Effect of CFRP Layer Orientation on the Behavior of Shear-Strengthened Steel Plate Girders

Mohammed J. Hamood
Building and Construction Engineering Department, University of Technology
Baghdad, Iraq
mjh_smm@yahoo.com

Wael Sh. Abdulsahib
Building and Construction Engineering Department, University of Technology
Baghdad, Iraq
waelalmuhsin@yahoo.com

Ali H. Abdullah
Building and Construction Engineering Department, University of Technology
Baghdad, Iraq
sbearhead@yahoo.com

Received on: 08/08/2017
Accepted on: 01/03/2018

Abstract- *The present paper investigates experimentally the impacts of fiber layer orientation on the structural behavior of CFRP strengthened steel-plated girders that are subjected to shear. Three of these girders were considered strengthened girders whereas the last one represents the reference girder. Each of the four steel-plated girders was tested aside and in different periods of time using the shear buckling test. A point load was applied to the center of the top flange of the four girders using Avery hydraulic machine. A laminated carbon fiber reinforced polymer sheet (CFRP) was fully adhesively attached to the web area of the three girders. The attached carbon fiber sheet took different patterns: either on one side or on both sides. Such a step helps to evaluate the most effective strengthening technique of each of the girders using CFRP composite. To check the behavior and the increase in the ultimate shear capacity of the girders, several parameters were examined. Results have revealed that both the unstrengthen and strengthened girders of different orientations of CFRP showed a similar stiffness behavior at a relatively low load levels. However, when the load is increased, the stiffness behavior significantly is increased in the three strengthened girders, compared to the strengthened girders. It has further shown that the ultimate shear load of the three strengthened girders were higher than that of the reference girder. Such a result can clearly be exemplified by the obtained ranges: 19.56% and 25% depending on the orientation of the CFRP laminates. Following Von Mises stresses, the researcher was able to predict the ultimate shear load of the four girders and to figure out the arrived at results from the four experimental tests.*

Keywords-*steel-plated girder, CFRP laminate, shear behavior, CFRP orientation, strengthened girders.*

How to cite this article: M.J. Hamood, W.Sh. Abdulsahib and A.H. Abdullah, "Effect of CFRP Layer Orientation on the Behavior of Shear-Strengthened Steel Plate Girders," *Engineering and Technology Journal*, Vol. 36, Part A, No. 7, pp. 709-714, 2018.

1. Introduction

Steel plate girder is a built-up beam, consisting of two horizontal flange plates (top and bottom) that are welded with a vertical web plate, forming an I section. It further contains the so-called stiffener plates that can be vertical, horizontal, or diagonal plates welded between that two flanges and the web. The stiffener plates help to increase the buckling strength of the plate girder web and resist the loads in the bending and shear modes. As for the two flanges, they resist the compression and tensile stresses generated from the bending moment resulting from the loads on the plate girder. With respect to the web plates, they primarily resist the shear stresses and secondarily contribute little to the bending resistance [1]. So far, there has been a limited number of research studies conducted on the use of carbon fiber reinforced plastic composite in strengthening and repairing the steel girders. The majority of such previously conducted research focused on the application of CFRP to either axial or bending with little attention was paid to strengthening and repairing web girders using CFRP. The standard strengthening techniques of steel plate girders include bolting or welding. However, the cons of these techniques include –but are not limited to- the impact of corrosion, the sensitivity of the repaired system to fatigue problem resulted either from the stressed concentration caused by the bolting or welding techniques or from the long-aged period of service interruption. Accordingly, the use of a modern technique that enables strengthening the girders has been crystalized. Cases in point are the use of externally attached (CFRP) composites as an alternative strengthening means. Such a means helps in preventing web buckling in steel plate girder by providing additional stiffness to the web of the girder out of the high degree of stiffness, tensile strength, and corrosion/fatigue resistance of FRP material [2-5].

https://doi.org/10.30684/etj.36.7A.2
2412-0758/University of Technology-Iraq, Baghdad, Iraq
This is an open access article under the CC BY 4.0 license http://creativecommons.org/licenses/by/4.0

2. Material Properties

The properties of the materials used before testing the plate girders are the follows:

I. Steel

Table 1 and Figure 1 illustrate details and properties of the steel plates to be used in the formation of the four steel plate girders as considered in this study. The modules of elasticity and poisons ratio are assumed to be (200000 MPa and 0.3), respectively.

Table 1: Properties of Steel Plates Used for Girders

Component	**Thickness (mm)**	**Σy (MPa)**	**Σu (MPa)**
Web	2	250	265 370
		260	
		270	375
		260	360
Flange Stiffeners	10	255	400 403
		55	
		255	405
		255	404

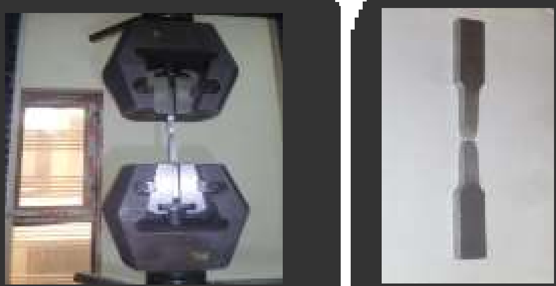

Figure 1: Tensile Strength Test for Steel Plates

II.CFRP laminate

The type of CFRP used to strengthen the girders is sika-warp-300 c. This type was produced by Sika Corporation [6] as set in the manufacturer data sheet attached to the CFRP laminate presented in Table 2 and Figure 2.

Table 2: CFRP properties

Sikadur®- 330	**Properties**
Parts A+B mixed: 1.3+0.1	Density (kg/l) at +23°C
30	Tensile strength (MPa)
Flexural: 3.8	E-Modulus (GPa)
Tensile: 4.5	
0.9	Elongation at break (Strain)%
30	Setting time (Minute) at 35°C
Part A: part B = 4: 1 by weight	Mixing ratio

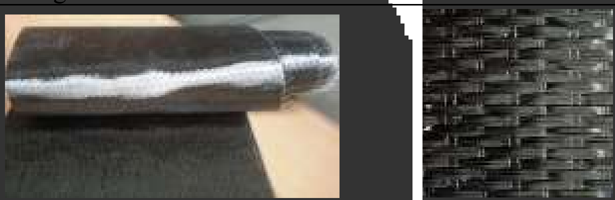

Figure 2: CFRP Laminate Used in the Present Work

III. Adhesive Epoxy

The adhesive material used with the carbon fiber sheet was Sikadur®-330, as illustrated in Table 3 and Figure 3. This type of adhesive consists of two parts: part A&B. the former is called (resin) and it is white whereas the latter is called (hardener), which has a grey color. The main properties of the adhesive materials are provided according to manufacturer data sheet [7] that was attached to the adhesive material package.

3. Type and Details of the Plate Girders

All four girders chosen in this study had no web opening. The shear stresses of the webs were relatively low in comparison to the bending stresses of the two flanges. That is; the web plate was (2mm) thick whereas the flanges were (10mm) thick. In other words, the web plate was generally thinner than the two flanges. For more information is presented in Table 4 and Figure 4.

Table 3: Sikadur®- 330 properties

Sika-warp-300 c	**Properties**
3900	Tensile Strength (MPa)
230	E-Modulus (GPa)
1.5	Elongation At Break (Strain)%
0.166	Thickness (mm)
1.79	Density (g/cm^3)

Figure 3: Sikadur®- 330 container used in the present work

Table 4: Details of plate girders in (mm)

girder	t_w	t_s	t_f	b_f	L	a	d	d_w/t_w	a/d	Reinf.
T2-0	2	10	10	125	1200	600	600	300	1	reference
T2-1										Type1
T2-2										Type3
T2-3										Type2

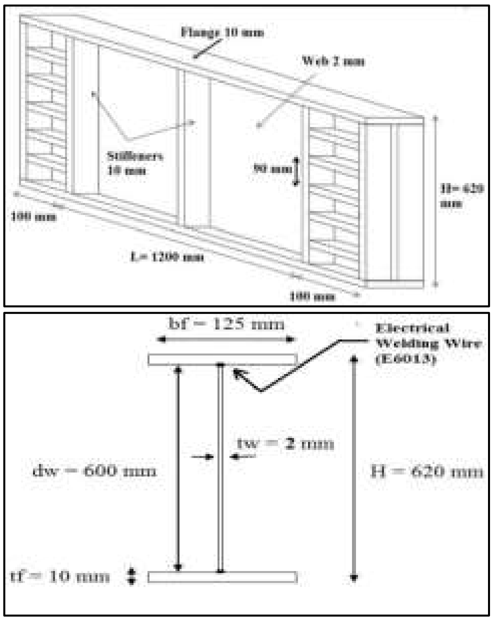

Figure 4: Details of plate girders

4. Types of Strengthening

As far as the types of strengthening techniques used in the study, they were three types as indicated below:

Type1 includes the strengthening of the web of girder was done by the CFRP laminates that fully covers the web from one side; ie., (600*600)mm. Moreover, the laminates were attached diagonally along the tension zone at (45) degree to the axis of the girder. This type is exemplified in (T2-1) girder as shown in Figure 5.

Type2 involves strengthening the web of girder via fully attaching CFRP laminates to one of the sides of the area of the web, ie., (600*600)mm. The laminates were attached diagonally along the compression zone at (135) degree, as illustrated in (T2-3) girder in Figure 6.

Type3 consists of strengthening the web of girder by simply attaching the CFRP laminates to the full area of the web; ie., (600*600)mm from both sides of the girder. That is; one of the sides involves attaching the laminates along the tension diagonally at (45) degree whereas the second involves attaching the laminates along the compression diagonally at (135) degree, as shown in Figure 7.

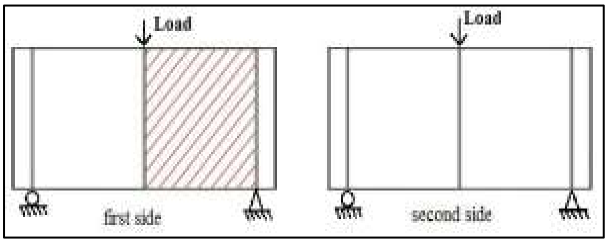

Figure 5: Strengthening technique used for girder (T2-1)

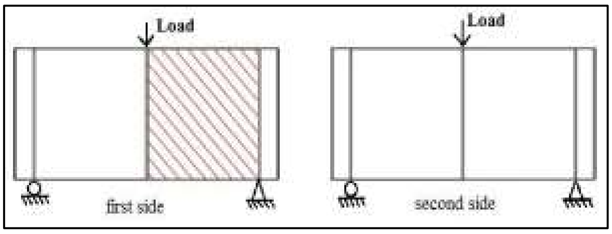

Figure 6: Strengthening technique used for girder (T2-3)

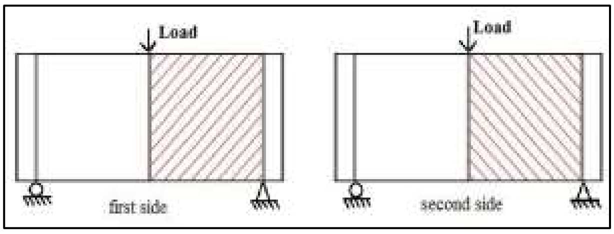

Figure 7: Strengthening technique used for girder (T2-2)

5. Testing Procedure and Instrumentation

All plate girders that were simply supported using (pin and roller) over span of (1200) mm were tested up to the failure. The test was done under the action of a single applied load at the mid span of the girder (applied centrally) to ensure that each of the panel used carries half of the applied load as shown in Figure 8. The maximum load capacity of applied machine, (Avery), is (120) tons, as illustrated in Figure 9. Furthermore, the deflection of all girders was obtained using a dial gage of (0.01) accuracy. The gage was installed at the mid span under the bottom flange of the girder, as clearly shown in Figure 10.

Figure 8: Test Setup of Plate Girder

Figure [redacted] er

Figure 10: The Dial Gage Used to Monitor Mid Span Deflection

Evaluation of the Ultimate Shear Strength of Girders [8]:

To evaluate the ultimate shear strength, the following equations are considered:

The critical shear stress (τ_{cr}) was calculated using (Cardiff Method):

$$(\tau_{cr}) = Ks * \frac{\pi^2 * E}{12(1-v^2)} * (\frac{t_w}{d})^2 \quad (1)$$

Where: (K_s): the shear-buckling coefficient is given by:

$$K_s = 5.35 + 4(\frac{d}{a})^2 \quad \text{where } (\frac{a}{d}) \geq 1$$

$$(2)$$

$$K_s = 5.35 * (\frac{d}{a})^2 + 4 \quad \text{where } (\frac{a}{d}) \leq 1$$

Where:

(d): Depth of the girder in mm;

(t_w): web thickness in mm;

(a): Clear distance of the web plate between the vertical stiffeners in mm;

(E): Modulus of elasticity in MPa; and

(v): poisons ratio.

$$\sigma_{yt} = \sqrt{F_{yw}^2 + \tau_{cr}^2 \left(\frac{9}{4} sin^2 2\theta - 3\right)} - \frac{3}{2}\tau_{cr} * sin2\theta \quad (3)$$

Where:

$$\Theta = \frac{2}{3} tan^{-1}(\frac{d}{a}) \quad (4)$$

(F_{yw}): the tensile stress of web in MPa.

$$M_{pf} = \frac{1}{4} * F_{yf} * b_f * t_f^2 \quad (5)$$

$$M_p* = \frac{M_{pf}}{d^2 * F_{yw} * t_w} \quad (6)$$

$$V_{cr} = \tau_{cr} * d * t_w \quad (7)$$

$$V_{post} = \sigma_{yt} * t_w * sin^2\theta(d * \cot\theta - a) + 4d * t_w * \sin\theta * \sqrt{F_{yw} * \sigma_{yt} * M_{p*}} \quad (8)$$

$$V_{ult} = V_{cr} + V_{post} \quad (9)$$

$$2V_{ult} = V_{ult} * 2/1000 \quad (10)$$

Where:

(F_{yf}): Tensile stress of flange in MPa;

(b_f) : flange width; and

(t_f) :flange thickness.

6. Test Results

The effects of fibers orientation on the performance of strengthened girders are illustrated below:

- Figure 11 shows the load deflection curves for all tested girders (T2-1), (T2-2) and (T2-3) that were strengthened by CFRP laminates together with the reference girder (T2-0).

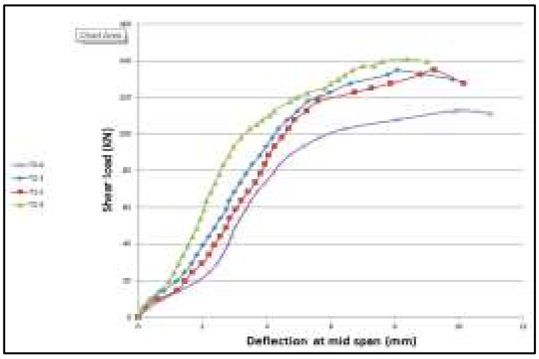

Figure 11: Load –Deflection curves for the girders (T2-0), (T2-1), (T2-2) and (T2-3)

- It can be observed that the girder (T2-1) shows higher stiffness and shear load capacity than that obtained for the reference girder (T2-0) by (119.56%). This result continued until CFRP laminate was debonded, as shown in Table 5, Type 1 of strengthening;
- The strengthened girder (T2-2) shows higher stiffness and load carrying capacity than that of the reference girder (T2-0) by (119.56%). This result continued until CFRP laminate was cracked, as given in Table 5, Type (3) of strengthening. Accordingly, the strengthened technique helps to increase the ultimate strength through the effective use of the CFRP strength. It can; therefore, be said that the additional stiffness was due to the bonded CFRP layers attached to steel plate girders;

- It can be noted that girder (T2-3) shows higher stiffness and ultimate shear load than that obtained from the reference girder (T2-0) by (125 %) as given in Table 5. This result was maintained until the failure of CFRP laminate, as shown in (Type 2), of strengthening technique.
- As shown in Figure 11, the behaviors of two of the CFRP-strengthened girders, (T2-1) and (T2-2) were almost identical. This reflects a similarity in the initial stiffness of the girders and the variability during the post-buckling range, after the cracking and debonding of CFRP. Despite the existence of this variability, the two girders gave a similar ultimate shear load capacity. Speaking of the behavior of Girder (T2-3), it was noticed that it was stiffer than the other two up to the failure load point;
- Accordingly, one can notice that the CFRP helps to reduce the deformation of the web panel, depending mainly on both the location and orientation of the fibers of CFRP used. Besides, type two of the diagonal strengthening that is compression-oriented has effectively helped to increase the shear load capacity of the girder. It further leads to have similar results to that obtained from the tension-oriented diagonal strengthening. This result is in line with that reached by [9] regarding the strengthening girders in the compression direction using GFRP;
- Figure 12 shows the failed girders after conducting the tests. The ultimate shear forces of the girders in comparison with the reference girders are given in Table 5.

Table 5: Ultimate shear forces of the strengthened girders compared to the ultimate shear force of the reference girder

Plate Girder	Max Ultimate Shear Force (kN) (experimental)	Ultimate Shear Force Compared to the reference girder (T2-0) (Experimental)
T2-0	112.776	-
T2-1	134.84	19.56 %
T2-2	134.84	19.56 %
T2-3	140.971	25 %

A) Plate Girder (T2-0) after Testing

B) Plate Girder (T2-1) after Testing

C) Plate Girder (T2-2) after Testing

D) Plate Girder (T2-3) after Testing

Figure 12: Tested Plate Girders after Failure after testing

7. Conclusions

1- The ultimate shear force is increased by about (19.56%) for the girder that was strengthened by CFRP laminates by fully covering the area of the web (600*600) mm at one side. The laminates were attached along the tension diagonally at (45) degrees to longitudinal axis of the girder as used in the front side of the girder (T2-1) (ie., Type 1 of the strengthening technique);

2- The ultimate shear force is increased by about (25%) for the girder that was strengthened by CFRP laminates. The latter (CFRP laminates) fully covered the area of the web (600*600) mm at one side. However, the laminates were attached diagonally along the compression zone (135) degrees as used in (T2-3) girder (ie., Type 2 of the strengthening technique);

3- The ultimate shear force is increased by about (19.56%) for the girder that was strengthened by CFRP laminates. The laminates fully covered the area of the web (600*600) mm from two sides (front and rear sides). However, the laminates of the first side were attached diagonally along the tension at (45) degrees whereas at the second side of the girder, they were attached diagonally along the compression zone at (135) degrees as used in

(T2-2) girder (ie., Type 3 of the strengthening technique);

4- The experimental results obtained for the plate girders have confirmed that the strengthening technique for the girders is applicable, effective and that it helps to increase the shear strength of the girders;

5- Strengthening the web of the girders diagonally along the compression zone set at (135) degrees (ie., parallel to the compression zone as in Type 2 of the strengthening technique) has led to obtain similar results to that of the ultimate shear force of Type 1 of the strengthening technique. In the latter type, the web of girders is strengthened diagonally along the tension zone set at (45) degrees. The results are further similar to the one obtained in Type 3 of the strengthening technique when the web of girders is strengthened diagonally along the tension zone set at (45) degrees at first side and the compression set zone at (135) degrees at the second side.

References

[1] Steel plate girders, bridge design practice–chapter 9- February in 2015.

[2] I.K. Abed "Improving the strength of steel perforated plate girders loaded in shear using CFRP laminates," M.Sc. Thesis structural engineering department, university of technology, Baghdad, September 2015.

[3] M.S. Abdul Gabar "Behavior of steel plate girders with web opening loaded in shear," M.Sc. Thesis structural engineering department, university of technology, Baghdad, September 2012.

[4] N.C. Hagen, P.K. Larsen, and A. Aalberg, "Shear capacity of steel plate girders with large web openings," – Part1: Modeling and simulations. Journal of constructional Steel Research; 65, 1, 142-50, 2009.

[5] M.J. Hamoodi, I.N. Korkess, and K.F. Sarsam, "Test and Analysis of Steel Plate Girders with Central Web opening," The 6th Engineering Conference, College of Engineering , Baghdad University, Volume 1: Civil Engineering, pp. 1-17, April 2009.

[6] Sika, "Sika warp® – 300c carbon fiber laminate for structural strengthening", technical data sheet, (web site:www.sika.co.id).2016.

[7] Sika, "Sikadur® – 330c", technical data sheet, (web site: www.sika.co.id).2016.

[8] K. Rockey, H. Evans, and D. Porter "A design method for predicting the collapse behavior of plate girders," Proceeding institution of civil engineers, part2, pp.85-112, March 1978.

[9] Z. Al-azzawi, Tim Stratford ,Michael Rotter and Luke Bisby "FRP Shear Strengthening of Thin-Walled Plate Girder Web Panels Subjected to Cyclic Loading," University of Anbar and The University of Edinburgh, pp. 1-11, January 2015.

Notation

a: Clear of the web plate between vertical stiffeners;
τ: Shear stress;
t_w: Thickness of the web;
d: Depth of girder;
M_{pf}: Plastic moment capacity of the flange plate;
τ_{cr}: Critical shear stress;
σ_{yw}: Tensile yield stress of the web;
σ_{yt}: Tensile membrane stress at yield;
k_o: Buckling coefficient for a perforated web;
ks: Shear buckling coefficient;
θ: Angle of inclination of the membrane stress with the longitudinal axis;
σ_{yf}: Tensile yield stress of the flange;
V_{post}: Post buckling shear force;
V_{ult}: Ultimate shear strength.
V_{cr}: Critical buckling shear force.
M_{p*}: Non-dimensional flange strength parameter;
τ_{crv}: Shear buckling stress of plate girder reinforced by CFRP;
σ_y: Yield stress of steel material; and
σ_u: Ultimate stress of steel material.

Author(s) biography

Dr. Mohammed Jaffar Hamood is Asst. Prof of Civil Engineering (Structural Engineering) at the University of Technology, Baghdad, Iraq. His research interests include Structural Behavior of Members under Static and Cyclic Loading. Structural Dynamics and Earthquake Engineering with Particular Emphasis on the Analysis of Soil-Structure Interaction Effects.

Dr. Wael Shawky Abdulsahib is Asst. Prof of Civil Engineering (Structural Engineering) at the University of Technology, Baghdad, Iraq. He received his BSc of Civil Engineering in 1997 and MSc (Structural Engineering) in 2000 from University of Technology, his PhD in 2008 from University of Technology. His Research interest is in steel and concrete structures. He is a member in the American Concrete Institute.

Ali Hameed Abdullah is a Civil Engineer (Structural Engineering) at the University of Technology, Baghdad, Iraq. He received his BSc of building and construction engineering in 2010 and MSc (Structural Engineering) in 2018 from University of Technology. His Research interests involve examining the behavior of steel plate girders that are with and without openings and strengthening such plate by CFRP laminates.