed that current design rules underestimated the shear capacity of CG-1-135 by 17% due to discarding the post-buckling strength. When a/h exceeded unity and/or h/t_w exceeded 135, the AISC was more conservative and underestimated the shear strength by 20% to 49% due to underestimating V_{cr} and discarding V_{pb} of end-web panels.

When a single CFRP strip was pasted on the web, the post-buckling strength of SG-1-135-1, SG-1-180-1 and SG-2-135-1 was almost doubled compared to reference girders. Therefore V_u increased by 8% in SG-1-135-1 and 13% in SG-1-180-1 and SG-2-135-1. When a/h increased to 3.5, the post-buckling strength of SG-3.5-135-1 increased by 18% relative to CG-3.5-135 thus causing a limited increase in V_u of 6%. When three CFRP strips were pasted on one side of the web, the post-buckling strength of SG-1-135-3 was increased to more than six times that of CG-1-135. On the other hand, the post-buckling strength of SG-1-180-3 increased to 2.2 times that of CG-1-180. Therefore, V_u of SG-1-135-3 and SG-1-180-3 increased by 70% and 22%; respectively. When two CFRP strips were pasted on both sides of the web of SG-2-135-2, V_{pb} was increased to ten times that of the reference girder CG-2-135. Therefore, V_u of SG-2-135-2 increased by 120%. When a/h increased to 3.5, the use of 2 CFRP strips on both sides of the web was less effective on V_{pb} and V_u.

Therefore it was concluded that strengthening of elastic end-web panels using intermediate-modulus CFRP strips oriented in the direction of diagonal tension was efficient and successful. This was attributed to the significant increase in the post-buckling strength whereas the elastic buckling strength was not improved. The increment in post-buckling strength of strengthened girders declined at long web panels with a/h = 3.5 or slender web plates with h/t_w =180. Increasing the number of CFRP strips improved the shear strength in all cases, however, it was less effective at long web panels with a/h =3.5

Figs 4 to 15 illustrate the failure mode of tested girders. After elastic buckling, out-of-plane displacements of the web increased to form folds in the diagonal tension direction while the girder supported additional loads in the post bucking stage till failure. In un-strengthened girders, out-of-plane displacements of the web were dramatically increased after buckling as depicted in Figs 8 and 11 till the ultimate load was reached. In strengthened girders of Groups 1, 2 and 3, out-of-plane displacements of the web and formation of tension folds were postponed till CFRP strips were de-bonded and/or detached (see Figs 4, 6, 7 and 12). In strengthened girders of Group 4 with long web panels, CFRP strips were de-bonded from one end (see Figs 9, 10 and 14). Edges of de-bonded or detached CFRP strips were delaminated as depicted in Figs 5, 13 and 15.

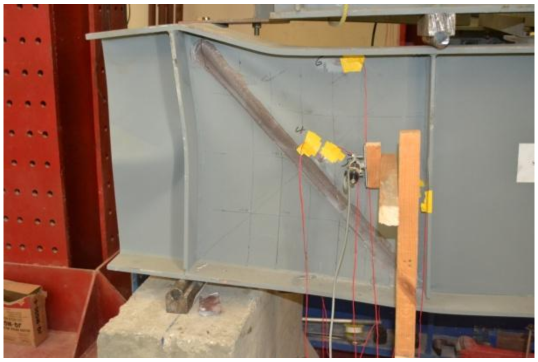


Figure 4: Web buckling and detachment of CFRP (SG-1-135-1)

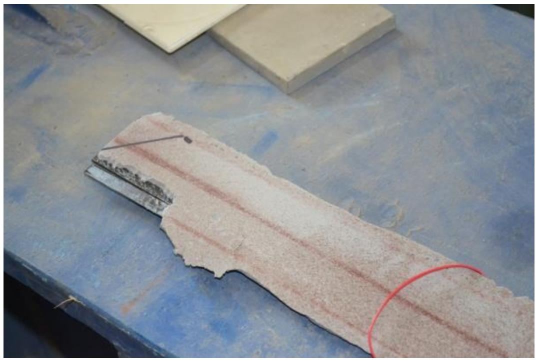


Figure 5: De-lamination of detached CFRP from SG-1-135-1

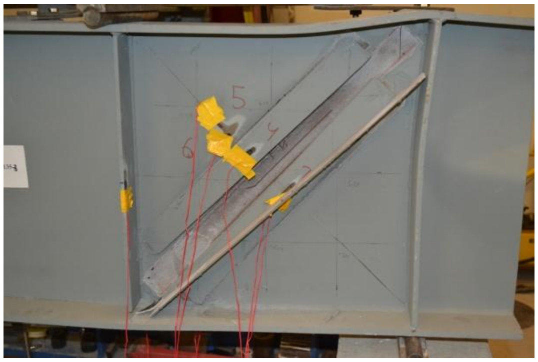


Figure 6: Web buckling and de-bonding of CFRP (SG-1-135-3)

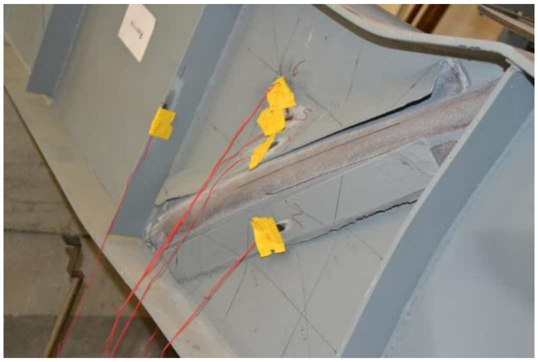


Figure 7: Web buckling and de-bonding of CFRP (SG-1-180-3)

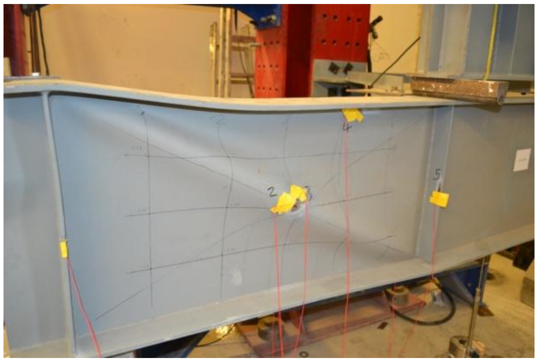


Figure 8: Web buckling and formation of tension folds (CG-2-135)

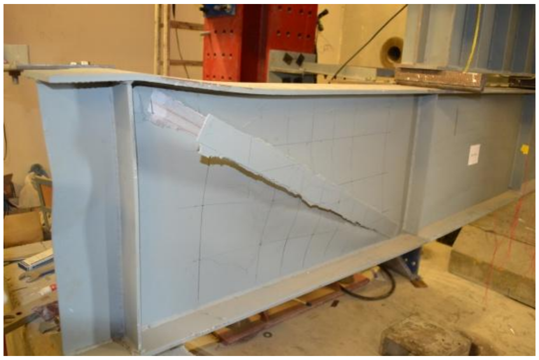


Figure 9: Web buckling and de-bonding of CFRP (SG-2-135-1)

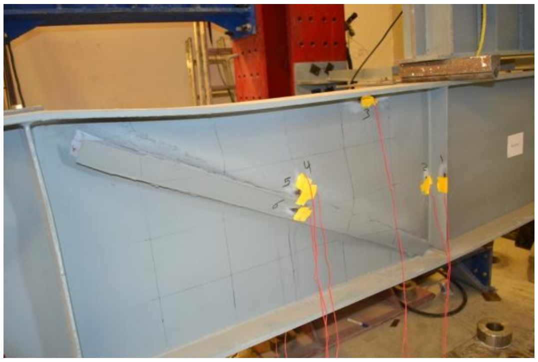


Figure 10: Web buckling and de-bonding of CFRP (SG-2-135-2)

Figure 11: Web buckling and formation of tension fold (CG-3.5-135)

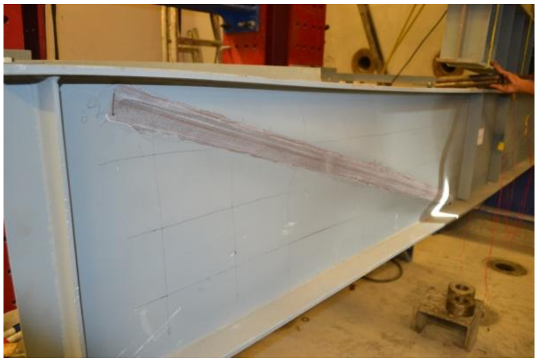


Figure 12: Web buckling and detachment of CFRP (SG-3.5-135-1)

Figure 13: De-lamination in detached CFRP (SG-3.5-135-1)

Figure 14: Web buckling and de-bonding of CFRP (SG-3.5-135-2)

Figure 15: De-lamination of CFRP strips (SG-3.5-135-2)

3.2 Strains in web and CFRP strips

Fig. 16 shows that middle surface compressive strains, ε_c, at the center of the web of strengthened and un-strengthened girders of Group 1 declined after web buckling. The maximum compressive strain at buckling was not affected by the application of CFRP strips. However, the effect of CFRP strips was clear on tensile strains as depicted in Fig. 17. The use of one CFRP strip was slightly effective on ultimate load. However, when three CFRP strips were used in SG-1-135-3, ε_t decreased and did not exceed yield strain, ε_y of 1200 μm/m at P_u. Therefore the strengthening effect of CFRP strip to V_{pb} of SG-1-135-1 and SG-1-135-3 was attributed to additional diagonal tension forces supported by CFRP strips after buckling and postponing yielding of web after buckling. Although CFRP strips enhanced V_{pb}, tensile strains in the CFRP strips did not exceed 25% of the design strain of 8500 μm/m (see Fig. 18). Tensile strains in CFRP strips were sharply increased after web yielding.

Fig. 19 shows that ε_c in webs of Group 2 were dramatically reduced after buckling. Unlike Group 1, the magnitude of compressive strains in the web was progressively reduced when the number of CFRP strips increased. Similarly tensile strains were reduced in strengthened girders and did not exceed ε_y as shown in Fig. 20. Therefore the strengthening effect of CFRP strips to V_{pb} was also attributed to reducing tensile strains in the web and supporting additional diagonal tension forces after elastic web buckling. Fig. 21 shows that strains in CFRP strips in SG-1-180-1 and SG-1-180-3 did not exceed 12% of design strains at P_u and were lower than tensile strains measured in CFRP strips pasted on thicker webs.

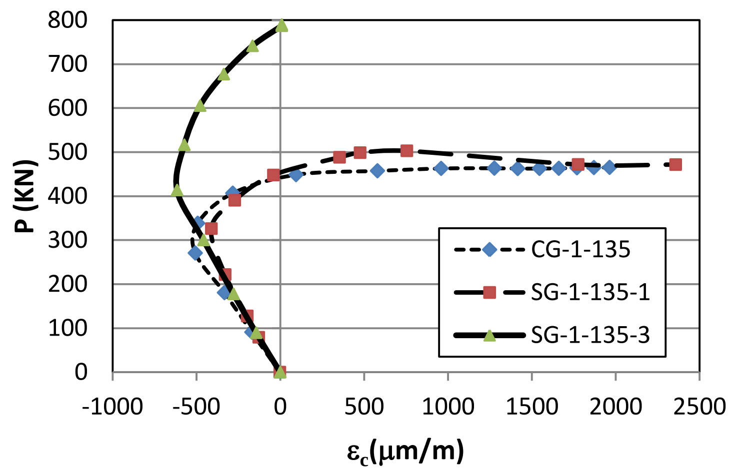


Figure 16: Compressive strains in webs of Group 1

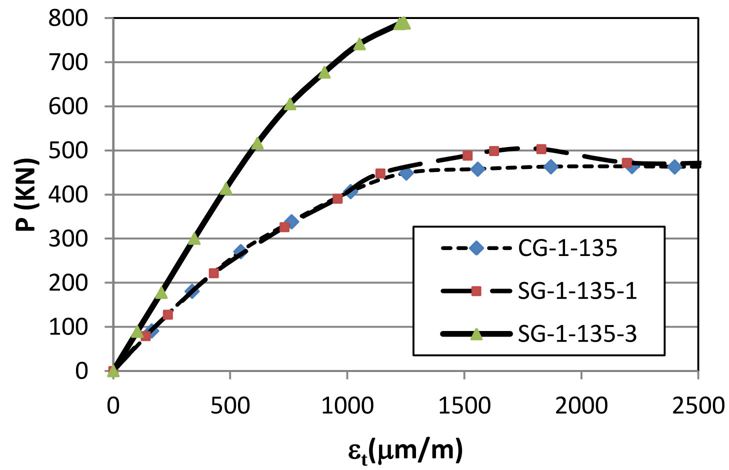


Figure 17: Tensile strains in webs of Group 1

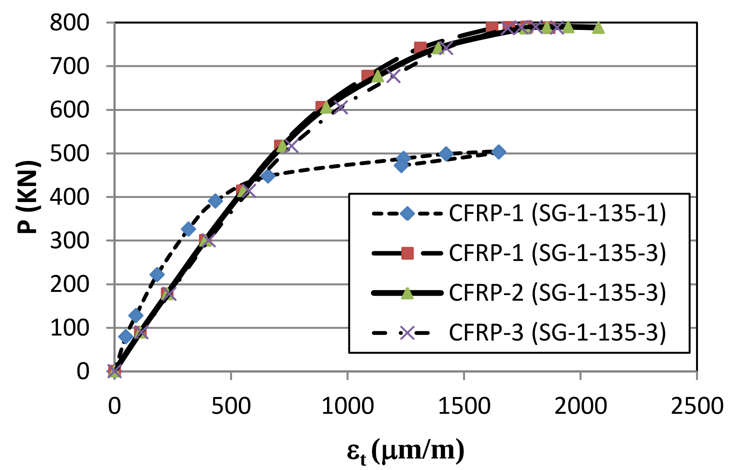


Figure 18: Tensile strains in CFRP strips on strengthened specimens of Group 1

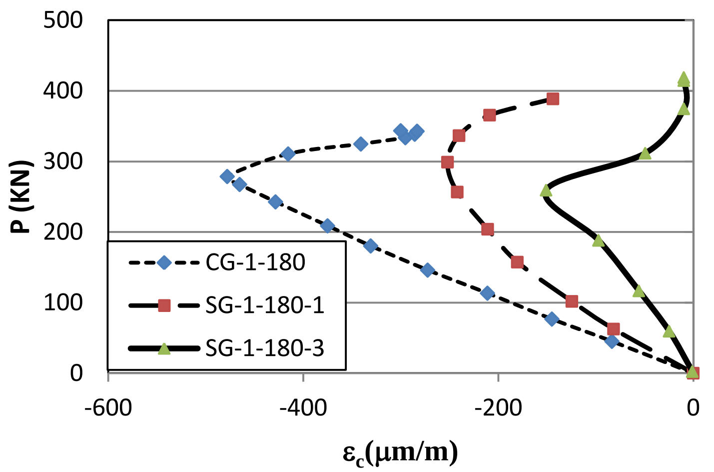


Figure 19: Compressive strains in webs of Group 2

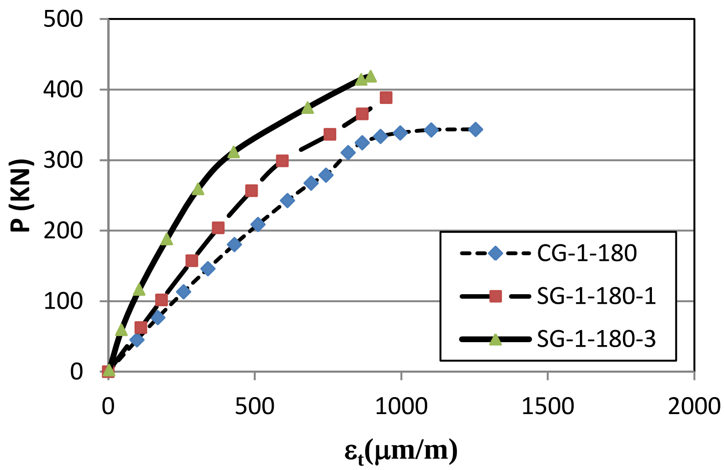


Figure 20: Tensile strains in webs of Group 2

Examination of ε_c and ε_t in webs of Group 3 in Figs 22 and 23 revealed that the use of one CFRP strip was almost ineffective. However, when two strips were used, V_{pb} was not only increased due to relieving ε_t in the web and supporting extra tension force after buckling but also due to bracing the web along the diagonal direction, thus allowing more ε_c after buckling (see Fig. 22). Such behavior caused a significant increase in V_u of SG-2-135-2 (see Table 6). Tensile strains in CFRP strips of SG-2-135-1 and SG-2-135-2 did not exceed 11% and 25%; respectively from the design strain (see Fig. 24). Comparison of strains measured in CFRP strips at ultimate load and increment of post-buckling strength of strengthened girders revealed that pasting CFRP strips on both sides of the was more effective than pasting them on one side (Narmashiri 2010).

Fig. 25 shows growth of ε_c in webs of Group 4. The magnitude of ε_c in CG-3.5-135 and CG-3.5-135-2 declined after buckling. However, ε_c in SG-3.5-135-1 were enhanced after buckling since the direction of lateral displacements in the web was opposite to that of initial geometric imperfections thus causing an arching effect in the web and ε_c exceeded ε_y. Fig. 26 shows that ε_t increased with loading in CG-3.5-135 and SG-3.5-135-2 and exceeded ε_y. However, due to the arching effect noticed in SG-3.5-135-1 and progressive increase in compressive strains, a sudden reduction in rate of growth of ε_t was noticed at after buckling of web and ε_t did not reach ε_y. Fig.

27 shows that tensile strains in CFRP strips used in SG-3.5-135-2 increased after web buckling and did not exceed 26% of the design strain of 8500 μm/m. However, due to arching effect, compressive strains were developed in CFRP strip applied on the web of SG-3.5-135-1.

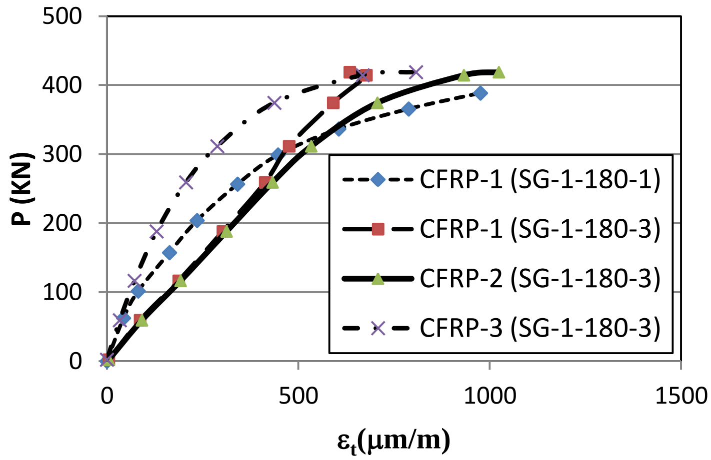


Figure 21: Tensile strains in CFRP strips on strengthened specimens of Group 2

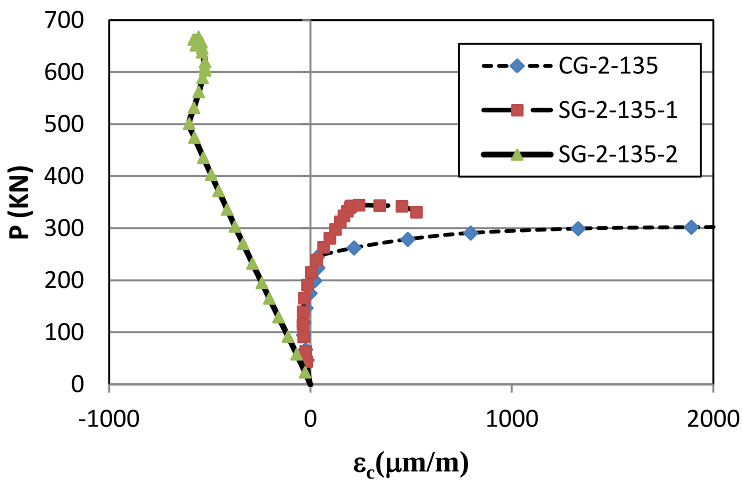


Figure 22: Compressive strains in webs of Group 3

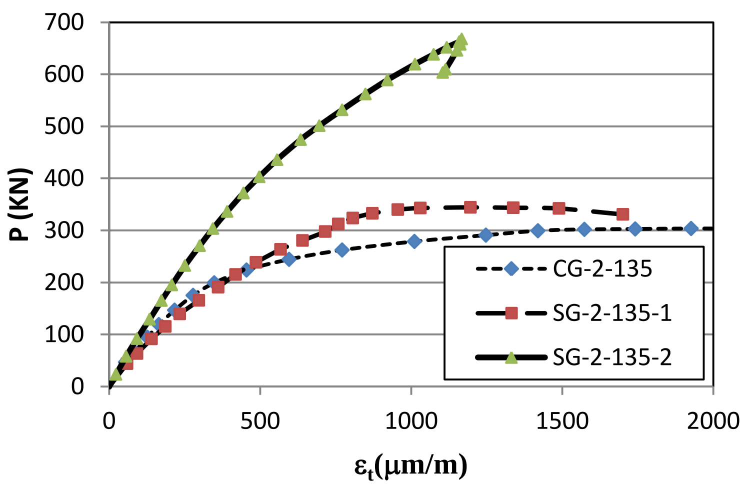


Figure 23: Tensile strains in webs of Group 3

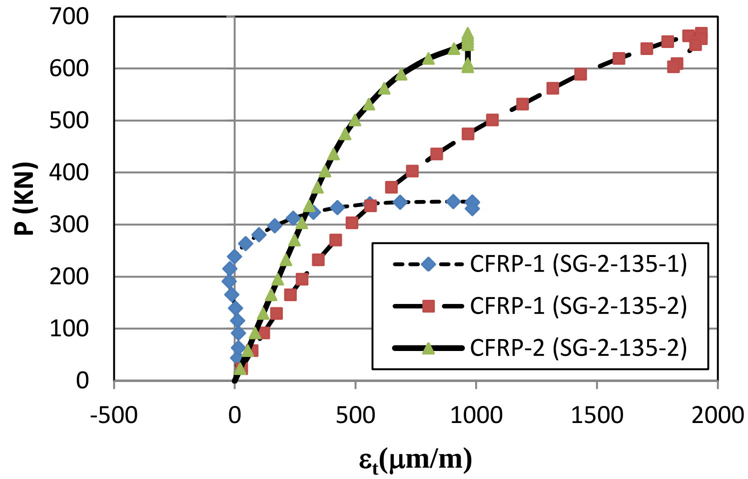


Figure 24: Tensile strains in CFRP strips on strengthened specimens of Group 3

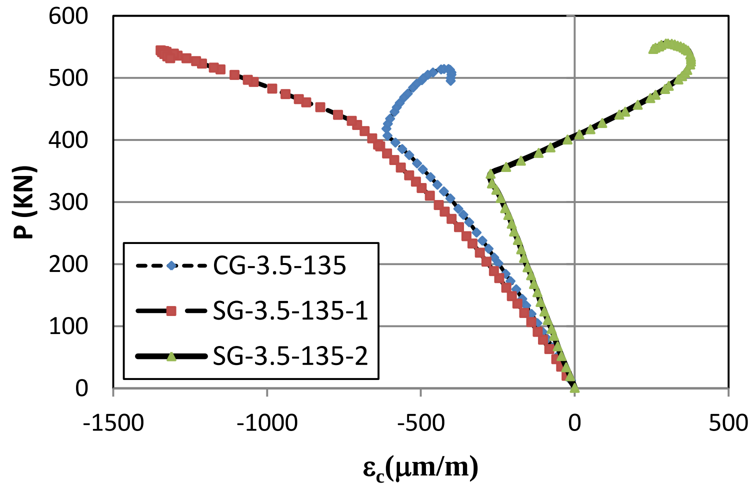


Figure 25: Compressive strains in webs of Group 4

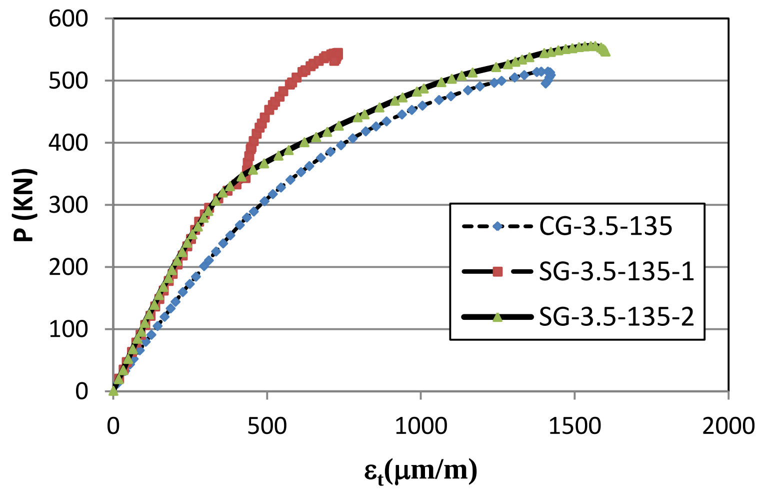


Figure 26: Tensile strains in webs of Group 4

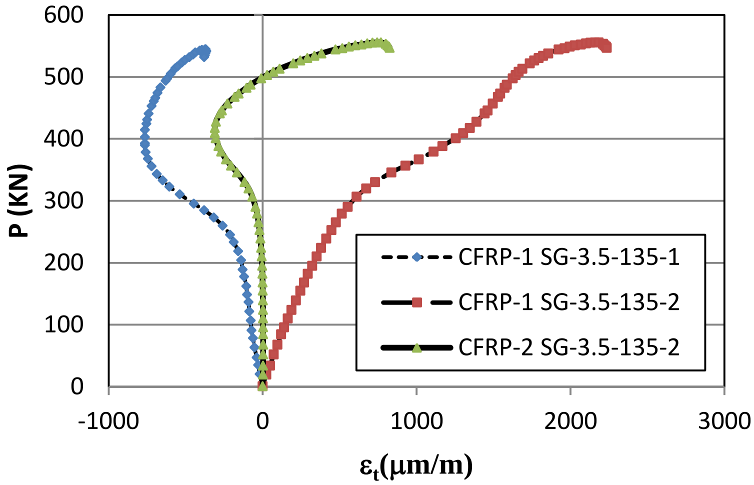


Figure 27: Tensile strains in CFRP strips on strengthened specimens of Group 4

3.3 Bending curvature of transverse stiffeners

Due to the effect of geometric imperfections and buckling of the web, transverse stiffeners were subjected to bending and axial compression forces rather than axial compression only (Safar 2011), as per conventional post-buckling theories of web plates. The bending curvature of transverse stiffeners, Φ_{stiff}, computed using measured strains ε_5 and ε_6 (see Fig. 1 and Eq (3)) was plotted versus load, *P*, for all tested Groups in Figs 28 to 31. It was observed that the bending curvature of transverse stiffeners reduced when the aspect ratio of the web increased. The use of CFRP strips reduced Φ_{stiff} in long web panels with a/h >1.

3.4 Vertical deflection

Examination of load-deflection curves of strengthened and un-strengthened girders in Figs 32 to 34 revealed that the application of CFRP strips on the web enhanced the girder stiffness in the post elastic range when a/h was less or equal to 2. Thus vertical deflections were reduced at the same load level in the post-elastic range. This was attributed to reduction or elimination of yielded portions of the web and increasing the effective section of the beam at ultimate load.

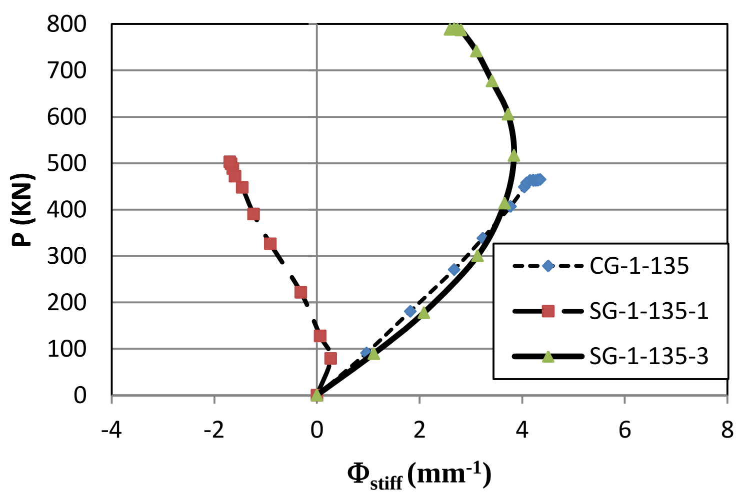


Figure 28: Bending curvature of transverse stiffeners of Group 1

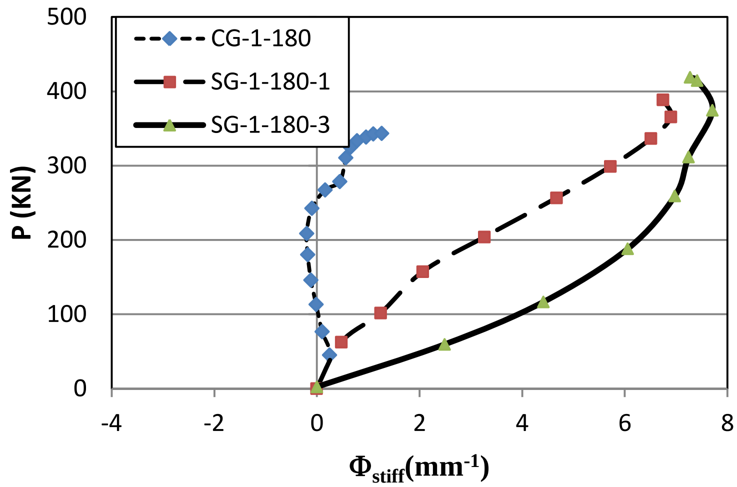


Figure 29: Bending curvature of transverse stiffeners of Group 2

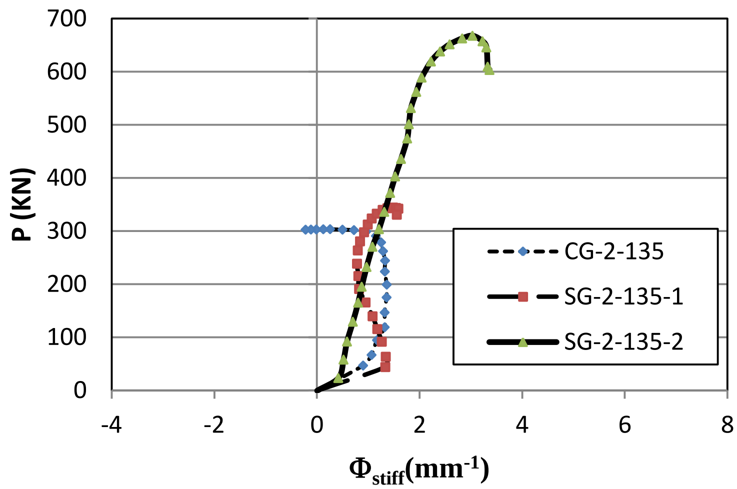


Figure 30: Bending curvature of transverse stiffeners of Group 3

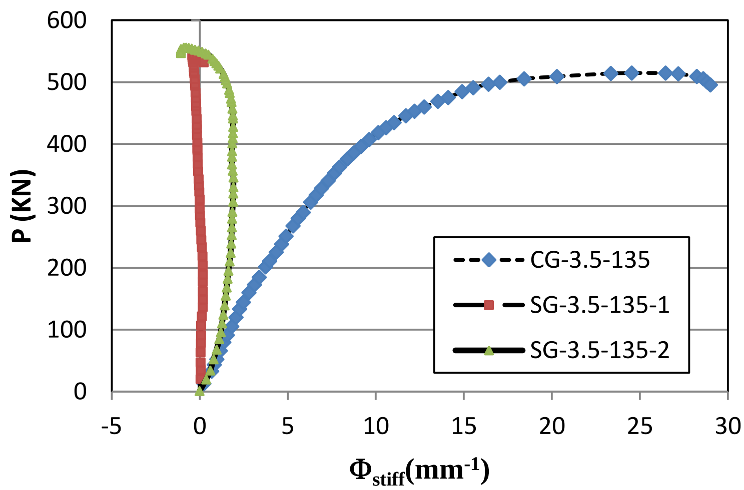


Figure 31: Bending curvature of transverse stiffeners of Group 4

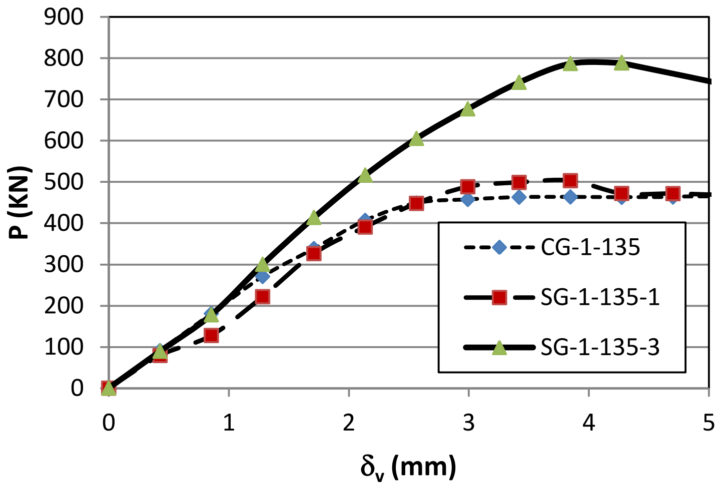


Figure 32: Load-deflection curves of specimens of Group 1

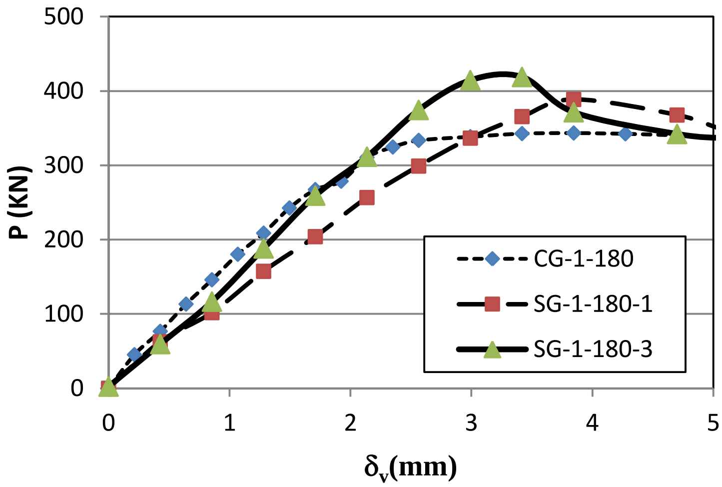


Figure 33: Load-deflection curves of specimens of Group 2

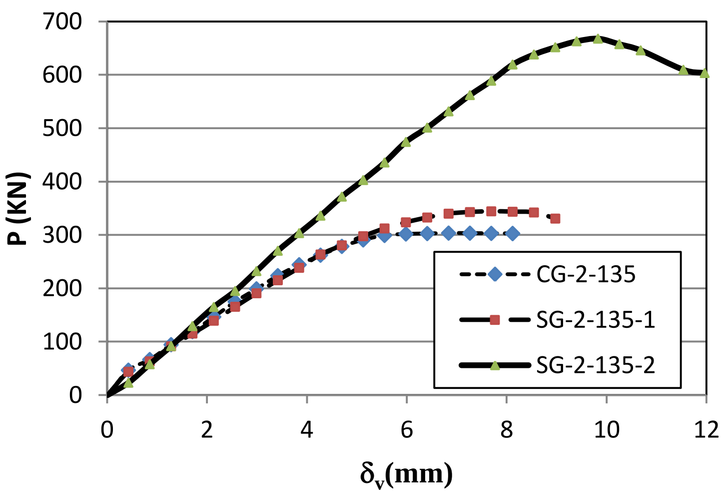


Figure 34: Load-deflection curve of specimens of Group 3

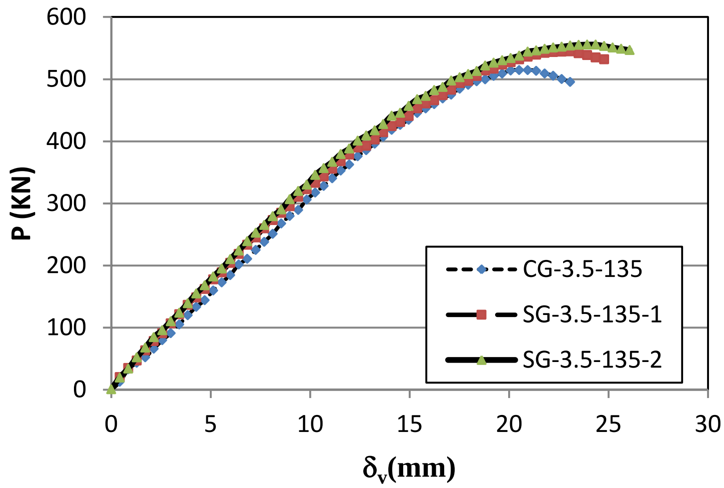


Figure 35: Load-deflection curves of specimens of Group 4

4. Summary and Conclusions

In this paper an experimental work was conducted to assess the shear strength of elastic end-web panels strengthened with intermediate-modulus CFRP strips. Test parameters included, aspect ratio, a/h, and width-to-thickness ratio, h/t_w, and number of CFRP strips. Unlike previous research work, the CFRP strips were pasted on the web in the diagonal tension direction. Twelve mild-steel girders with elastic web plates and having different a/h and/or h/t_w ratios were examined in a four-point bending test till failure. Four girders were un-strengthened to serve as reference girders whereas the remaining girders were strengthened by pasting various numbers of CFRP strips on one or both sides of the web. Based on test results, the following was concluded:

a. Intermediate-modulus CFRP strips could be successfully used to upgrade the ultimate shear strength of elastic end-web panels. The value of V_u increased by 6% to up to 120% when CFRP strips were pasted on the web in the direction of diagonal tension. Such increase was attributed to the increase of post-buckling strength, V_{pb}, resulting from additional tension forces supported by the CFRP strips and reduction of tensile strains in the web after buckling.
b. The increment of V_{pb} was proportional to number of CFRP strips and declined when the aspect ratio and/or width-to-thickness ratio of web plate increased. The use of CFRP strips on both sides of the web was more efficient and increased tensile strains supported by CFRP strips at ultimate load.
c. The magnitude of V_{pb} of strengthened end-web panels could be dramatically enhanced due to bracing effect of CFRP strips to the web in long web panels.
d. Current design rules for ultimate shear strength of end-web panels must be revised to account for the significant post-buckling strength of elastic end-web panels that ranged from 0.12 to 0.66 (V_y-V_{cr}).
e. Vertical deflections of strengthened girders with $a/h \leq 2$ were reduced in the post elastic range due to reduction or elimination of yielded portions of the web at ultimate load.

Acknowledgments

The School of Sciences and Engineering at the American University in Cairo is acknowledged for sponsoring the research work conducted herein. The authors would like to express their gratitude for the sincere cooperation and assistance of the lab engineer and technicians of the structures lab at the American University in Cairo.

References

Miller, T.C., Chajes, M.J., Mertz, D.R., Hastings, J.N. (2001). “Strengthening of steel bridge girder using CFRP plates” *Journal of Bridge Engineering*, 6 (6) 514-522.

Tavakkolizadeh, M., Saadatmaneh, H. (2003a), “Strengthening of steel-concrete composite girders using carbon fiber-reinforced polymer sheets”, *Journal of Structural Engineering*, 129(1), 30-40.

Tavakkolizadeh, M., Saadatmaneh, H. (2003b), “Repair of damaged steel-concrete composite girders using carbon fiber-reinforced polymer sheets”, *Journal of Composites for Construction*, 7(4), 311-322.

Tavakkolizadeh, M., Saadatmaneh, H. (2003c), “Fatigue strength of steel girders reinforced with carbon fiber-reinforced polymer patch”, *Journal of Structural Engineering*, 129(2), 186-196.

Al-Saidy, A.H., Klaiber, F.W., Wipf, T.J. (2004). “Repair of steel composite beams with carbon fiber-reinforced polymer plates.” *Journal of Composites for Construction*, 8(2), 163-172.

American Institute for Steel Construction (2005). *Manual of steel construction: load and resistance factor design. Forth edition.*

Dawood, M. (2005), “Fundamental behavior of steel-concrete composite beams strengthened with high modulus carbon fiber reinforced polymer (CFRP) materials”, *Master’s Thesis, North Carolina State University, Raleigh, North Carolina*.

Machaly, E.B., Safar, S.S., Abdel-nabi, A.E., (2007), “Parametric analysis of plate girder web plates subjected to pure shear”, *Journal of Engineering and Applied Sciences*, Cairo University, 54, 617-634.

Sika Product Information, (2008), Second Edition, Cairo: Sika Egypt.

Machaly, E.B., Safar, S.S., Abdel-nabi, A.E., (2008), “New design for plate girder web panels subjected to pure shear”, *Journal of Engineering and Applied Sciences*, Cairo University, 55, 21-40.

Narmashiri, K.., Jumatt, M.Z., Sulong, N/H. (2010). “Shear Strengthening of Steel I-beams by using CFRP strips.” *Scientific Research and Essays*, Academic Journals, 5 (16) 2155-2168.

Tabar, B. D.S., Davaran, A., (2010), “Experimental study on bonding improvement of CFRP strips used for strengthening of steel beams”, *Asian Journal of Civil Engineering*, 11(1), 57-70.

Peiris, N.A. (2011), “Steel beams strengthened with ultra high modulus CFRP Laminates”, *PhD’s Thesis, University of Kentucky, Kentucky*.

Safar, S.S., (2011),”Effect of transverse stiffeners on shear strength of web panels”, *Proceeding of international bridge conference*, No 32, Pittsburgh, Pennsylvania.

Narmashiri, K.., Jumatt, M.Z., Sulong, N/H. (2012). “Shear Strengthening of Steel I-beams by using CFRP strips: An investigation on CFRP bond length” *Advances in Structural Engineering*, 15 (12) 2191-2204.

Safar, S.S., (2013), “Shear strength of end-web panels”, *Thin-walled structures*, 67, 101-109.