Behavior of Steel Plate Girders with Web Opening Subjected to shear conditions

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Abstract

The structural behavior of steel plate girders with web opening is investigated in this study. An experimental and theoretical investigation of plate girders with different types of openings in the web was conducted. Two types of web opening is investigated (square & circular) opening. The experimental work included testing of seven plate girder specimens under two point loads. Three specimens were tested to observe the influence of the circular web opening. The influence of the presence of square web openings was studied by testing other three specimens. While the last one was tested without opening as a reference (control) specimen. These specimens had the same dimensions. From experimental results the ultimate load of girders decreases with increasing opening size, and the position of plastic hinge depends on the size of hole A nonlinear 3D finite element model was deveioped using FE program ANSYS to validate the experimental results

Four- nodes shell element (SHELL 181) was used to represent the steel plate. The proposed finite element model was used to study the effect of web slenderness on shear resistance of plate girder with web opening. Equation was suggested to predict the shear resistance. The analysis study give good agreement with experimental work.

Keywords: Steel plate girders, web opening, experimental and finite element method.

تصرف العتبات الحديدية التي تحتوي على فتحات والمعرضة الى أجهاد القص

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الخلاصة

التصرف الانشائي للعتبات الخرسانية التي تحتوي على فتحات تم دراستها في هذا البحث . حيث تم اجراء الدراسة العملية والنظرية للعتبات الحديدية التي تحتوي على انواع مختلفة من الفتحات في منطقة (wep) حيث هناك نوعين من الفتحات تم دراستها (النوع الدائري والمربع). الدراسة العملية تتضمن فحص سبع عتبات تحت تأثير حمل يتم تسليطه على شكل نقطتين . ثلاثه من هذه العتبات تم فحصها لإيجاد تأثير الفتحات الدائرية الموجودة في (wep) . تأثير الفتحات المربعة الموجودة في منطقة ال (wep) تم دراستها بثلاث نماذج الاخرى . اما بالنسبة للعتب المتبقي تم فحصه بدون وجود اي فتحه يعتبر كمرجع . هذه العتبات صممت لتكون لها نفس الابعاد . نتائج العملية بينت ان الحمل الاقصى للعتب يقل بازدياد الفتحة وحجمها ومكانها . تم اجراء التقصي النظري باستخدام برنامج (ANSYS version) وتم استخدام (shell181) لتمثيل العتب الحديدي حيث ان اقتراح النموذج باستخدام ANSYS version كان الغرض منه لدراسة نحافة ال wep في منطقة ال shear الموجودة في العتب الحديدي المصاحب لوجود الفتحات .تم اقتراح معادله للتنبؤ بمقاومة القص , الدراسة النظرية اثبتت نجاحها وقربها من الدراسة العملية .

Notations

b panel web wide (mm)

d web deep (mm)

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bf flange wide(mm)
Ao area of circle or square opening (mm)
tf flange thickness (mm)
tw web thickness (mm)

1. Introduction

A plate girder is a assemblage of many steel plate and welded it to make beam with large depth to achieve more efficient arrangement of material than is possible with rolled steel sections[1].

There are many forms of instability, shear buckling of web, compression buckling of webs, lateral-torsional buckling of girders and local buckling and crippling of webs are considered in the design procedures.

Web plate is slender so that it buckle at the early stages of the loading, therefore, the shear buckling and failure of web elements is one important design aspect of plate girders. The stress causes buckling of a web can be calculated from the theory of plate buckling. After buckling of the web, the stress distribution in the web changes and additional post buckling strength is mobilized [2].

The behavior of a plate girder subjected to a shear load may be divided into three stages as shown in Figure (1).The first stage is prior to buckling, tensile and compressive principal stresses are equal and develop in the plate as shown in Figure (1-a). The second stage is post-buckling, no more increase in compressive stress and only an inclined tensile membrane stress field is developed, as shown in Figure (1-b). The value of σt at which yield occurs is identified as the basic tension field strength failure of the girder occurs when of the girders, as shown in Figure (1-c). The collapse mechanism is the third stage in which the girder faille by forming four plastic hinges in the flange [3 , 4].

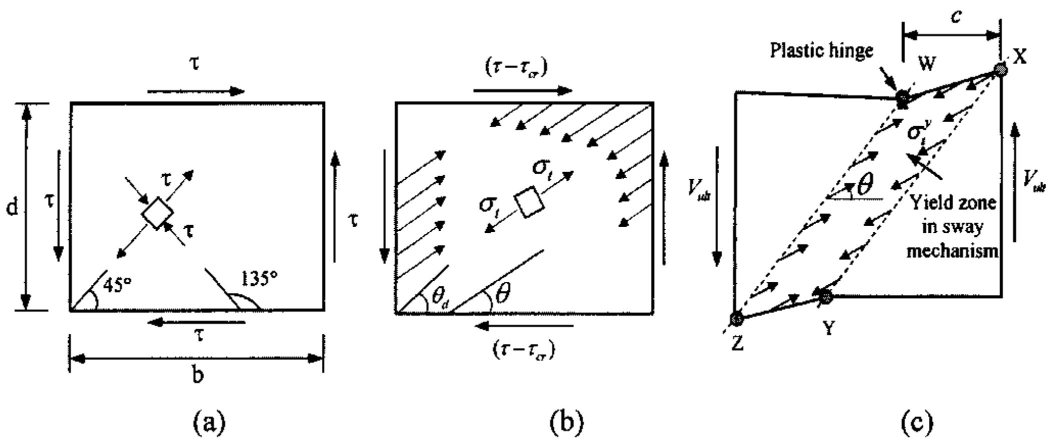


Figure (1): Stages of girder behavior (a) Unbuckling behavior (b) Post-buckling behavior (c) Collapse behavior[2].

2. Openings in webs

In some cases, make Openings in the web of plate girders to facilitate inspection and for providing service. Presence of openings in a web cause distribution of stress within the member and lead to reduce in its strength and stiffness[5].

Hoglund (1971)[6] studied the effect of the presence of rectangular and circular holes in the thin web of plate girders subjected to static loading. This study showed making holes in webs reduces in shear capacity of plate girder. Also, flexural capacity of girder reduce when web have openings by approximately 2 to 5%, Baranda et al. (1978)[7] , that is because of reduction in bending stresses. But flexural capacity does not significant reduce when openings less than 30% of the section height, Redwood and Shrivastava (1980)[8]. Narayanan and Der Avanessian (1984)[9] studied the effect of the reinforced of openings on the ultimate capacity of plate girders. Hamoodi and Hadi (2011)[10] studied the behavior of of simply supported composite beams, in which the steel I-beam have opening in the web. Hamoodi and Abdul Gabar (2013)[11] presented an experimental study to investigate the behaviour of circular opening at the center of plate girder and the effect of the installed of a reinforced strip around that circular opening on the ultimate shear load.

3. Aim of the study

The objective of the work reported in this study is to assess the effectiveness of the hole in the web. The following parameters were considered in this study: (a) hole size and (b) hole shape (circular or square). The study divide in to two groups; the first group is to investigate experimentally seven simply supported plate girders with web opening. The second group deals with a nonlinear finite element analysis which has been carried out to analyze the plate girder specimens. The software ANSYS version 12.0, is used to model the plate girder specimens. The validity of the used analysis is examined with the results of the experimental work.

4. Experimental investigations

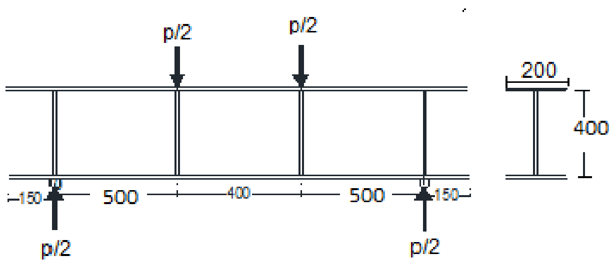
4.1 Details of test specimens

Seven plate girder specimens were tests in this study. Group A contain three specimens has circular opening and group B contain three specimens with square opening while one of the specimen as a control specimen. The depth 400 mm and the flanges is 200 mm with thickness of 7 mm (tf) while web thickness is 2 mm (tw) for all girders. Table (1) summarized the dimensions of girders and the girders details are shown in Figure (2). The study was carried out for three different size opening, the ratio of opening area to web area Ao/Aw equal to 0.18, 0.34 and 0.51. The average yield stress and modulus of elasticity of the steel plate are 258 MPa and 221000 MPa, respectively, which were measured by testing three tensile coupons.

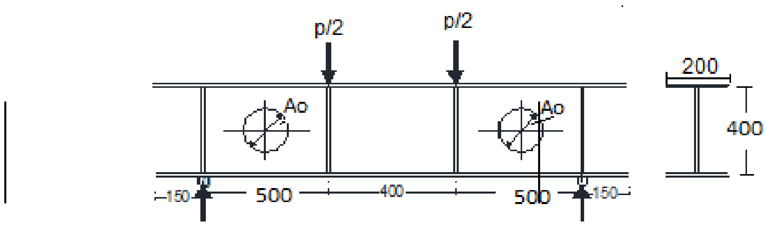
Table (1): Details of the tested plate girders

Groups	Girders designation	Opening Shape	Ao Cm2	Ao/Aw
Control	Po	----	----	----
A	PC1	Circle	19.6	0.18
	PC2		78.5	0.34
	PC3		176.6	0.51
B	PS1	Square	19.6	0.18
	PS2		78.5	0.34
	PS3		176.6	0.51

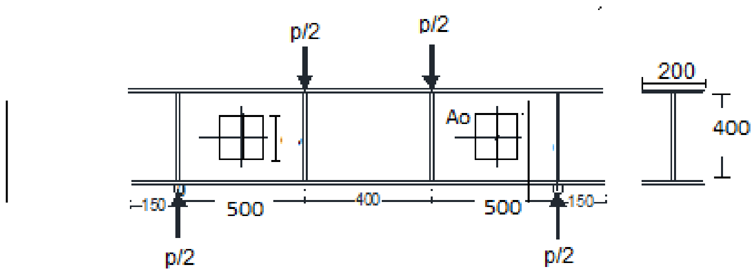
- A_o is an area of circle or square.



a) solid web plate girder (control specimen(Po)),Dimension in (mm)



b) plate girder with circular web openings(PC1, PC2, PC3),Dimension in (mm)



c) plate girder with square web openings(PS1, PS2, PS3),Dimension in (mm)

Figure 2: Dimensions and details of plate girders

4.2 Test procedure

For testing, Torsee's Universal Testing Machine with a capacity of 200 ton was used, as shown in Figure (3). Vertical deflection at the beam mid-span was measured by using a dial gauge(put at the center of beam) with accuracy 0.01 mm.

The girders were tested as simply supported under two point loading. The load was static and gradually increased up to failure. When the total load started to drop off the test was terminated.

Figure (3): Test setup (Al-Basrah university lab)

5. Experimental results and discussions

The load on beams was applied monotonically in increments. The ultimate load of the girder represents the maximum load recorded by the testing machine. Experimental results of specimens are presented in Table (2) and Figure (4) shows mode failure.

Table (2): Results of tested girders.

Groups	Girders	Experimental ultimate load Pult (kN)	Puo/Pus
Control	PO	138	----
A	PC1	108	0.77
	PC2	68	0.49
	PC3	38	0.27
B	PS1	92	0.66
	PS2	55	0.39
	PS3	26	0.19

●P_{us} is the ultimate load of the girders with solid web(control specimens).

●P_{uo} is the ultimate load of girders which have opening.

a) Beam B0 (left support

b) Beam BC1(left support)

c) Beam BC2 (Right and left support)

d) Beam BC3 (left support)

e) Beam BS1(Right support)

f) Beam BS2 (Right support)

g) Beam BS3(Right support)

Figure (4): Specimens after failure

We can showed that the mode failure of the solid web and web with small opening area is similar for both circular or square shape (Po, PC1 and PS1). Shear failure, as shown in Figure (5), located approximately along the diagonal of the web and the plastic hinge formed at the webs and close to the stiffeners, see Figures (5-a, 5-b and 5-c). While the shear failure located at angle approximately 45 degree with horizontal line (as schematically shown in Figure (6)) for girder with large opening area in its web (Ao/Aw=0.34 and 0.51), see Figure (5-c,d,f,and g). The plastic hinge formed away from the stiffeners. This mean that the location of plastic hinge is associated with the size of opening in the web.

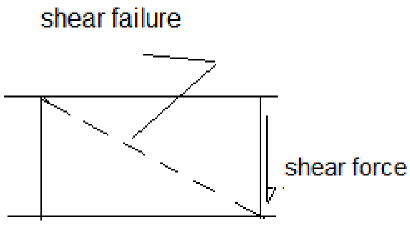
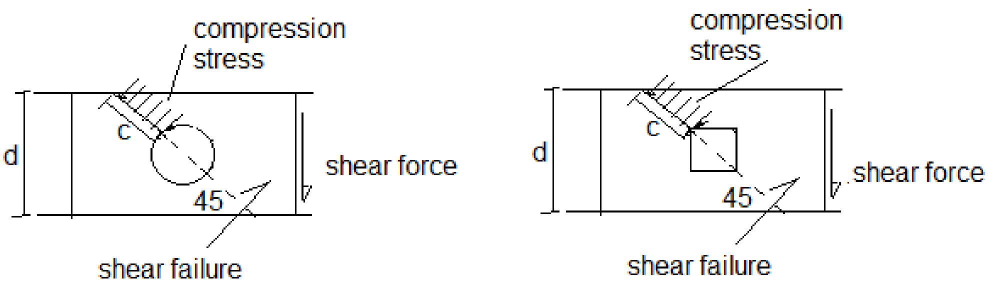


Figure (5): Explain shear failure line



(a) Circular opening **(b) Square opening**

Figure (6): Shear failure pattern for opening web

From the failure mode of the girder with square opening (results by Ansys) it can be noted that, the stress concerted at edges of the opening. Therefore, the corners of square openings are more susceptible to crack.

The results of Table (2) indicate that the presence of opening in the web leads to decrease the ultimate load and the ultimate load decreases as the size of opening increases. This leads to reduce the strength of web against the buckling and the beam will fail early.

The experimental results of the ultimate load were plotted versus the mid span deflection for selected girders. Figure (7) shows load deflection curves for girders PO, PC2, & PS2.

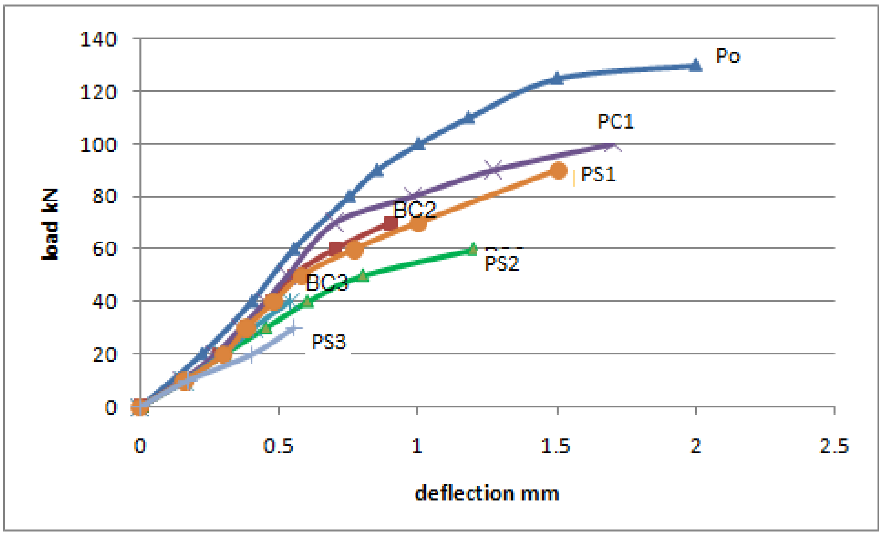


Figure (7): Load-deflection curves of specimens

These curves are noted all girders remain linear until the critical buckling load occurs then post buckling stage starts. At this stage, the curve of the beam PO becomes nonlinearly, and the load increases by forming the tension field at web panel. And form plastic hinges at top and bottom flanges. Also, beam PC2 becomes nonlinear behavior after the critical buckling load and post buckling occur, the tension field action cannot develop adequately as a result of the large removed area from the web. So that, beam PC2 fail in load less than that of beam PO. Behavior of PS2 is similar to that of beam PC2.

Finite element analysis

Finite element (FE) analysis(nonlinear) were constructed by ANSYS Version 12.0 program for all tested specimens. Properties of material which were used in program are same as used in experimental work. Plate girders were modeled by SHELL181 element with dimensions of 1 x 1 mm. This element is suitable for analyzing 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 welding area is represented as rigged conection. Because the symmetry of the girders, half specimen was used in the program, as shown in Figure (8). Table (3) re[resents the analytical failure load of specimens. Figures (9) and (10) shows typical comparison load deflection and mode of failure of the specimens(Po, PC1, PC3 and PS3), respectively.

From all results, we conclude that the finite element modeling is able to predict buckling and ultimate load with sufficient accuracy.

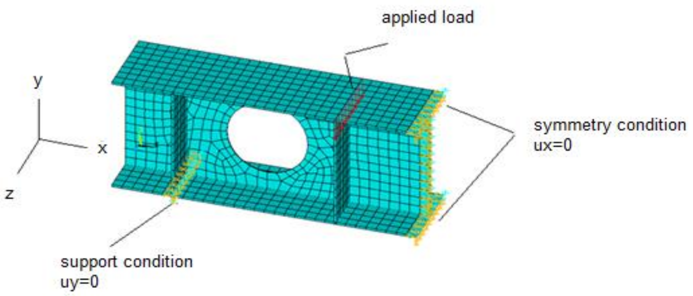
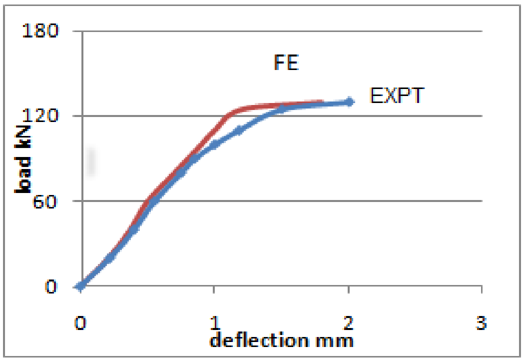


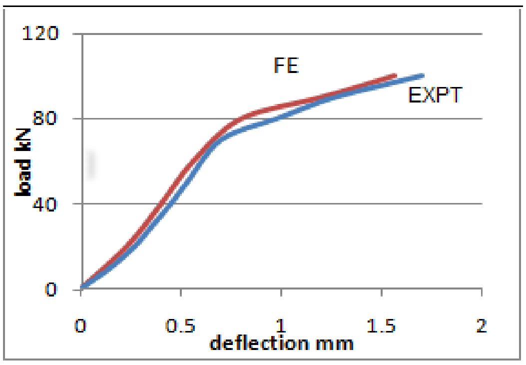
Figure (8): The FEA model corresponds to which test specimen, please include.

Table (3): Finite element results

Groups	Girders	Analytical ultimate load PFE (kN)	PFE / Pult
Control	PO	151	1.10
A	PC1	184	1.07
	PC2	76	1.12
	PC3	44	1.16
B	PS1	98	1.06
	PS2	63	1.15
	PS3	30	1.17

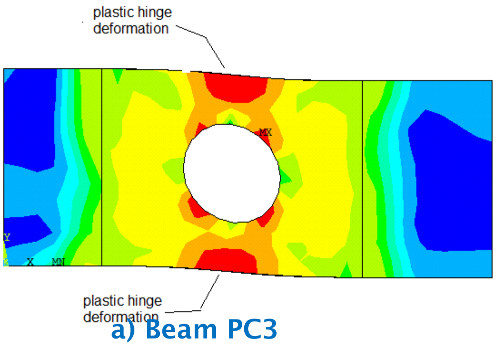


a) Beam Po

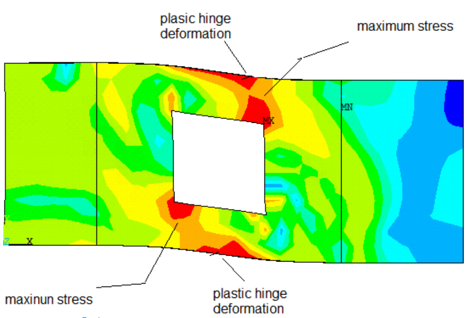


b) Beam PC1

Figure (9): Typical load deflection curves



a) Beam PC3



b) Beam PS3

Figure (10): Von Mises stress

6. Parametric study

Different values of web slenderness were studied using the numerical model developed in this study.

Same material properties were employed for all models. Ten girders were analyzed, five of them are solid web and other five has circular opening with area 176.6 cm2.

Table (4): Effect of web slenderness ratio on ultimate loads

tw (mm)	d/tw	Ultimate load of girders with solid web Pus (kN)	Ultimate load of girders with opening web Puo (kN)	Puo/Pus
3.5	114	190	110	0.58
2.8	142	142	73	0.51
2.3	173	121	54	0.45
1.7	235	100	38	0.38
1.5	267	74	22	0.29

From Table (4), it can be noticed, as the web slenderness ratio (d/tw) increases the ultimate load decreases. Increasing (d/tw) will decreasing ultimate load of solid web girder with reduction of 50 % and will decreasing ultimate load of girder with circular opening web with reduction of 64 %). That mean that the girders with web opening are more sensitive to the changing in the web slenderness ratio than those with solid web.

Shear resistance of the web with opening depend on the part above the opening (top tee), can be signed as Vt, and the part below the opening (bottom tee), can be signed as Vb and the shear resistance of flanges (Vf). Also, we find that there is important factor which is depend on slenderness ratio of the web. This factor effects on the shear capacity of web, the shear capacity of the web decreases with increasing this factor, due to that the mode of failure becomes depending on buckling of web when this factor increasing.

$$V = (V_t + V_b)\lambda + V_f \text{------}(1)$$

7. Conclusions

The following conclusions can be drawn from this investigation:

1. Failure of girders with solid web and web with small area of opening (circular and square) is due to shear buckling along the diagonal of the web and the plastic hinge formed at a point close to the interaction line between the web and the flange. While girders with large opening the shear failure occurs at approximately 45 degree angle through the hole and the plastic hinge forms close to the center of panel.

2. Presence of openings in the web decreases the carrying capacity of girder and its effect increases with increasing the opening area.

3. Concentrate the stresses at the edges of the square openings. Thus, to minimize or eliminate that stress must be curved the corners of these openings.

4. As the web slenderness ratio increase, the ultimate load decreases. And specimens with web opening are more sensitive to the changing of the web slenderness than those with solid web.

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