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Research paper



Shear Strengthening of Composite Steel-Concrete Girders with Web Openings Using CFRP Sheets

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Abstract

This study presents an experimental investigation of subjecting one-point load at mid-span of five composite steel-concrete girders that are loaded predominantly in shear. Three of girders are reference girders with no web openings, square web openings, and circular web openings, respectively. The both other girders are strengthened girders. The compressive strength of concrete, slab reinforcement and all dimensions of girders are kept. The CFRP laminates were adhesively attached to the webs of strengthened girders in various patterns and were done to estimate the effect of strengthening scheme by CFRP composite on increasing of the ultimate load capacity of the web openings girders. The research purposes to examine the behavior and effect of increasing in the ultimate shear capacity of strengthened girders that have constant dimensions and locations of web openings which is about 40 % of web depth. The results show the increase in ultimate load capacity of strengthened girders containing square and circular web openings with about 23.75% and 25.9%, respectively compared to that of reference girders. Furthermore, the ultimate shear strength was predicted by von Mises stresses were used for girders without and with square and circular web openings.

Keywords: *CFRP; Shear Strength; Steel-Concrete Composite; Strengthening; Web Opening.*

1. Introduction

Steel-concrete composite girder consists of built-up Steel-I -section including two flanges of steel plate (top and bottom) that were welded with a web plate in the vertical direction, then concrete deck slab which connected together by shear connectors (welded to the top of the flange of the steel- I- section). Composite plate girders behave in a different way from that of the steel plate girder alone because of the "composite action [1]. In the design of plurality bridge girders through steel-concrete composite plate girders, the opening in a steel plate girder is usually utilized to give path services for uses ducts and pipes. Therefore, it is essential to investigate the influence of the openings in web steel plate on the performance of the composite plate girders if the designers wish in providing suitable openings in the structural members without decreasing the load carrying capacity of these structural members [2]. The using of composite steel-concrete beams containing uniform web-openings was increased in multi-story building structure [3,4]. In ship structures and highway bridges, the web openings of girders are provided so as to reduce the weight of the structure and to provide the space for maintenance and services [5-6]. Using of CFRP sheets in strengthening the web panels containing openings of the composite plate girders to improve the stiffness and ultimate load strength of girders. Concrete-Steel composite beams have the advantage that is the high tensile resistance of steel has been combined with the high compressive resistance of the concrete [7]. The stiffness of CFRP sheets is providing the high stiffness and tension resistance to the girders [8,9].

2. Experimental program

In this research, five composite plate girders are simply supported, and they were tested to study the behavior and to increase in the ultimate load capacity for strengthened girders with CFRP sheets, and they have constant dimensions and position of web openings which is 240 mm in height. Two types of composite plate girders were used. The first type is the reference girders which has no web openings(CPG1), and two girders have square, and circular web openings are (CPG2) and (CPG3) respectively. The second kind contains two strengthened girders with CFRP sheets containing square, and circular web openings are (CPG6) and (CPG7) respectively. All the girders have constant dimensions were tested under one-point load at mid-span of the top girder as shown in Table (1) and Figure (1).

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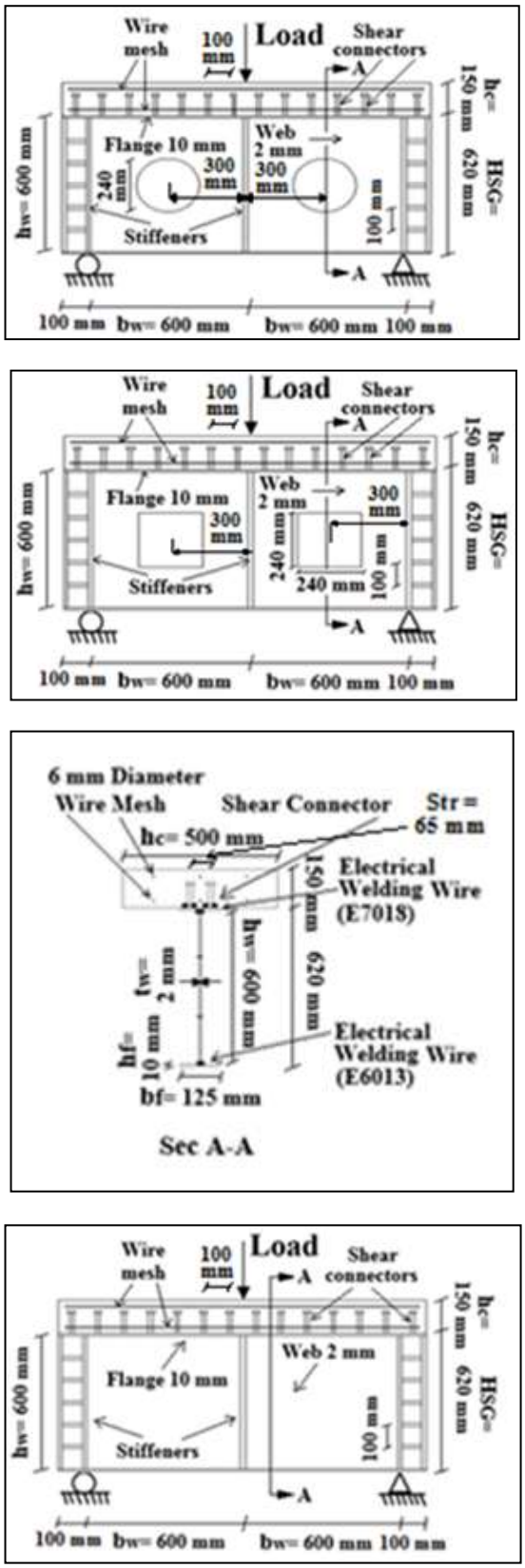


Fig. 1: Dimensions of Composite Plate Girders

Table 1. Details of Composite Plate Girders (mm)

GIRDER	CPG1	CPG2	CPG3	CPG6	CPG7
Details of Concrete Deck Slabs in Girders					
bc (mm)	500				
hc (mm)	150				
Rc(mm)	25				
Details of Steel Plates in Girders					
tf(mm)	10				
bf(mm)	125				
tw(mm)	2				
hw(mm)	600				
tes(mm)	15				
tms (mm)	20				
D of SPG (mm)	620				
bw(mm)	600				
Details of Girders					
D (mm)	770				
hw/tw	300				
hw/bw	1				
ho/hw for square opening	-	0.4	-	0.4	-
d/hw for circular opening	-	-	0.4	-	0.4
Reinf. With CFRP	reference	reference	reference	reinforced	reinforced

The depth of girder and concrete deck slab is used in order to study the shear failure and effect of shear strengthening in the girders. Desk slab was reinforced with two layers of 6mm diameter wire mish with 150mm spacing in both directions. The details of shear connectors were satisfied with the limits of Euro code 4[10] provisions as shown in Table (2) and Figure (2).

Table 2. Details of shear connectors

Head diameter (B) (mm)	Head thickness (mm)	Stud diameter (d stud) (mm)	Stud total length (mm)	Stud stem length (G) (mm)	Stud longitudinal spacing (mm)	Stud transverse spacing (Str) (mm)
28	8	16	100	92	100	65

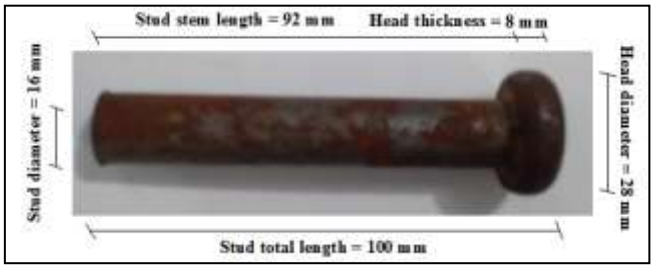


Fig. 2: Details of Shear Connector

3. Strengthening techniques

Type1: Involves strengthening the web of the composite plate girder(CPG6) using strips of 100mm width of CFRP in both faces. In the first face, the strips were parallel to the-web axis because of the fibers direction of CFRP is horizontal at the corners of web openings, and it has high tensile strength to prevent the tearing of

corners while it was vertical to the web axis in the second face as shown in Figure (3).

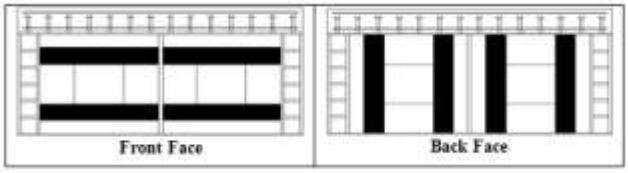


Fig. 3: Type (1) of Strengthening (CPG 6) girder.

Type2: The web of the girder (CPG7) is strengthened by CFRP strips of 120mm width for two faces of the girder so that the diameter of circular web openings in this girder is 240 mm and divided by 2 to equal 120 mm that it is representing the width of strips instead of 100 mm. The first face of web openings has been bonded with CFRP strips in which the fibers are along the diagonal ($\theta = 45^0$) because of the fibers direction of CFRP is the same direction of the tension field action in the web panels, and the fibers of CFRP have high tensile strength to prevent the deformation of web panels. In the second face, the fibers are along the composite diagonal ($\theta = 135^0$) as shown in Figure (4).

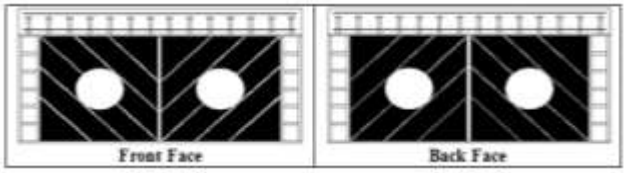


Fig. 4: Type (2) of Strengthening (CPG 7) girder

4. Properties of fresh and hardened concrete

The normal fresh concrete has a slump of 90mm using vibrator according to (ASTM C-143/C-143 M-03) [11]. In hardened concrete manner after 28 days the compressive strength of cubes (150*150*150 mm) is (57 MPa) according to BS1881 [12], and the splitting tensile strength of cylinders (150*300 mm) is (4.1 MPa) according to ASTM C496/C496M -04 [13].as shown in Figure (5).



Fig. 5: Slump and Compressive Strength Test

5. Properties of materials

1. Cement: Ordinary Portland Cement (OPC) (Mass factory) was used in this search, and it satisfied with Iraqi Standard Specification No.5/ 1984 [14].
2. Fine aggregate (Sand): Natural sand has the fineness modulus of 2.57 is used. The sieve analysis of this aggregate is within the zone 2 according to the requirements of the IQS No.45/1984 [15], and the physical properties of this aggregate are satisfied to IQS No.45/1984 [15].
3. Coarse aggregate: The maximum size of Crushed gravel is 14 mm. The physical properties and grading of this aggregate are according to the requirements of the Iraqi Standard IQS No.45 (1984) [15].
4. High-range water reducer: A superplasticizer named as SikaViscoCrete-5930 was used to produce normal concrete depending on an aqueous solution of modified polycarboxylate.
5. Steel plates: The details of steel plates specimens are according to ASTM A370 [16], and tensile strength test is done on steel plates that are used to form the five composite plate girders, as shown in the Table (3) and Figure (6). The poison ratio and modulus of elasticity are assumed to be 0.3 and ($200*10^3$) MPa respectively.
6. Shear connector: To supply information about the ultimate tensile strength (pull-out) capacity of shear connectors that were used in the composite plate girders, three specimens of these shear connectors were tested under direct tensile test [16], as shown in the Figure (6) and Table (3).
7. Welded wire mesh: Tensile strength tests completed on wire mesh according to ASTM A615/615M-14 [17]. Properties of wire mesh that was used to reinforce the slab of five composite plate girders were shown in Figure (6) and Table (3).

Table 3. Properties of Steel Components

Component	Dimension (mm)	Yield Stress fy (MPa)	Ultimate Tensile Stress fu (MPa)
Flange	10 Thickness	391	425
Web	2 Thickness	426	556
Intermediate stiffener	20 Thickness	301	419
Bearing stiffeners	15 Thickness	373	522
Wire mesh reinforcement	6 Diameter	543.86	569.5
Shear stud Connectors	16 Diameter	488	532



Fig. 6: Tensile Strength Test for Steel Components

8. CFRP sheet: Figure (7) and Table (4) show the CFRP properties agreeing to the data sheet of the manufacturer. The CFRP type was sika-warp-300 c produced through Sika Corporation [18] and used to strengthen the girders.

Table 4. Properties of CFRP*

Properties	Sika Warp - 300 c NW
Tensile Strength (MPa)	3800
E-Modulus (GPa)	242
Elongation At Break (Strain)%	1.55
Thickness (mm)	0.171
Density (g/cm3)	1.81

*Properties are provided according to manufacturer data sheet[18].



Fig. 7: CFRP Laminate and Sikadur®- 330 Container

9. Adhesive Material (Epoxy): Adhesive material has been used together with carbon fiber sheets. This material is Sikadur®-330, as illustrated in Figure (7). adhesive material involves two parts: part A, resin, that is white and part B, hardener, that is grey. The properties of the adhesive material are found according to data-sheet of manufacture [19], as shown in Table (5).

Table 5. Sikadur®- 330 Properties*

Properties	Sikadur® 330
Density (kg/l) at +23°C	Parts A+B mixed : 1.3
Tensile Strength (MPa)	30
E-Modulus (GPa)	Flexural: 3.8 Tensile : 4.5
Elongation At Break (Strain)%	0.9
Setting Time (Minute) at 35°C	30
Mixing ratio	Part A : part B = 4 : 1 by the weigh

* Properties are provided according to manufacturer data sheet[19].

6. Test technique and instrumentation

All girders are simply supported with a roller and pin (hinge) along the span of 1200 mm. The upper load capacity of testing machine (Avery) is 1600 KN. The girders are experienced up to the failure mode under the effect of applying the load at mid-span of the top girder, see Figure (8). The vertical deflections of girders were measured with a dial gauge with 0.01 accuracy that is mounted at mid span under bottom flanges of girders. In slab deck, patterns of cracks and first crack load were observed during the test.

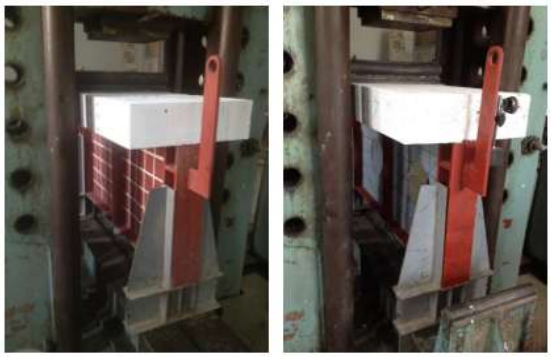


Fig. 8: Setup of The Tested Composite Plate Girder

7. Evaluation of ultimate shear strength [20,21,22]

7.1. Composite plate girders that have no web opening:

Shear capacity of the concrete slab, Vcs:

$$v_{cs} = 0.79 * b * d_c * \left(\frac{100 * A_{rs}}{b * d_c}\right)^{\frac{1}{3}} * \left(\frac{400}{d_c}\right)^{\frac{1}{4}} * \left(\frac{f_{cu}}{25}\right)^{\frac{1}{3}} \quad (1)$$

Calculate the pull–out capacity of a group of the adjacent connectors, provided on one side of the plastic hinge in top flange, Tgr (as applicable):

$$T_{gr} = (\pi(B + (G - R_c) * cot\emptyset) + 2S_{tr})(G - R_c) * \sigma_{ct} * cot\emptyset \quad (2)$$

Calculate the degree of vertical shear interaction, γ as following:

$$\gamma = \frac{T_{gr}}{v_{cs}} \leq 1 \qquad and \qquad v_c = \gamma * v_{cs} \quad (3)$$

The inclination of web panel diagonal, θ_d:

$$\theta_d = tan^{-1}\left(\frac{h_w}{b_w}\right) \quad (4)$$

The shear buckling coefficient, k:

$$k = 5.35 + 4\left(\frac{h_w}{b_w}\right)^2 \qquad when \frac{b_w}{h_w} \geq 1 \quad (5)$$

$$k = 5.35\left(\frac{h_w}{b_w}\right)^2 + 4 \qquad when \frac{b_w}{h_w} \leq 1$$

The elastic critical stress shall be:

$$\tau_{cr} = k * \frac{\pi^2 * E}{12(1 - \nu^2)} * \left(\frac{t_w}{h_w}\right)^2 \quad (6)$$

The tensile membrane stress, σ_{yt}, using Von–Mises yield criterion:

$$\sigma_{yt} = -\frac{3}{2} * \tau_{cr} * sin2\theta + \left({\sigma_{yw}}^2 + {\tau_{cr}}^2\left((\frac{3}{2}sin2\theta)^2 - 3\right)\right)^{\frac{1}{2}} \quad (7)$$

$$J = \frac{1}{2}\left(h_c cot\theta - \frac{v_c}{D}\right) \quad (8)$$

$$M_{pt} = \sigma_{yft} * b_{ft} * \frac{{t_{ft}}^2}{4} \quad (9)$$

$$M_{pb} = \sigma_{yfb} * b_{fb} * \frac{{t_{fb}}^2}{4} \quad (10)$$

$$M_{cu} = f_{yr*}A_{rs}\left(d_c - 0.75\frac{f_{yr*}A_{rs}}{f_{cu} * b}\right) \quad (11)$$

The hinge distance in the top and bottom flanges, C_t and C_b:

$$C_t = J + \left(J^2 + \frac{2}{D}(M_{pt} + M_{cu})\right)^{\frac{1}{2}} \qquad for\ \gamma = 1 \quad (12)$$

$$C_b = \frac{2}{sin\theta}\left(\frac{M_{pb}}{\sigma_{yt} * t_w}\right)^{\frac{1}{2}} \qquad 0 < \gamma \leq 1 \quad (13)$$

The ultimate shear strength of SCCPG for the selected θ , Vult:

$$v_{ult} = \tau_{cr} * t_w * + \sigma_{yt} * t_w * sin^2\theta(C_t + C_b) + \sigma_{yt} * t_w * h_w * sin^2\theta(cot\theta - cot\theta_d) + \gamma * v_{cs} \quad (14)$$

7.2. Composite plate girders with square web opening:

$$d^* = b_0 sin\theta + h_0 cos\theta \quad (15)$$

d^* : is the effective width of cut-out.

$$k_m = k_b\left(1 - \frac{d^*}{h_w}\right) \quad (16)$$

$$\theta_m = 0.75\theta_d * \left(1 - 0.71\frac{d_g}{h_w}\right) \quad (17)$$

θ_m: is the angle of the tension field for perforated plates with central rectangular cut-outs.
d_g: is the diagonal of the rectangular cut-out($d_g = (b_0^2 + h_0^2)^{0.5}$)
With the application of the remaining laws above used for the girders without opening.

$$v_{ult} = \tau_{cr\cdot m} * t_w * h_w + \sigma_{t\cdot m} * t_w * sin\theta\big((C_t + C_b)sin\theta + (h_w - b_w * tan\theta)cos\theta - d^*\big) + \gamma * v_{cs} \quad (18)$$

7.3. Composite plate girders with circular web opening:

$$k_m = k_b\left(1 - \frac{d}{h_w}\right) \quad (19)$$

$$k_b = 8.98 + 5.6\left(\frac{h_w}{b_w}\right)^2 \qquad when\frac{b_w}{h_w} \geq 1 \quad (20)$$

$$k_b = 8.98\left(\frac{h_w}{b_w}\right)^2 + 5.6 \qquad when\frac{b_w}{h_w} \leq 1$$

d: The diameter of the cut-out
With the application of the remaining laws above used for the unperforated girders.

$$v_{ult} = \tau_{cr\cdot m} * t_w * h_w + \sigma_{t\cdot m} * t_w * sin^2\theta(C_t + C_b) + \sigma_{t\cdot m} * t_w * h_w * sin^2\theta(cot\theta - cot\theta_d) - \sigma_{t\cdot m} * t_w * d * sin\theta + \gamma * v_{cs} \quad (21)$$

8. Results and discussion

The girders (CPG1) has no web openings and (CPG2) has square web openings are reference girders. Then, the girder (CPG6) had a square web opening and strengthened with CFRP strips. The Results show that the presence of square web openings decreases ultimate load capacity to 28.57 %, and they increase the deflection to 68.73%. Girder (CPG6) which was strengthened with CFRP strips, as shown in Type 1 of strengthening, this girder shows an increase of stiffness and load compared to (CPG2) with 23.75%, and it has less deflection of 36.84% compared to (CPG2). Then this girder (CPG6) shows a decrease of load compared to (CPG1) with 11.6%; then it has increased deflection of 26.02% compared to (CPG1), as shown in Figure (9).
The girders (CPG1) has no web openings and (CPG3) with circular web openings where together act reference girders, as well the girder (CPG7) containing circular web openings was strengthened with CFRP strips. The results show that circular web openings reduce ultimate load strength to 26.25%, and they increase the deflection to 28.02%. The girder (CPG7) that has been strengthened with CFRP strips, as shown in Type 2 of strengthening, this girder shows increasing of stiffness and increasing in load capacity than that of (CPG3) with 25.9%, and it has decreasing in the deflection with 22.29% comparing to (CPG3). Then this girder (CPG7) shows a decrease of load compared to (CPG1) with 7.14%; then it has increased in the deflection with 10.47% comparing to (CPG1), as shown in Figure (10). Figure (11) represents the failure mode of the girders. The comparing between the experimental and theoretical results have been studied. Moreover, the ultimate load has been compared with reference girder, as shown in Table (6).

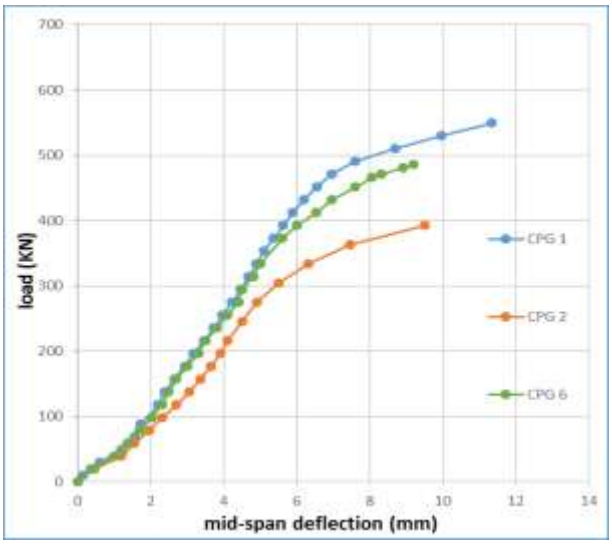


Fig. 9: Load –Deflection Curves for Girders (CPG 1), (CPG 2) and (CPG 6)

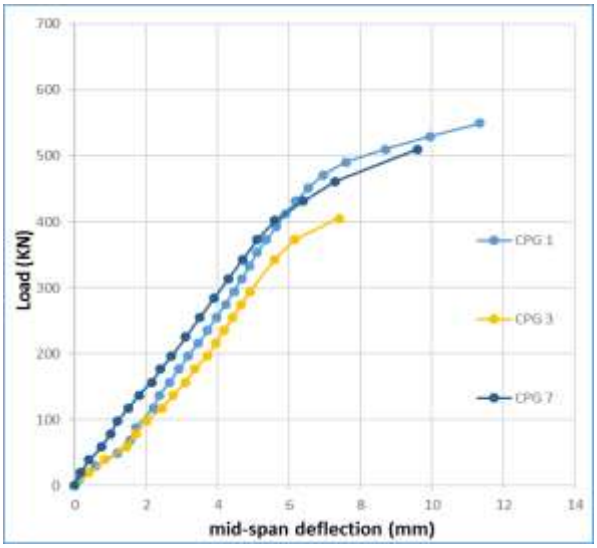
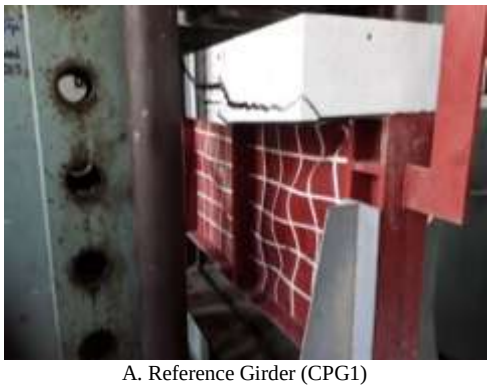


Fig. 10: load –deflection curves for girders (CPG 1), (CPG 3) and (CPG7).



A. Reference Girder (CPG1)



B. Girder containing square Web Openings (CPG2)



C. Girder with square Web Openings (CPG6)



D. Reference Girder (CPG3)



E. Girder with Circular Web Openings (CPG7)

Figure 11. Composite Plate Girders After the Mode of Failure

Table 6. The Theoretical and Experimental results of Ultimate Load for Girders in comparing with Reference Girders.

Girder designation	Pu (KN) (Theoretical)	Pu (KN) (Experimental)	Increase In Ult. Load in Comparing to Their Reference(%)	Decrease in Ult. Load in Comparing to CPG1 (%)
CPG 1	544.87	549.36	-	-
CPG 2	290.65	392.4	-	28.57
CPG 3	356.70	405.15	-	26.25
CPG 6	-	485.59	23.75	11.6
CPG 7	-	510.12	25.9	7.14

9. Conclusions

1-All girders were failed predominantly in shear, mode of failure was diagonal splitting in slab deck of girders while it was buckling in the web, then forming of plastic hinges in top steel flange. The strengthened girders were failed with complement many modes of the failure such as CFRP deponding or rupture in CFRP.

2-All strengthened girders revealed an increasing in ultimate load resistance compared with their reference girders with a range of 23.75% to 25.9% for girders containing on square and circular web openings respectively.

3-The strengthened girders indicated higher stiffness and reducing in deflection values with a range of 22.29% to 36.84% in comparing to their reference girders.

4-The ultimate load strength decreases in a range of 26.25% to 28.57% for the girders with circular and square web openings respectively compared to the girder without web openings.

5-the theoretical results obtained by von Mises stresses were approximated to the experimental results.

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