Improving the Strength of Steel Perforated Plate Girders Loaded in Shear Using CFRP laminates

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ABSTRACT

The structural behavior of perforated composite web plate girders under shear loading is studied. Five steel plate girders have been tested. Two of them are reference girders, not perforated and perforated. The perforated webs in the three other girders are strengthened with carbon fiber reinforced polymer (CFRP) laminates in different patterns. The diameter of the central circle opening is 300 mm, where is 60% of the web depth. It is found from the experimental work that the ultimate shear load for the perforated composite web plate girder is higher than the reference perforated girder in a range of 100% to 134% depending on the orientation of the fiber in CFRP laminates. Through the experimental results, new formulas are presented to predict the ultimate shear load of perforated strengthened steel girders by CFRP laminates. A nonlinear finite element analysis is carried out for the tested plate girders using the package software program (ANSYS V.14.5). The analytical results contain the distribution of Von Mises stresses, which is useful to have a better understanding to the results obtained from the experimental tests.

Keywords: Steel plate girder, CFRP, web opening, Composite web, ANSYS.

تحسين مقاومة العوارض اللوحية الفولاذية المثقبة المحملة بالقص بأستخدام صفائح ألياف الكاربون البوليمرية المسلحة.

الخلاصة:

في هذا البحث يدرس السلوك الأنشائي للعوارض اللوحية المثقبة الوترة والمدعمة تحت أحمال القص. خمسة عوارض لوحية فولاذية تم أختبارها. أثنان منها عوارض مرجعية, غير مثقبة ومثقبة. الوترات المثقبة في العوارض الثلاثة الأخرى تقوى بصفائح ألياف الكاربون البوليمرية المسلحة بعدة طرق. قطر الفتحة الدائرية في الوترة هو 300mm اي مايساوي 60% من عمق الوترة. من التجارب العملية وجد أن الحمل الأقصى لقوى القص للعارضة اللوحية المثقبة والمدعمة الوترة أعلى من العارضة المثقبة المرجعية بمعدل من 100% الى 134% بالأعتماد على أتجاه الألياف في صفائح ألياف الكاربون. تم أستنتاج من خلال النتائج العملية معادلات جديدة لمعرفة الحمل الأقصى لقوى القص للعوارض الفولاذية المثقبة والمقواة بصفائح الياف الكاربون.تم أستعمال التحليل اللاخطي بواسطة العناصر المحددة للعوارض اللوحية المفحوصة بأستخدام البرنامج الجاهز ANSYS v.14.5. النتائج التحليلية تتضمن ق توزيع الأجهادات Von Mises التي كانت مفيدة في فهم افضل للنتائج المستحصلة من الجانب العملي.

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INTRODUCTION

A plate girders may be defined as structural members that resist loads primarily in bending and shear and shaped similarly to commonly used steel I-section. I-section plate girders are generally fabricated by welding together two flanges, a web and a series of transversal stiffeners. Flanges resist the axial tensile and compression forces arising from the bending action, whereas web plate resists the shear force.

Standard techniques of steel structure strengthening include welding or bolting of steel cover plates to the existing systems. The disadvantages of these techniques are corrosion effects, sensitivity of the repaired system to fatigue problems due to stress concentrations produced by welding or bolting techniques and long period of service interruption. Recently, the use of epoxy bonded FRP materials has become a promising alternative due to its high tensile strength, stiffness, and corrosion and fatigue resistance.

Openings in steel plate girders may be required to provide access for ducts, cables and other services or just to reduce the weight. However, the presence of such openings in web plate leads to change in stress distribution at the web panel and decrease the ultimate shear load. In recent years, a great deal of progress has been made in the analysis of composite steel- concrete plate girders with web openings due to the need for inspection and maintenance and economic considerations [1]. Therefore, a reinforcing CFRP strips on the web and around the opening is to reduce the stress concentration and to increase the ultimate shear load.

Material Properties

The properties of the materials that were used in the tested girders are:

Steel

The yield and ultimate stress of the steel used for the flanges and webs obtained from the tensile tests are summarized in Table (1). The modulus of elasticity, E, and the Poisson´s ratio, ν, are assumed to be 200000 MPa and 0.3, respectively.

Table (1):Properties of the steel used for the girders

Component	Thickness (mm)	σ_y (MPa)		σ_u (MPa)	
Flange and vertical stiffener	6	280.92	273.12	431.21	423.73
		263.31		416.51	
		275.12		423.48	
Web	2	313.07	302.4	435.41	419.44
		276.71		408.09	
		317.43		414.82	

CFRP Laminates

The normal modulus CFRP laminates used for strengthening the perforated plate girders were Sika CarboDur S1012**,** produced by Sika Corporation. Thickness of the laminate is (1.2mm) and the width is (100 mm) . Tensile tests for the CFRP laminates were performed according to ASTM D3039[2] specifications. The specimen for the tensile test was 381 mm long and 25 mm wide with a gage length of 229 mm, Figure

(1).The result of these tests with the average value of the tensile strength are given in Table(2).

a)The specimen before test b) The specimen after Failure
Figure (1): Tensile test of CFRP laminate

Table (2): Tensile strength of CFRP laminates

No.of specimen	σ_u (MPa)	Average
1	2378.37	
2	2333.33	
3	2364.15	2358.61

Adhesive Epoxy

The Spabond 345produced by SP-High Modulus Gurit Corporation has been used to adhere CFRP laminates to the webs of plate girders. The 400 ml Spabond 345 twin cartridge mixed with a ratio of 2:1 by weight for the components resin and fast hardener, respectively. Tensile test for the epoxy adhesive was done according to ASTM D638[3] specifications. Epoxy coupon of 11 mm wide and 7 mm thick was prepared and tested. The behavior of the adhesive in tension was approximately linear until failure. The tensile strength is (39.43 MPa) with ultimate brittle failure.

Surface Preparation and Installation of CFRP laminates

The proper surface treatment of metals should produce a rough surface free from contamination with a fresh, stable oxide that has a favorable chemical composition. Additionally, a rough surface will have a larger surface area than a smooth one. Sandblasting was used to remove weak layers from the web surfaces and to create a rough, chemically active surface. Then the fine abrasive dust was removed by brushing, A final solvent cleaning was carried out using acetone. The prepared web surfaces were left for 24 hours before coating with adhesive [4].

The CFRP was cut according to the dimensions that it was needed by using hand saw and rasp. The surface of CFRP was also lightly sanded using P80 sand paper to improve the bonding quality and then it was cleaned with acetone [5].

The two part epoxy (SPabond 345) was applied onto the surface of the web using the dispenser gun. The epoxy was spread using a small trowel for even layer. The CFRP strips were pressed on the steel prepared surface in order to avoid air bubbles and the adhesive in excess was removed.

Details of the Plate Girders

The tested girders PG and PGO are shown in Figure (2). Each plate girder has two panels. The girders (PGOC1) , (PGOC2) and (PGOC3) have the same dimensions and web opening of girder (PGO), however the perforated webs in these plate girders are reinforced with CFRP laminates in different patterns . The distance between the two vertical stiffeners in the girder, a, is 500 mm. The distance between the top and bottom flanges, d, is 500mm. The width of the flange, b_f, is 120 mm. The thickness of the web plate, t_w, is 2 mm while the thickness of the flanges, t_f, is 6 mm. The web and flanges thicknesses were fixed for all tested girder. The detailed dimensions of the plate girders are given in Table (3). These dimensions are the true measured values. The aspect ratio of each panel (width to depth ratio) is one. The slenderness ratio of the girders (depth to thickness of web) is 250. The diameter of the openings is 60% of the web depth.

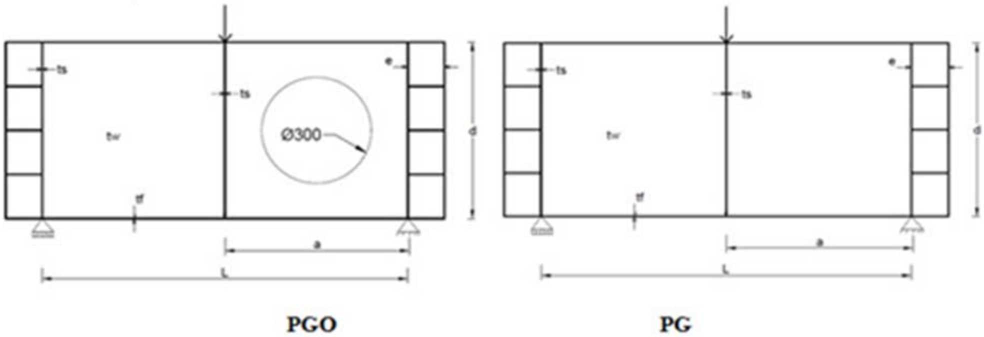


Figure (2):The reference plate girders PG and PGO

Table (3): Dimensions and details of the tested girders, all dimensions is millimeter

Girder	t_w	t_s	t_f	b_f	L	a	d	e	d/t_w	a/d	Reinf.
PG	2	6	6	120	1000	500	500	100	250	1	—
PGO	2	6	6	120	1000	500	500	100	250	1	—
PGOC1	2	6	6	120	1000	500	500	100	250	1	Typy1
PGOC2	2	6	6	120	1000	500	500	100	250	1	Type2
PGOC3	2	6	6	120	1000	500	500	100	250	1	Type3

Composite web Steel Plate Girders

The perforated webs in PGOC1, PGOC2 and PGOC3 plate girders have been strengthened by bonding CFRP laminates.

For girder PGOC1, Type1 of strengthening is used. The first face of the perforated web has been bonded with CFRP where the fibers are parallel to the flange ($\theta=0^o$). In the second face the fibers are perpendicular to the flange ($\theta=90^o$), Figure (2.A).

Type 2 of strengthening is used for girder PGOC2.The first face of perforated web has been bonded with CFRP where the fibers are along the diagonal ($\theta=45^o$).For the second face the fibers are along the other diagonal ($\theta=135^o$), Figure (2.B).

The strengthening of Type 3 is used for girder PGOC3, where three strips of CFRP is used for each face. The first strip is along the diagonal and the two others are tangent to the circular opening. The orientation of the fibers in the first face is ($\theta=45^o$) and the second face is($\theta=135^o$), Figure (2.C).

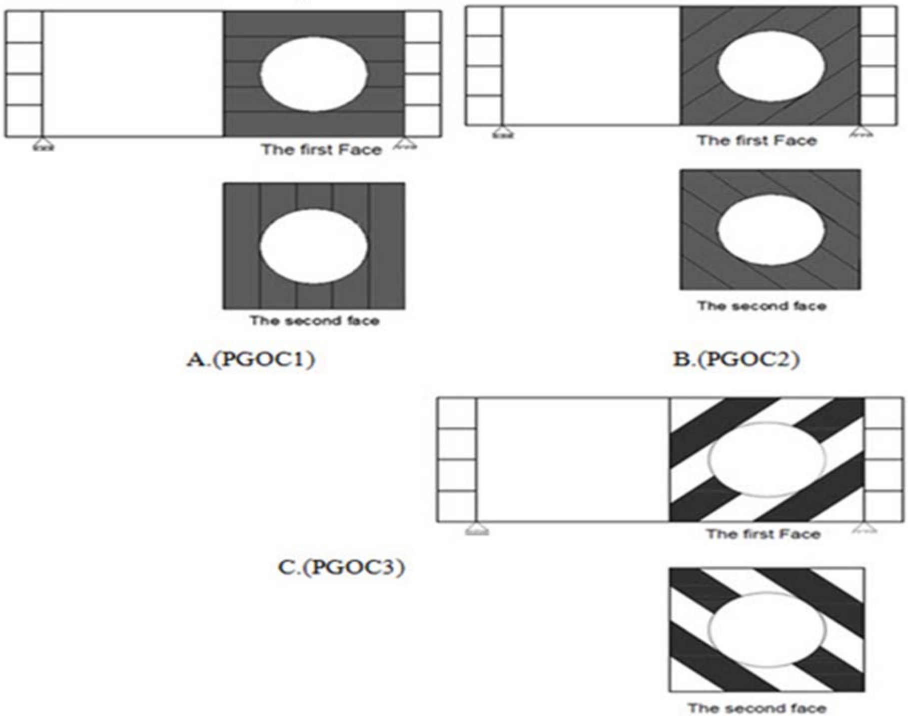


Figure (3): The three types of strengthening, A- plate girder PGOC1,B-plate girder PGOC2 and C-plate girder PGOC 3

Testing Procedure and Instrumentation

Each girder was set as simply supported over span of 1000mm as shown in Figure (4). The girder specimen was tested up to failure under the action of an applied line load at mid-span through a cylinder welded to a plate. The applied load is distributed across the entire width of the flange. The load was applied centrally so that each panel was subjected to a shear loading equals to the half the applied load. The maximum load capacity of the tested machine is 2000 kN, which can be applied by hydraulic pressure. The deflections of all girders were obtained with dial gauge of 0.01mm accuracy. The dial gauge was installed under the bottom flange at the mid-span of girder.

Figure (4): Test setup for plate girder specimen

Evaluation of Ultimate Shear Strength

Ultimate Shear Strength of Steel Plate Girder without Web Opening.

The ultimate shear capacity of plate girder without web opening loaded in shear can be obtained as follows [6]:

$$V_{ult.} = (\tau_{cr.})dt_w + \sigma_{yt}sin^2\theta(dcot\theta - a) + 4dt_w sin\theta\sqrt{\sigma_{yw}\sigma_{yt}M_p^*} \quad ...(1)$$

Where

$$Mp^* = \frac{M_{pf}}{d^2\sigma_{yw}t_w} \quad ...(2)$$

Ultimate Shear Strength of Steel Plate Girder with Web Opening.

The Equation (1), can be modified to be used for a perforated web plate girder with small openings as follows [7]:

1. The buckling coefficient for a perforated web(k_0) can be expressed as :

$$k_o = k\left(1 - \frac{d_h}{d}\right) \quad ...(3)$$

Where, d_h is the opening diameter .Thus, the buckling shear stress for web plate with the circle cutout is

$$(\tau_{cr.})o = k_o\frac{\pi^2 E}{12(1-V^2)}\left(\frac{t_w}{d}\right)^2 \quad ...(4)$$

The presence of large opening in web panels, such in plate girder (PGO), the post-buckling shear capacity (Vpost.) has a more reduction due to the discontinuity in the tension field,[8] thus

$$(V_{post.})o = 0.5 * V_{post} \quad ...(5)$$

So the ultimate collapse shear load for plate girder with web opening has a diameter equal to 60% of the web depth is:

$$(V_{ult.})o = (\tau_{cr.})o\ dt_w + \left[\sigma_{yt}t_w sin^2\theta(dcot\theta - a) + 4dt_w sin\theta\sqrt{\sigma_{yw}\sigma_{yt}M_p^*}\right] * 0.5$$

The ultimate shear capacity of a perforated composite web plate girder web opening loaded in shear can be obtained as follows :

$$(V_{ult.})o = (\tau_{crv.})o\ dt_w + \left[\sigma_{yt}t_w sin^2\theta(dcot\theta - a) + 4dt_w sin\theta\sqrt{\sigma_{yw}\sigma_{yt}M_p^*}\right] * 0.5$$

Where

$$\tau_{crv.} = k_o D_v\frac{\pi^2}{d^2(t_w + 2t_{Fo} + 2t_{F1} + 2t_{F2})} \quad ...(6)$$

Where, d is the depth of the web, t_{Fo} is thickness of putty layer, t_{Fi} are thickness in layer *i* of CFRP (*i* =1, 2). D_V is flexural rigidity of steel plate bonded CFRP laminates, which is given as[9]:

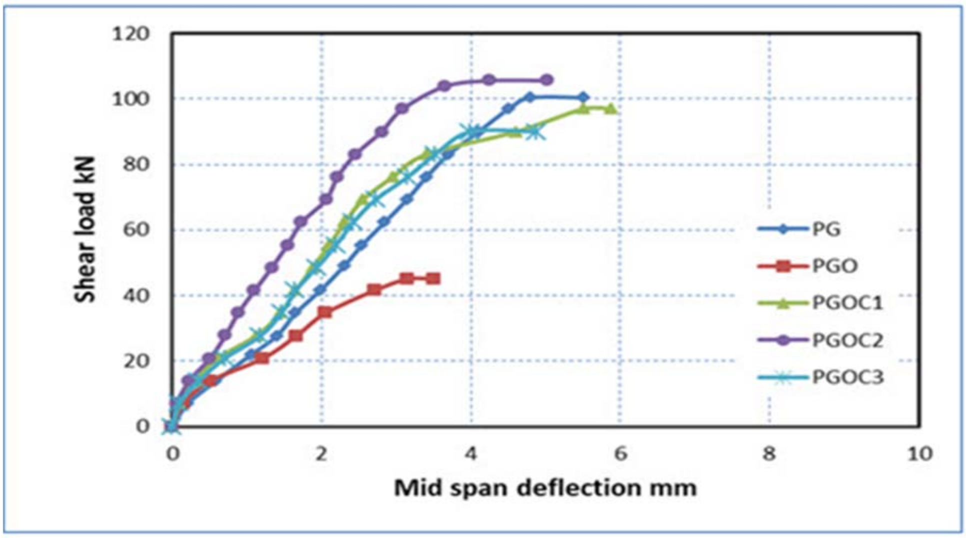
$$D_V = \frac{E_s t_w^3}{12(1 - v_s^2)} + \frac{2E_{Fo}}{3(1 - v_{Fo}^2)}\left\{\left(\frac{t_w}{2} + t_{Fo}\right)^3 - \left(\frac{t_w}{2}\right)^3\right\} + \frac{2E_{F1}}{3(1 - v_{F1}^2)}\left\{\left(\frac{t_w}{2} + t_{Fo} + t_{F1}\right)^3 - \left(\frac{t_w}{2} + t_{Fo}\right)^3\right\} + \frac{2E_{F2}}{3(1 - v_{F2}^2)}\left\{\left(\frac{t_w}{2} + t_{Fo} + t_{F1} + t_{F2}\right)^3 - \left(\frac{t_w}{2} + t_{Fo} + t_{F1}\right)^3\right\} \quad ...(7)$$

Where,

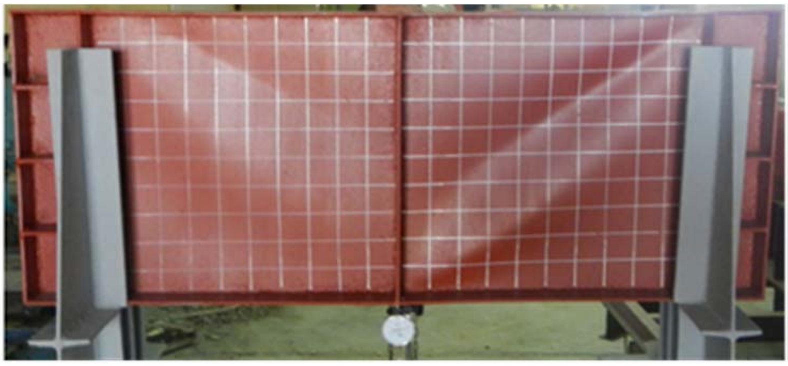
E_{Fo} is young's modulus of putty, v_{Fo} is Poisson's ratio of putty, t_{Fo} is the thickness of the patty. $E_{Fi}$and v_{Fi} are young's modulus and Poisson's ratio of CFRP in layer i (i=1, 2), respectively.

Test Result

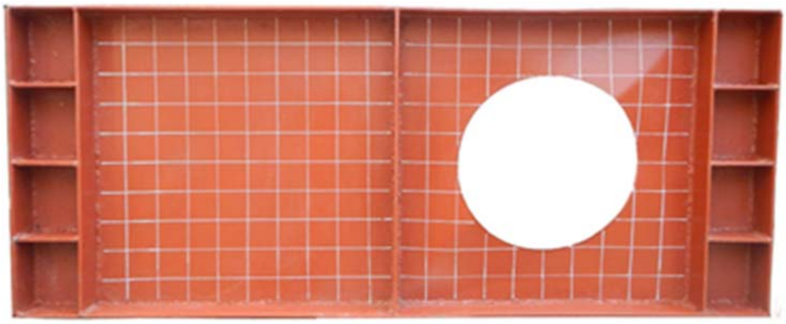
The load-deflection curves for the tested girders are shown in Figure (5),the girder PGOC2 shows higher stiffener and higher load even than the unperforated plate girder PG. Figure (6) shows the failed girders after tests, cracking in CFRP strips started at the opening edge regions and then debonding hear the failure loads. The CFRP strips with fibers along the tension diagonal had only small cracks at the corners near the failure load. The ultimate shear load for the girders and a comparison with the reference plate girders are given in Table (4).



Figure(5):Load-deflection curves for PG,PGO,PGOC1,PGOC2 and PGOC3

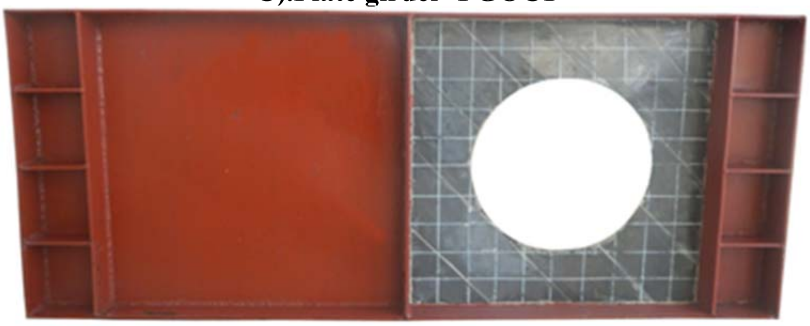


A).Plate girder without web opening PG



B).Plate girder with web opening PGO

C).Plate girder PGOC1



D).Plate girder PGOC2

E).Plate girder PGOC3

Figure(6):Tested plate girders after failure

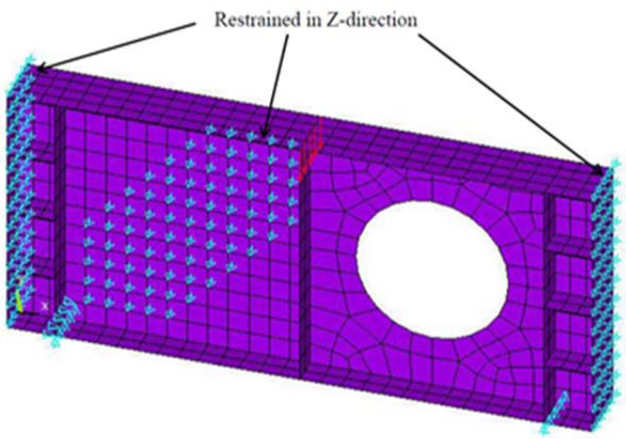
Table (4):The results of the critical shear buckling and ultimate loads for tested girders

Plate girder	Max.ultimate shear load.V_{exp}.(kN)	Effect of reinforcing comparing to PGO (%)	Ultimate shear load comparing to PG (%)
PG	100.34	—	—
PGO	45	—	-55.15
PGOC1	96.88	115.28	-3.45
PGOC2	105.53	134	5.17
PGCO3	89.96	100	-10.34

Finite Element Modeling

Element Geometry

A SHELL181 element is used for the finite element analysis through the software ANSYS Version 14.5 to model plate girders (PG and PGO). The element is suitable for analyzed thin to moderately-thick shell structures. It is a four-nodal element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z axes. The element is well-suited for linear, large rotation, and for large strain nonlinear application. The distributed load across the width of the top flange is modeled as point loads act at the nodal points of the elements across the top flange at mid-span to consequently obtain a constant shear load in each of the two web panels, Figure (7). Material properties which have obtained from the experimental work for girders are adopted in this present analysis.



Figure(7): Applied load and Boundary Condition.

Analysis results

For plate girder (PG), the Von Mises stress distribution at failure, which is shown in Figure (8), describes the stresses at the web panels. The highest stress concentrated underneath the top flange and adjacent to the intermediate transverse stiffener is 260.720 MPa.

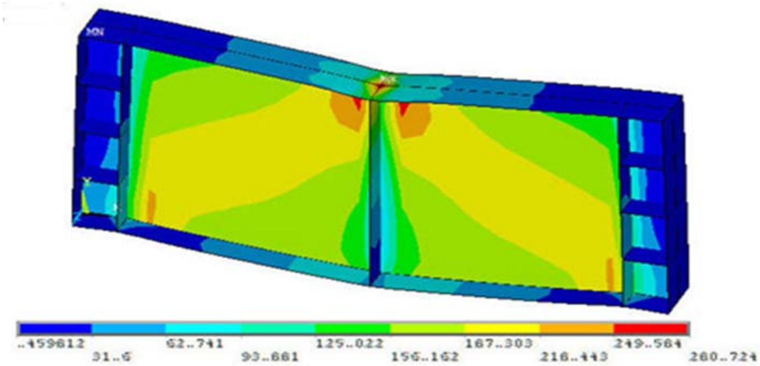


Figure (8): Von Mises stress distribution of plate girder (PG) at failure

The Von Mises stress distribution for plate girder (PGO) is displayed in Figure (9). It can be noted from this distribution that there are four zones around the opening edge at which the stresses are the highest in the web. This indicates that these four positions have the highest strains and deformations.

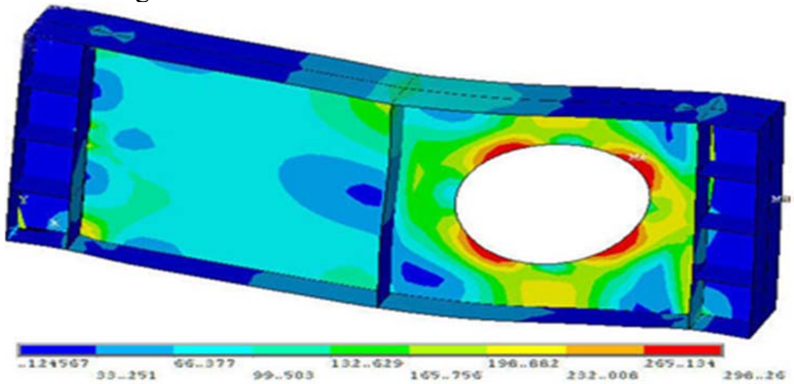


Figure (9): Von Mises stress distribution of plate girder (PGO) at failure

CONCLUSIONS

1. The presence of opening with diameter of 60% of the web depth in plate girder will decrease the ultimate shear load by about (55%) comparing to girder without opening.
2. The experimental results confirm that the strengthening technique for perforated webs with CFRP laminates is applicable and can increase the shear strength of plate girders with web opening.
3. The best confining the web opening with CFRP laminates is found to be when the fibers in CFRP laminates are along tension and compression diagonal (Type 2 strengthening).The ultimate shear load is increased by 134% comparing to the control perforated plate girder.
4. Initial stiffness of the plate girders is almost the same. As the load increased the strengthened perforated plate girders show higher stiffness comparing to the control perforated plate girder. This indicates that the CFRP laminates help to restrain the buckling of the web.
5. Depending on the results of stress distribution obtained from the program analysis, the stresses are concentrated at the web opening edges in four zones.

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Notations

a The clear of the web plate between vertical stiffeners
d Depth of girder
M_{pf} Plastic moment capacity of the flange plate
d_h Diameter of the opening
t_w Thickness of the web
τ Shear stress
τ_{cr} Critical shear stress
k_s Shear buckling coefficient.
θ The angle of inclination of the membrane stress.
σ_{yw} Tensile yield stress of the web
σ_{yf} Tensile yield stress of the flange
σ_{yt} Tensile membrane stress at yield
$V_{ult.}$ Ultimate shear strength
$V_{cr.}$ Critical buckling shear force
V_{post} Post buckling shear force
M_p^* Non-dimensional flange strength parameter.
k_o Buckling coefficient for a perforated web.
τ_{crv} Shear buckling stress of plate girder reinforced by CFRP
D_v Flexural rigidity of plate girder bonded CFRP laminate .
σ_y Yield stress of steel material
σ_u Ultimate stress of steel material