CFRP strengthening of steel plate girders with web openings subjected to shear and bending.

Mohammed Abdulkareem Kadhim, Wael Shawky AbdulSahib and Ammar Abbas Ali

1 Civil Engineering Department, University of Technology, Baghdad, Iraq

Email: kareemo_94@yahoo.com

Abstract. The present study illustrates the effect of applying combined shear and bending loading on steel plate girders having web openings strengthened with CFRP wrap. Five steel plate girders have been tested under the above-mentioned action; one of these plate girders which can be considered as a control specimen has no web opening whereas the other four girders have openings of circular or square cut-outs. Strengthening by attaching CFRP sheets using a type of adhesives has been applied to two of the plate girders, one with square opening and the other with circular web opening. Web opening size is chosen to have a depth equal to 40% of the web depth. In comparison with the reference girders with openings, results have shown that the ultimate load of the strengthened plate girder containing square and circular web openings increased 63.6% and 52.6%, respectively.

1. Introduction
Numerous researches up to now have spotlighted the use of Carbon Fiber Reinforced Polymers (CFRP) in retrofitting or strengthening webs or flanges of steel girders. Earlier studies focused primarily on improving the strength of the girders under bending, axial, or shear stresses individually. The ordinary methods involved bolting and welding external plates. Yet, disadvantages may take place in these procedures; cases to be stated, for example, corrosion, the sensitivity of fatigue of the repaired part due to the stress concentration caused by either the anchoring or welding processes. Another issue is the extended disruption of service. Lately, different structural retrofitting systems have been followed, for instance, using the externally attached composites of (CFRP). Such systems followed to improve web buckling resistance in steel girders by enhancing the web stiffness. Which means that the CFRP stiffness grants to the girders the required improvements in strength and fatigue resistance [1,2]. Ducts are used for cooling systems, sewage pipes, sanitary plumbing, electrical cables and other different services which are necessary to be existed in buildings or bridges. To run such services, additional depth between floors is required. Thus, web openings must be made on some girders in order to overcome such a problem. This is a solution in piping of services without affecting the height of the related stories. But, these web openings, for sure, shall affect the distribution and transition of stresses at the web besides ultimately reducing both, bending and shear strength of the girder [1, 3].

Reestablishing loss in strength due to cut-outs, requires studying the lost strength in addition to these openings’ locations, furthermore, strengthening the locations surrounding the openings through different forms of CFRP. In addition to that, it is critical to avoid making such cut-outs in high stress positions.

2. Materials properties
The properties of materials used in manufacturing the girders are important to be investigated.

2.1 Steel

The most significant property to this study is the yield strength of the steel plates. Tensile test has been applied to 9 plate specimens according to ASTM A370-14 procedure.

In table (1), the properties and details of the steel plate used in assembling the five girders are presented, see figure (1). 200000 MPa is the average of the modulus of elasticity for the tested plates and poison’s ratio is assumed to be 0.3.

| Component | Thickness (mm) | σy (Mpa) | σu (Mpa) |
|-----------|---------------|----------|----------|
| Flange    | 6             | 280      | 395      |
|           | 283           | 277      | 396      |
|           | 270           |          | 390      |
| Web       | 2             | 245      | 316      |
|           | 243           | 246      | 315      |
|           | 250           |          | 317      |
| Stiffener | 8             | 290      | 445      |
|           | 280           | 287      | 442      |
|           | 293           |          | 445      |

2.2 CFRP fabric

SikaWrap 300-C NW is the type of CFRP wrap used in this experiment, see figure (2). Properties of CFRP are expressed in table (2) according to the data sheet of the product.

| Properties          | Sika Wrap 300-C NW |
|---------------------|--------------------|
| Tensile Strength (MPa) | 3800               |
| Elongation at Break (Strain) % | 1.55               |
| E-Modulus (GPa)     | 242                |
| Thickness (mm)      | 0.171              |
| Fiber density (g/cm3) | 1.81               |

2.3 Epoxy

Sikadur-330 is the structural adhesive epoxy suitable with the above-mentioned wrap which is shown in figure (3). Sikadur-330 consists of resin and hardener of white and grey colors, respectively. The related properties of this product are found in table (3).

| Properties                  | Sikadur-330 |
|-----------------------------|-------------|
| Tensile Strength (MPa)      | 30          |
| Density (kg/lt) at +23°C    | 1.31        |
| E-Modulus (GPa)             | 3.8 (Flexural) |
| 4.5 (Tensile)               |             |
| Setting Time (Minute) at 35°C | 30         |
| Elongation at Break (Strain) | 0.9        |
3. Geometrical details of Specimens
This study consists of two main types of girders. The first type is the main reference girder which did not have web opening while the second type was with openings in web. The later type has further subdivision into two groups: circular and square web cut-outs. The height of web opening is 200 mm in all specimens. Although the area was different due to the shape parameter, the height was selected to be constant, as the depth cut is the most critical effect on the strength of the section. Generally, web thickness is chosen to be thinner than the thickness of flange, this is due to the large depth of the web while the flanges kept are of narrower width [4]. Details about the related girders are clarified in table (4, 5) and figure (4). Three of the tested girders are considered references whereas the other two plate girders are strengthened with CFRP wrap in different patterns on both sides of girder.

Table 4. Geometrical details of all plate girders (mm).

| t_f | t_w | t_s | b_f | L | a | d_w | d_w/t_w | a/d_w |
|-----|-----|-----|-----|---|---|-----|--------|------|
| 6   | 2   | 8   | 120 | 2300 | 575 | 500 | 250 | 1.15 |

Table 5. Geometrical parameters of plate girders.

| G_0 | GS_0 | GC_0 | GSC | GCC |
|-----|------|------|-----|-----|
| Without openings | With two square openings | With two circular openings | With two square openings strengthened with CFRP | With two circular openings strengthened with CFRP |

4. Strengthening with CFRP
Web openings lead to reduction in the shear stress capacity of the girder, thus, strengthening with CFRP wrap strips of 100mm in width has been applied to these areas surrounding web cut-outs in order to overcome this reduction. These strips were applied parallel to flanges on one side of the girder and perpendicular to it on the other side for square openings, while the strips were diagonally directed in girders with circular openings, see figure (5).
5. Testing procedure
All of these steel plate girders were simply supported with clear span of 2300mm. The test was applied with a mid-span concentrated monotonic loading up to failure, as the effect of the combined action of shear and bending becomes higher due to this loading mechanism. Also, an application of such loading helps guaranteeing each of the two shear spans equally partake half of the external mid span load, see Figure (7). However, all the necessary precautions have been taken to avoid undesirable local failures. The machine used in the test had a maximum load capacity of 120 tons, deflections were measured at mid-span with a dial gauge of 0.01 mm accuracy which was installed under the tested girder.

6. Analytical Study
When a plate girder is under the action of shear stresses, the web undergoes two principle tension and compression stresses diagonally on panels. The existence of bending action reduces the web resistance to shear due to the additional tension and compression stresses on the extreme regions. The following formulas estimate the shear resistance of plate girders according to Cardiff Method for girders with or without web openings [5,3].

6.1 Girders without web cut-out:
The ultimate shear stress is found by summing up the critical shear force and the post buckling shear capacity, while shear stress in critical stage (\( \tau_{cr} \)) is given by applying the following procedure:

\[
\tau_{cr} = K_s * \frac{\pi^2 \cdot E}{12(1 - v^2)} * \left( \frac{t_w}{d} \right)^2
\]

Where:
(K\(_s\)): the shear buckling coefficient is given by:

\[
K_s = 5.35 + 4 \cdot \left( \frac{a}{d} \right)^2 \quad \text{where} \quad \left( \frac{a}{d} \right) \geq 1
\]

\[
K_s = 5.35 \cdot \left( \frac{a}{d} \right)^2 + 4 \quad \text{where} \quad \left( \frac{a}{d} \right) < 1
\]

Where:
(d\(_w\)): Depth of web in mm;
(a): clear distance between vertical stiffeners in web plate in mm;
(t\(_w\)): web thickness in mm;
(v): poisons ratio;
(E): Modulus of elasticity in MPa; and

\[ \sigma_{yt} = \sqrt{\left(\sigma_{yw}\right)^2 + \left(\frac{\tau_{cr}}{\tau_{yw}}\right)^2 \frac{\sigma_{yw}}{4} \sin^2(2\theta) - 3} - \frac{3}{2} \frac{\tau_{cr}}{\tau_{yw}} \sin(2\theta) \]  

(3)

Where:

\[ \theta = \frac{\pi}{3} \tan^{-1}\left(\frac{d}{a}\right) \]  

(4)

\[ \tau_{yw} = \frac{\sigma_{yw}}{\sqrt{3}} \]  

(5)

\((\sigma_{yw})\): tensile stress of web in MPa.

\[ M_{pf} = \frac{1}{4} \cdot \sigma_{yw} \cdot b_f \cdot t_f^2 \]  

(6)

\[ M_p = \frac{M_{pf}}{d^2 \cdot \sigma_{yw} \cdot t_w} \]  

(7)

\[ V_{cr} = \tau_{cr} \cdot d \cdot t_w \]  

(8)

\[ V_{post} = \sigma_{yt} \cdot t_w \cdot \sin^2 \theta \left( d \cdot \cot \theta - a \right) + 4d \cdot t_w \cdot \sin \theta \sqrt{\sigma_{yw} \cdot \sigma_{yt} \cdot M_p} \]  

(9)

\[ V_{ult} = V_{cr} + V_{post} \]  

(10)

Where:

\((\sigma_{yw})\): shear stress of flange in MPa;

\(t_f\): flange thickness.

\(b_f\): flange width; and

6.2 Girders with web cut-out

Significant effect occurs when a web opening takes place at the web of girders, this effect is higher when shear stresses exist. The opening leads to a drop in the shear resistance of the web; this reduction depends on the size and the location of the opening.

\[ K_o = K_s \left( 1 - \frac{dh}{d} \right) \]  

(11)

Where:

\(K_s\): the shear buckling coefficient from equation (2); and

\(dh\): the opening diameter or length.

\[ \left(\tau_{cr}\right)_o = K_o \cdot \frac{\pi^2 \cdot E}{12(1 - v^2)} \cdot \left(\frac{t_w}{d}\right)^2 \]  

(12)

\[ \sigma_{yt} = \sqrt{\left(\sigma_{yw}\right)^2 + \left(\frac{\tau_{cr}}{\tau_{yw}}\right) \frac{9}{4} \sin^2(2\theta) - 3} - \frac{3}{2} \frac{\tau_{cr}}{\tau_{yw}} \sin(2\theta) \]  

(13)

Where:

\(\left(\tau_{cr}\right)_o = \left(\tau_{cr}\right)_o \cdot d \cdot t_w\); and

\[ V_{post} = \sigma_{yt} \cdot t_w \cdot \sin^2 \theta \left( d \cdot \cot \theta - a \right) + 4d \cdot t_w \cdot \sin \theta \sqrt{\sigma_{yw} \cdot \sigma_{yt} \cdot M_p} \]  

(14)

\[ V_{post}(o) = \frac{d - dh}{d} \cdot V_{post} \]  

(15)

\[ V_{ult}(o) = V_{cr}(o) + V_{post}(o) \]  

(16)

7. Test results

On one hand, figure (8) below shows the load-deflection relationship curves for the studied plate girders \((G_0)\) which is without an opening and \((G_{o0})\) with square web opening considered as reference plate girders. Additionally, \((GSC)\) is the CFRP strengthened plate girder with square opening. Test results have proved that the square web cut-out decreases 49.5% of the reference girder capacity to resist the ultimate load, whereas the strengthened girder \((GSC)\) shows a higher resistance and stiffness.
than that of \((G_S_0)\) of about 63.6%. On the other hand, and as illustrated in figure (9) which shows the behavior of the other girders with web openings of circular shape, lines representing \((G_S_0)\) and \((G_S)\) have been replaced with \((G_C_0)\) and \((G_C)\), respectively. Also, here it is noticeable that the opening had decreased 30.27% of the load capacity, while for the CFRP strengthened girder \((G_C)\) the ultimate load had increased significantly to 52.6% in comparison with \((G_C_0)\). It is clear that the square shaped opening decreases the capacity more than the circular shaped opening of the same depth, this is referred to the stress concentration at the corners of the square opening.

Furthermore, table (6) shows the ultimate load capacity at mid span for the five tested girders. However, the CFRP strengthened girder load capacity depends on the slenderness of the girder in addition to the thickness, area, pattern, and direction of the CFRP wrap used to be attached to the web of the girder.

| Plate Girder | \((G_0)\) | \((G_S_0)\) | \((G_S)\) | \((G_C_0)\) | \((G_C)\) |
|--------------|-----------|-----------|-----------|-----------|-----------|
| Ultimate experimental mid-span load kN | 109 | 55 | 90 | 76 | 116 |
| Effectiveness of using CFRP in girders percentage to their references (%) | - | - | 163.6% | - | 152.6% |
| Ultimate analytical mid-span load kN | 138.7 | 76.26 | - | 76.26 | - |

Table 6. Ultimate experimental shear load for the girders and comparison to reference girders

In figure (9), the failure mode of the tested steel girders is shown in photos, the shear buckling failure occurred in the outer panels of these tested samples due to the ultimate load applied. The CFRP wrap failed in both tearing and debonding off the web plate in stress concentration regions.

![Figure 7. Load-Deflection curves for \((G_0)\), \((G_S_0)\), and \((G_S)\)](image1)

![Figure 8. Load-Deflection curves for \((G_0)\), \((G_C_0)\), and \((G_C)\)](image2)

In figure (9), the failure mode of the tested steel girders is shown in photos, the shear buckling failure occurred in the outer panels of these tested samples due to the ultimate load applied. The CFRP wrap failed in both tearing and debonding off the web plate in stress concentration regions.

a. The reference girder \((G_0)\) without cut-outs
8. Conclusions

The study has arrived to the following points as a conclusion to the collected results.

1- The ultimate resistance for shear has been affected and decreased almost half of the ultimate strength when the girder had a square opening height of 40% of the web depth in comparison to the solid girder, while the circular opening of the same depth lead to a decrement of about 30.3% and this is mostly referred to stress concentrations at the corners of the square opening;

2- The strengthening with CFRP strips made an increment in shear resistance and raised up the ultimate load by 63.6% and 52.6% for the girders with square and circular web openings, respectively;

3- These experimental results lead to the fact that the strengthening of plate girders using this technique is effective and applicable; and

Figure 9. The girders after failure in shear buckling
4- The presence of bending action in addition to shear reduces the shear stress capacity of the plate girders.

References
[1] Abdullah A H 2018 The effectiveness of CFRP strengthening of steel plate girders subjected to shear, MSc Thesis, Structural Engineering Department, University of Technology, Baghdad, pp.11
[2] Hamoodi M J, Korkess I N and Sarsam K F April 2009 Test and analysis of steel plate girders with central web opening, The 6th Engineering Conference, College of Engineering, Baghdad University 1, pp 1-17
[3] Abed I K 2015 Improving the strength of steel perforated plate girders loaded in shear using CFRP laminates, MSc Thesis, Structural Engineering Department, University of Technology, Baghdad, pp 6
[4] Al-azzawi Z, Stratford T, Rotter M and Bisby L January 2015 FRP Shear Strengthening of Thin-Walled Plate Girder Web Panels Subjected to Cyclic Loading, Conference: Response of Structures under Extreme Loading- Protect, The University of Edinburgh UK. pp 1-11
[5] Rockey K, Evans H and Porter D 1978 A design method for predicting the collapse behavior of plate girders, Proceeding Institution of Civil Engineers, part2, pp 85 - 112