Behavior of Steel Plate Girders with Web Openings Loaded in Shear

Dr. May J. Hamoodi
Building and Construction Engineering Department, University of Technology/Baghdad
Marwa S. Abdul Gabar
Building and Construction Engineering Department, University of Technology/Baghdad
Email:marwasafa@yahoo.com

Received on: 8/10/2012 & Accepted on: 9/5/2013

ABSTRACT

The structural behavior of three steel plate girders under shear is studied. The first one is the reference plate girder (G) which is prepared without web openings, and the second one (GO) is fabricated to contain circular opening at the center of each web panel, the diameter of the opening is 60% of the web depth, while the third plate girder (GOR) is with reinforced strip welded around the circular web openings. The aspect ratio of the panels is one and they all have the same dimensions. The experimental results obtained from second and third plate girders have been compared with those obtained from the reference plate girder. The comparison indicates that the reduction in the ultimate shear load for plate girder with web opening is 51% and for the plate girder with reinforced web opening is 35%. Also through the experimental results, new formulas are presented to predict the ultimate shear load of perforated steel girders with large openings.

A nonlinear finite element analysis is carried out for the tested plate girders using the package software program (ANSYS V.11). The analytical results contain the ultimate shear capacity and Von Mises stress distribution. The results of finite element models are compared with results of experimental tests. The difference in ultimate shear load was 10%, 9% and 1.5% for plate girders GO, GOR and G, respectively. Also a parametric study with varying size of the reinforcement around the web openings is performed by using the ANSYS program, and it is found that the thickness of the reinforcement strip has higher effect than its width on the ultimate shear capacity of perforated plate girder.

Keywords: Steel plate girder, web opening, Reinforced web opening, ANSYS.

تصرف العوارض اللوحية الفولاذية ذات الوترات المثقوبة المحملة بقوى القص

الخلاصة

تم دراسة التصرف الانشائي لثلاث عوارض لوحية فولاذية محملة بقوى القص. الاول هوالعارضة اللوحية المرجع (G) والتي هي خالية من الفتحات, والثانية (GO) تحتوي على فتحات دائرية ذات مراكز

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

متطابقة مع مراكز وترات اللوحات, قطر الفتحات ٦٠% من عمق الوتره, والعارضة اللوحية الثالثة (GOR) تحتوي على فتحات دائرية مسلحة بشرائح فولاذية تم لحمها حول الفتحات. النسبة الباعية (نسبة العرض الى العمق) لكل لوحة هي واحد وجميعها تمتلك نفس الابعاد. تم مقارنة نتائج الفحص العملي للعوارض اللوحيه الثانية و الثالثة مع العارضة اللوحية المرجع. اظهرت المقارنة النقصان في تحمل العارضه الفولاذية ذات الفتحات بما يعادل ٥١% و العارضه الفولاذية ذات الفتحات المسلحة بما يعادل 35%. كذلك من خلال النتائج العملية, تم استنتاج معادلات لمعرفة مقاومة القص القصوى للعوارض اللوحيه الفولاذية ذات الفتحات الكبيرة.

تم انجاز تحليل لاخطي للعوارض اللوحية المفحوصة مختبريا باستخدام البرنامج الجاهز (ANSYS V.11). حيث تضمنت نتائج التحليل ايجاد قوة القص العظمى و توزيع اجهادات Von Mises. اجريت مقارنة لنتائج تحليل البرنامج مع النتائج المستحصلة من الجانب العملي. أظهرت نتائج المقارنة أن الفرق في الحمل الاقصى كان ١٠% ,9% و ١,٥% للعوارض اللوحيه الفولاذية (GO) , (GOR) و (G) على التوالي. كذلك تم دراسة تأثير تغيير حجم شريحة التسليح حول فتحات الوترات بواسطة برنامج ANSYS. وقد أظهرت نتائج الدراسة ان سمك شريحة التسليح حول الفتحات له تأثير اكبر من عرضها على مقاومة القص القصوى للعوارض اللوحية المثقوبة .

INTRODUCTION

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. Therefore, a reinforced strip around the circular opening is added to reduce the stress concentration around the opening and to increase the ultimate shear load.

In recent years, a great deal of progress has been made in the analysis of both steel and composite steel- concrete plate girders with web openings due to the need for inspection and maintenance and economic considerations [1, 2, 3, 4].

In general, the shear capacity for un-perforated plate girder is composed of three components: the buckling strength, the post- buckling tension field that is supported by the transverse stiffeners and the third component represents the contribution of the flanges.

EXPERIMENTAL WORK

Steel properties

The yield stress and the ultimate stress for the steel used for the flanges, webs and reinforcing strips, are obtained from the tensile test and are summarized in Table (1). The modulus of elasticity, E, is 197000 MPa and the Poisson´s ratio, ν, is assumed to be 0.3.

Details of the tested girders

The tested girders G, GO and GOR are shown in Figure (1). Each of the three girders has a span of one meter with two panels. The distance between the two vertical stiffeners in the girder, b, is 500 mm. The distance between the top and bottom flanges, d, is 500 mm. 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 (2). These dimensions are the true measured values. The aspect ratio of each panel (width to depth ratio) is one for all tested girders. The slenderness ratio of the three girders (depth to thickness of web) is 250. The diameter of the openings is 300mm.

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

Reinforcement around the openings is provided to recover the strength reduction of the web due to the opening. Reinforcing strip has a constant thickness of (2 mm). The area of each strip is equal to the area of the steel of the opening which is cutout from the web panel, thus the width of the reinforcement is equal to,

$$\textbf{Width of the strip } (W_s) = \frac{\text{area}}{\text{perimeter}} = \frac{\pi r^2}{2\pi r} = \frac{150}{2} = 75 \text{ mm}$$

The strip is welded on both faces of the web plate with a continuous welding.

Instrumentation and Testing procedure

Tests were carried out using a testing machine "AVERY" at the structural laboratory in the University of Technology. The maximum load capacity of the machine is 2500 kN, which can be applied by hydraulic pressure. The load was applied to the mid-span of the simply supported plate girder, and it was distributed across the width of the top flange. The applied load is automatically shown on a large dial contained in the indicator cabinet of the testing machine.

The deflections of all girders were obtained with dial gauge of 0.01mm accuracy. Dial gauge for deflection measurement was installed under the bottom flange at the mid-span of girder, and the deflection was read at every increment of load of 5 kN.

The test was terminated when the girder had shown collapse at the web panel and flanges or when considerable deformation had occurred at web openings with increasing mid-span deflection. After the girders had failed, the load was removed.

Experimental results

All girder specimens failed in shear. The ultimate failure shear loads for the tested girders are given in Table (3). The deformed shapes of the tested girders are shown in Figure (2).

As a comparison, the shear load- mid span deflection curves for all the tested girders are shown in Figure (3). The plots for the three girders remain linear until the critical buckling shear load. After this stage the plot for the plate girder (G) behaves nonlinearly within the post buckling stage, and the shear load increased by forming the tension field at web panel which is adequately resisted by transverse vertical stiffeners and the flanges. The panel reached its ultimate failure shear load by forming plastic hinges at top and bottom flanges.

The plot for girder (GO) in Figure (3), has also nonlinear behavior after the critical buckling shear load. At the post buckling stage the tension field action cannot develop adequately as a result of the large removed area from the web. The moment capacity of the flanges at the four corners of the panel share in improving the shear capacity of this panel by forming the plastic hinges and reaching to its failure shear load. Thus, the ultimate shear load of plate girder (GO) is less than that for plate girder (G).

The plot for plate girder (GOR) behaves similar to plate girder (G) but with less stiffness and less failure shear load, Figure (3). The shear load- deflection curve of this girder is linear up to initial buckling, then the web panel develops tension field action better than plate girder (GO) due to the reinforced strip around the circular opening, thus

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

there is considerably increase in shear resistance than girder (GO), and forming the final collapse of the panel within the plateau region.

PROPOSAL FOR ESTIMATING ULTIMATE SHEAR LOAD OF PERFORATED PLATE GIRDERS

The ultimate shear capacity of plate girder without web opening loaded in shear can be obtained as follows [5]:

$$V_{ult.} = (\tau_{cr}) d\, t_w + \sigma_t^y\, t_w \sin^2\theta\, (d \cot\theta - b) + 4\, d\, t_w \sin\theta \sqrt{\sigma_{yw}\, \sigma_t^y\, Mp^*} \quad \dots (1)$$

Where

$$M_p^* = \frac{M_{pf}}{d^2 \sigma_{yw}\, t_w}$$

Although the experimental work was limited and more experimental results are needed, equations to predict the ultimate shear strength for plate girder (GO) and plate girder (GOR) have been proposed as follows:

Shear resistance of plate girder (GO)

The method that used to determine the ultimate shear load for un-perforated plate girder, from Equation (1), can be modified to be used for a perforated web plate girder with small openings as follows [1, 2]:

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

$$\kappa_O = \kappa\left(1 - \frac{d_h}{d}\right) \quad \dots (2)$$

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

$$(\tau_{cr.})_O = \kappa_O \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t_w}{d}\right)^2 \quad \dots (3)$$

2. The value of the yielding tensile membrane stress is:

$$\sigma_t^y = \sqrt{\sigma_{yw}^{\,2} + (\tau_{cr})_O^2 \left(\frac{9}{4}\sin^2 2\theta - 3\right)} - \frac{3}{2}(\tau_{cr})_O \sin 2\theta \quad \dots (4)$$

3. The critical load of the web plate can be expressed as :

$$(V_{cr.})_O = (\tau_{cr})_O\, d\, t_w \quad \dots (5)$$

4. The post-buckling shear capacity is:

$$V_{post.} = \sigma_t^y\, t_w \sin^2\theta\, (d \cot\theta - b) + 4\, d\, t_w \sin\theta \sqrt{\sigma_{yw}\, \sigma_t^y\, Mp^*} \quad \dots (6)$$

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

The presence of large opening in web panels, such in plate girder (GO), the post-buckling shear capacity ($V_{post.}$) has a reduction due to the discontinuity in the tension field, as observed through the experimental work, thus:

$$(V_{post.})_O = 0.5 * V_{post.} \qquad \dots (7)$$

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

$$(V_{ult.})_O = (\tau_{cr})_O \, d \, t_w + (V_{post.})_O \qquad \dots (8)$$

Shear resistance of plate girder (GOR)

The presence of a web opening cause loss in plate girder's strength and that is unacceptable, so the web opening will need to be reinforced around its periphery to recover its strength. It would then be necessary to estimate the strength of the reinforced web, and it may be given by:

1. The adjustment for the buckling coefficient is obtained by adding a term representing the contribution of the reinforced strip which is the ratio of the area of reinforced strip to the area of the web. Thus, (k_{OR}) can be defined as:

$$k_{OR} = 5\, k_O * \frac{A_{Rein.}}{A_w} \qquad \dots (9)$$

Where:

$A_{Rein.}$ is the area of the circular reinforced strip (π d_h* W_s).

W_s is the width of reinforced strip.

A_w is the area of web plate (the width X the depth).

2. The modified critical shear stress can be expressed as follows:
3.

$$(\tau_{cr})_{OR} = k_{OR} \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t_w}{d}\right)^2 \qquad \dots (10)$$

4. The yielding tensile membrane stress σ_t^y is,

$$\sigma_t^y = \sqrt{\sigma_{yw}{}^2 + (\tau_{cr})_{OR}^2 \left(\frac{9}{4}\sin^2 2\theta - 3\right)} - \frac{3}{2}(\tau_{cr})_{OR} \sin 2\theta \qquad \dots (11)$$

5. The critical load of the web plate can be expressed as :

$$(V_{cr})_{OR} = (\tau_{cr})_{OR}\, d\, t_w \qquad \dots (12)$$

The presence of large opening with reinforcement in the web panel causes a reduction in post-buckling shear capacity less than the opening without reinforcement, according to the observation through the experimental work, therefore:

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

$$(V_{post.})_{OR} = 0.75 * V_{post.} \quad \dots (13)$$

5. The ultimate collapse shear load for girder (GOR) is obtained as follows:

$$(V_{ult.})_{OR} = (\tau_{cr})_{OR}\, d\, t_w + (V_{post.})_{OR} \quad \dots (14)$$

FINITE ELEMENT MODELING

Element Geometry

Eight nodes shell element (SHELL93) is used for the finite element analysis through the software ANSYS Version 11. This element has plasticity, stress stiffening, large deflection, and large strain capabilities. The element has six degrees of freedom at each node: translations in the nodal X, Y, and Z directions and rotations about the nodal X, Y, and Z axes.

All girders are modeled as simply supported and constrained from the movement in Z- direction. 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 (4).

Material properties which have obtained from the experimental work for all three girders are adopted in this present analysis. These properties are given in Table (4).

Analysis results

For plate girder (G), the Von Mises stress distribution, which is shown in Figure (5), describes the distribution of the stresses at the web panels. The highest stress concentrates underneath the top flange and adjacent to the intermediate transverse stiffener with value of 290.513 MPa.

The Von Mises stress distribution for plate girder (GO) is displayed in Figure (6). It can be noted from this distribution that there are four zones around the opening edge at which the stresses are high. This indicates that these four positions have the highest strains or highest deformations.

For plate girder (GOR), Von mises stress distribution is plotted in Figure (7). It can be observed that the four zones of high stresses are appears at the circular reinforcement strip, and not within the web panel. Each zone has less area than that at (GO), which indicates less strain has taken place.

Parametric study

The present section assesses the ultimate shear load due to varying the cross-sectional size of the circular reinforcement:

1- Effect of the various width of reinforced circular strip (W_s) with constant thickness 2mm: It can be noted that the effect of the width size of the circular reinforced strip on increasing the ultimate shear load is more pronounced from 5mm up to 25mm; and when the width size ranges from 65mm up to 95mm the ultimate shear load of the reinforced perforated plate girder is almost constant, Table (5) and Figure (8).

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

2- Effect of the various thickness of reinforced circular strip (t_s) with constant width 75 mm: It can be noted from Table (6) and Figure (9) that the two models at which the thickness t_s= 0mm and t_s= 2mm have the highest increasing rate in ultimate shear load. However, the increased thickness for the reinforcing strip has a continuous effect in increasing the ultimate shear load for the reinforced perforated plate girder.

CONCLUSIONS

1. Experimental work confirms the general idea that the presence of central openings decreases the shear strength of steel plate girder. Therefore, the web panel of plate girder (GO) shows large deformation under lower shear load.
2. The presence of web opening causes loss in strength, due to lack in the resistance in web panel against out of plane deformation. The reduction in strength due to the presence of circular cutout which has diameter 60% of the web depth, is 51%.
3. In the web panel of plate girder (GOR), the reinforced strip recovers the shear strength of this girder. The reinforcement around circular opening increases the strength by 32% compared to similar panels with circular cutout without reinforced strips.
4. Depending on the results from the program analysis, the Von Mises stress distribution concentrates at the web opening edges of plate girder (GO) in four zones. In plate girder (GOR) these stresses concentrate at the reinforced strip with less intensity.
5. It can be noted from the parametric study that the effect of the thickness of the reinforcing strip around the opening is greater in increasing the shear strength than the width; this is may be due to the larger effect of thickness than the width on the value of moment of inertia of reinforced strip section, and subsequently increasing in the web stiffening.

6. Through a comparison for the results of the ultimate shear load obtained from laboratory tests with those obtained from the design equations and from the finite element analysis, Table (7), it can be observed that there is a good agreement between them.

REFERENCES

[1].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.

[2].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.

[3].N. E. Shanmugam, and K. Baskarb, "Ultimate load behavior of webs in steel-concrete composite plate girders", The IES Journal Part A: Civil & Structural Engineering, 1:2, pp. 123 - 140, January 2008.

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

[4]. M. Hamoodi, and W. Hadi, "Tests of composite beams with web openings", Engineering and technology Journal, Vol. 29, No.10, pp. 2073-2086, May 2011.

[5].K. Rockey, H. Evans, and D. Porter, "A design method for predicting the collapse behavior of plate girders", proceedings institution of civil engineers, Part 2, pp. 85-112, March 1978.

NOTATIONS

A_w	The area of web plate.
b	The clear distance of the web plate between vertical stiffeners, mm.
b_f	The width of flange plate, mm.
d	The depth of the girder, mm.
d_h	Diameter of the opening, mm.
E	Modulus of Elasticity, MPa.
H	The clear web height between flanges, mm.
K	The buckling coefficient.
k_o	The buckling coefficient for web with opening.
k_{OR}	The buckling coefficient web with reinforced opening.
Mp_f	The plastic moment capacity of the flange, N.mm.
M_P^*	Non- dimensional flange strength parameter.
r	Radius of the opening, mm.
t_w	The thickness of web plate, mm.
t_f	The thickness of flange plate, mm.
t_s	The thickness of reinforced strip, mm.
V_{cr}	The critical shear capacity, N.
V_{ult}^{m}	The post buckling shear capacity, N.
$V_{ult.}$	The ultimate shear strength, N.
W_s	The width of reinforced strip, mm.
N	Poisson´s ratio.
σ_y	The yield stress of steel material, MPa.
σ_{yw}	The yield stress of the web material, MPa.
σ_t^y , σ_t	Tensile membrane stress, MPa.
σ_u	The ultimate stress of steel material, MPa.
τ_{cr}	Critical shear stress, MPa.
Θ	The angle of inclination of the membrane stress field.
θ_d	The yield stress of the flange material, MPa.

Table (1) Material properties of the girders.

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

Component	Thickness (mm)	σ_y (MPa)		σ_u (MPa)	
Flange and vertical stiffener	6	232	228	351	350
		228		347	
		226		353	
web and reinforced strip	2	301.02	289	343.21	343
		277.8		343.20	

Table (2) Dimensions and details of the tested girders.

Girder	Web details			Flange Details		Parameters		
	b (mm)	d (mm)	t_w (mm)	b_f (mm)	t_f (mm)	b/d	d/t_w	Mp* x 10^{-5}
G	500	500	2	120	6	1	250	170
GO	500	500	2	120	6	1	250	170
GOR	500	500	2	118	6	1	250	167

Table (3) Experimental results.

Girder	Ultimate shear load ($V_{Exp.}$) (kN)	Reduction in ultimate shear load (% of G)
G	101	----
GO	50	51%
GOR	66.15	35%

Table (4) Material properties adopted in the ANSYS program analysis.

Steel plate girders parameters	ANSYS symbols	Value	Units
Thickness of web plate	TK (Thickness of shell layer)	2	mm
Thickness of flanges	TK (Thickness of shell layer)	6	mm

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

Modulus of elasticity	EX	200000	MPa
Poisson's ratio	PRXY	0.3	-----
Yield stress for web plate	Yield Stss	289	MPa
Yield stress for flange plates	Yield Stss	228	MPa

Table (5) Ultimate shear load for various width of the circular reinforced strip.

Width of reinforced strip (W_s)(mm)	Thickness of reinforced strip (t_s) (mm)	Ultimate shear load (V_{ANSYS}) (kN)
0	0	45
75	2	60
75	4	63
75	6	65.5
75	8	71
75	10	72
75	12	75

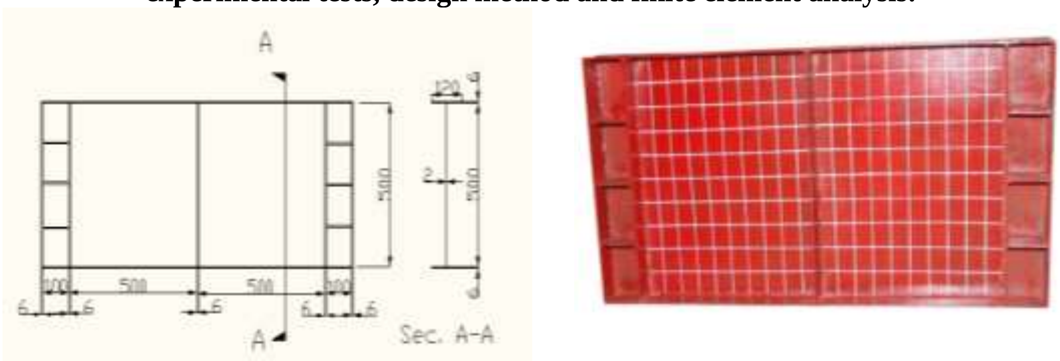
Table (6) Ultimate shear load for various thickness of circular reinforeed strip

Plate girder	$V_{Exp.}$ (kN)	Equation number	Predicted ultimate shear load $V_{Ult.}$ (kN)	V_{ANSYS} (kN)	$\frac{V_{Ult.}}{V_{Exp.}}$	$\frac{V_{ANSYS}}{V_{Exp.}}$
G	101	Eq. (1)	95.442	102.5	0.94	1.015
GO	50	Eq. (8)	47.55	45	0.95	0.9
GOR	66.15	Eq. (14)	69.2	60	1.04	0.91

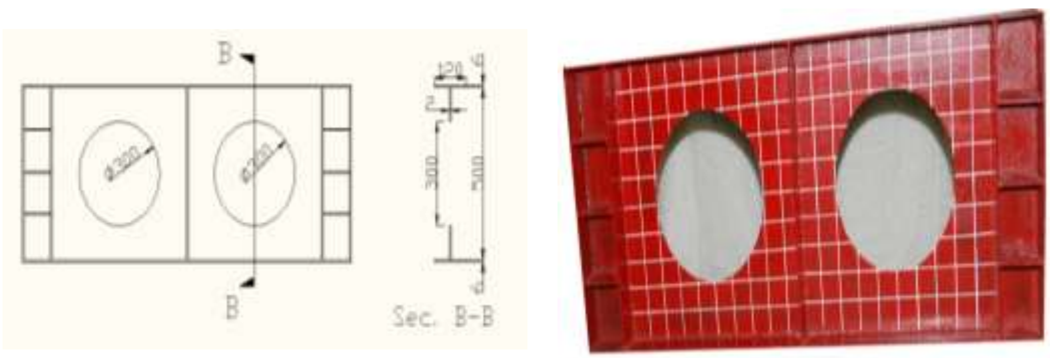
Thickness of reinforced strip (t_s) (mm)	Width of reinforced strip (W_s)(mm)	Ultimate shear load (V_{ANSYS}) (kN)
2	95	61
2	85	60.5
2	75	60
2	65	59.5
2	55	59
2	45	58.5
2	35	58
2	25	57
2	15	55
2	5	51
0	0	45

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

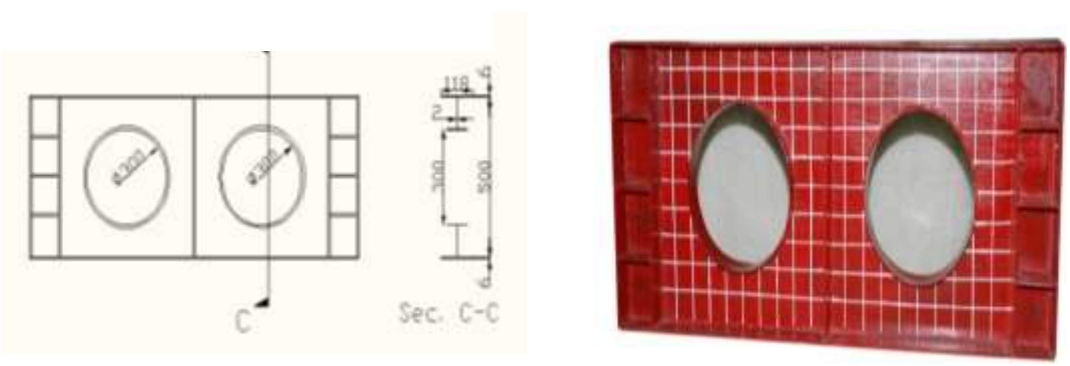
Table (7) Comparisons of ultimate shear strength obtained from experimental tests, design method and finite element analysis.



A)Plate girder without web openings(G)



B) Plate girder without web openings (G)
A) Plate girder with web openings (GO)



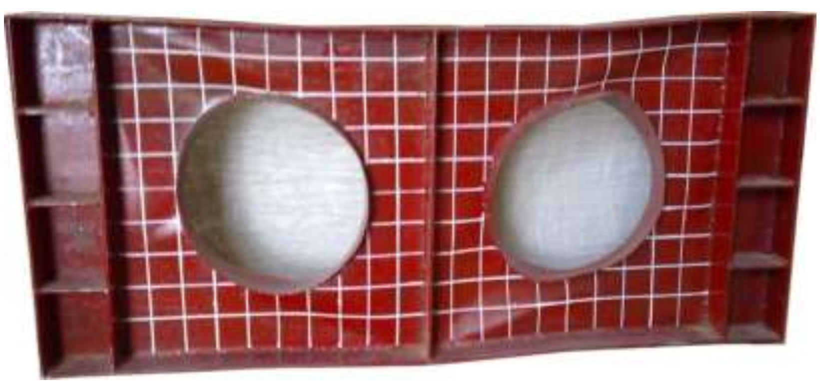
C) Plate girder with reinforced web openings (GOR)

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

Figure (1) Dimensions and details of the tested plate girders.

A) Plate girder with web openings(G)

B)Plate girder with web openings(GO)



C) Plate girder with reinforced web openings (GOR)

Figure (2) Plate girders at failure.

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

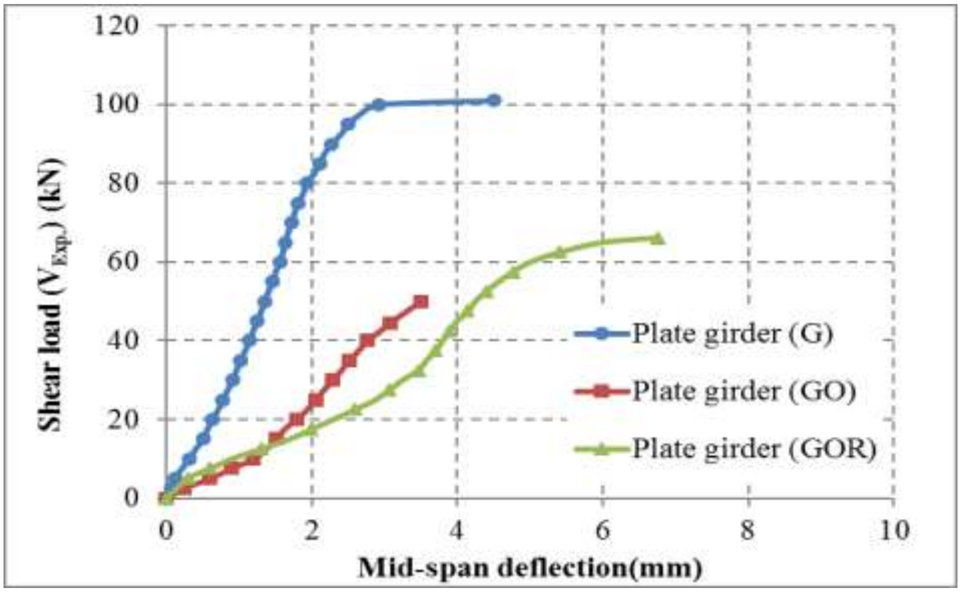
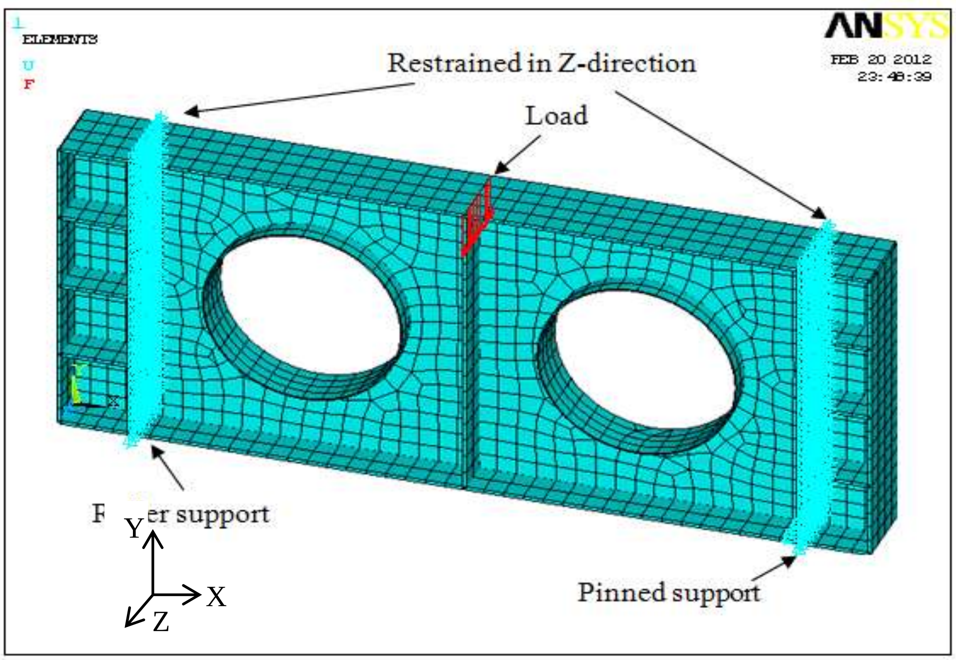
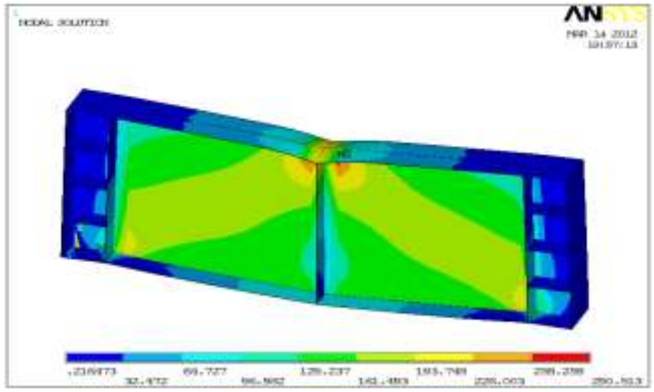


Figure (3) Shear load –mid span deflection curves for all tested panels.

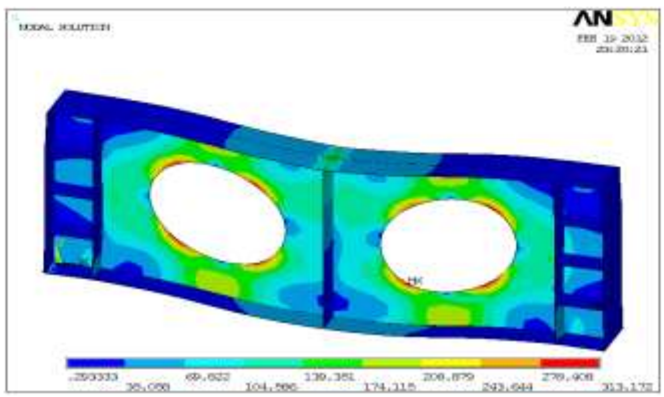


Figure(4): Mesh modeling with the boundary conditions created for the girders

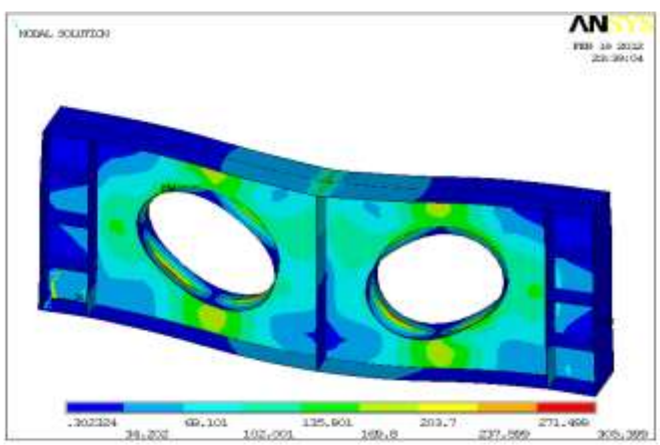
https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq



Figure(5): von Mises stress distribution of plate girder (G) at failure



Figure(6): Von Mises stress distribution of plate girder (GO) at failure



Figure(7): Von Mises stress distribution of plate girder (GOR) at failure

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

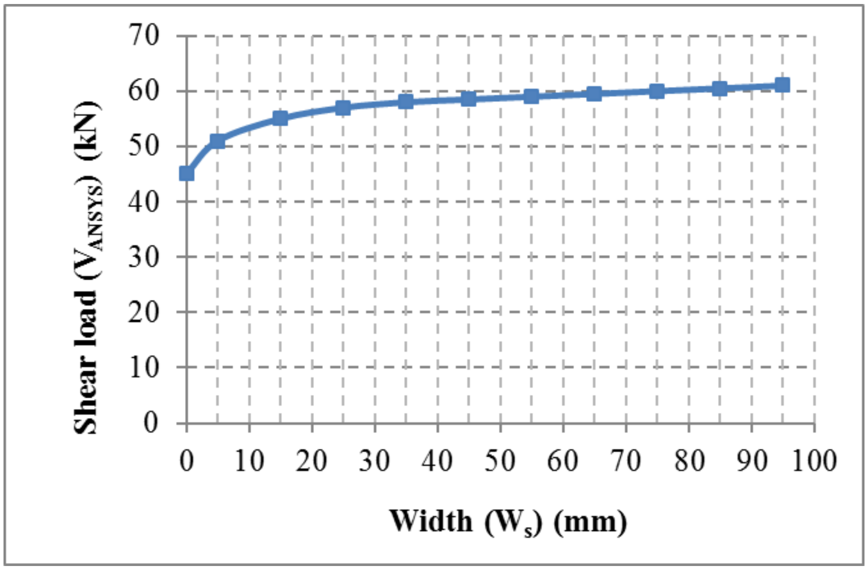


Figure (8): Shear load- width of the circular reinforced strip (W_s) relationship

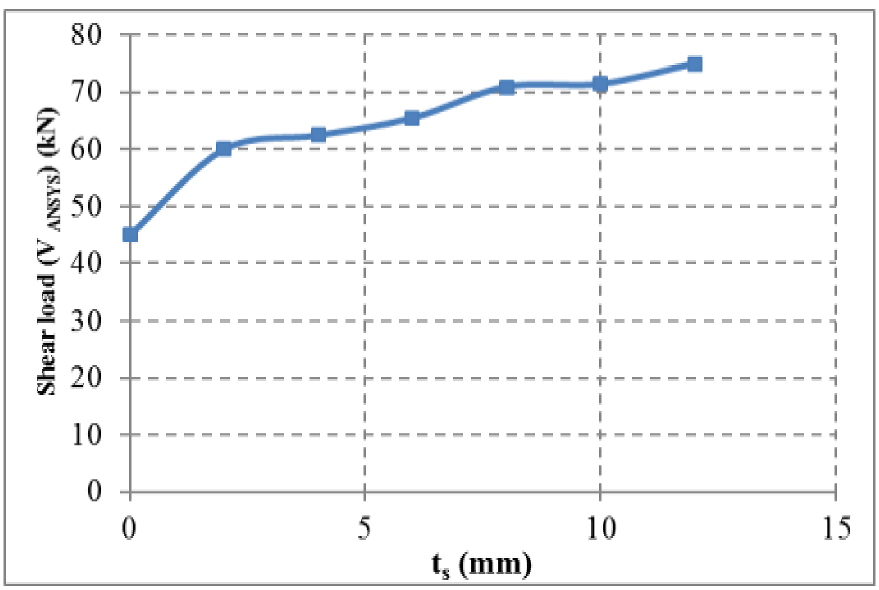


Figure (9): Shear load- thickness of the circular reinforced strip (t_s) relationship

https://doi.org/10.30684/etj.31.15A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq