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Investigation the effect of central openings in the web on the behaviour of the plate girders

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Abstract. The effect of web openings in steel girders were investigated experimentally by testing six girders under two point loads with circular, square and rectangular opening webs. The last girder was a plate girder with a solid web; however, similar dimensions were used for all girders. Results of experimental work revealed that girders' critical buckling decreased with increases in openings sizes, also depending upon the shape of the opening. Also, theoretical equations were initiated due to elastic local buckling and compared with experimental. Both experimental and analytical work was adopted to carry out the numerical investigations of the structural response of the girders with different shape of holes by using ANSYS (version 12.0). SHELL 181 was utilized to create the steel plate. Finite element model adopted though out the parametric study to investigate the critical buckling of plate girder with different web width ratios and slenderness ratios to determine the effects of changing size and shape for different web width and slenderness ratio.

1. Introduction

The plate girder was built-up as a steel member that consisted of flange plates linked to a web plate with fillet welds. The purpose of the plate girder was to give support for the loads over long spans (60 ft. to 200 ft.) and to assist the loads that were too heavy to be held by the rolled steel shapes. They were used as transfer the structural effect of the girders in building to support columns above large column-free areas. Plate girders adopted as carrying crane girders in heavy engineering with long spans. In lots of cases, the web plate considered as one of the slender proportions and is therefore disposed to collapse due to applying any small shear [1]. The web of plate girder in general is slim plate, so it buckles at the beginning of loading, consequently shear buckling with failure of the web are the main factors in plate girders design. Plate girders web buckles at a stress that might estimate with the theory of plate buckling. When collapsing occurs, different amount of stress will be distributed in the web also incremental strength of post-buckling is mobilized [2].

Openings were provided in the webs of the I-section plate girders are mainly used to pass the service pipes. This would reduce the strength stiffness in the plate girders especially when the openings placed in the highest shear areas [3,4]. Much research has done to study steel and composite steel with web openings to checkup and protection and for economic reasons [5,6,7,8,]. Overall, shear strength for plate girder without holes is combined of three factors: the strength of web to buckling, the effect of tension field action at post-buckling stage the support of the flanges.

The elastic local shear buckling stress can be explained by the standard plate buckling theory [7] as

$$\tau_{cr,l} = k_s \cdot \frac{\pi^2 \cdot E}{12 \cdot (1-\upsilon^2)} \cdot \left(\frac{t_w}{b}\right)^2 \quad (1)$$

$$k_s = 5.34 + 4.0\left(\frac{b}{h_w}\right)^2 \quad (1,a)$$

$$k_s = 5.34 + 2.31\left(\frac{b}{h_w}\right) - 3.44\left(\frac{b}{h_w}\right)^2 + 8.39\left(\frac{b}{h_w}\right)^3 \quad (1,b)$$

where E is the elastic modulus, ν is Poisson's ratio, tw is the web thickness and b is the panel width. The local shear buckling coefficient ks is a function of the web panel aspect ratio b/h and the panel boundary conditions [8]. The first equation is applied once all ends of the plates are simply supported for the steel girders and the second equation is valid when the longer borders of the plates are simply supported while the shorter sides are fixed.

2. Experimental investigation

In this study, seven plate girders were tested to estimate the structural response of the web openings. One of the girders was flat web so it was considered as a control girder and the other six girders were divided into three groups: A, B and C. Group A represents the plate girder with circular opening in the centre of the web and series B indicates the plate girder with central square opening in the web while C depicts the plate girders containing rectangular opening in the centre of the web. The depth of all girders was 300 mm with top and 220 mm and nominal thickness of 7 mm. The girders consist of web panels 450 mm wide (b), 300 mm deep (d) and 3 mm thick (t_w). The nominal value of d/t_w ratio was, consequently, 100 and the nominal web aspect ratio (b/d) was 1.5. The girders information listed in Table 1 and features of the girders are shown in Figure 1.

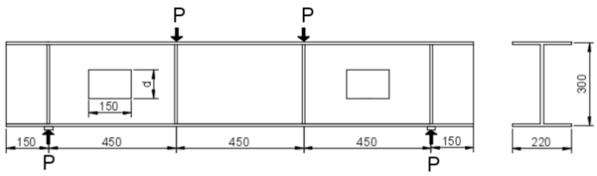
The influence of the central circular web openings on the critical buckling was investigated by adopting holes with two different diameters, the diameters 100, and 150 mm respectively. Also, two different sizes of central square web openings (100x100, and 150x150 mm) and two different size of central rectangular web opening (50x100 and 100x150) were used to understand the effect of the square and rectangular openings on the critical buckling strength.

The Grade of steel which used in the plate girder was 250. The webs and flanges were cut from a single sheet. Following the arrangements, the modules are organized, the girders are built by tack welding flange plates to the top and rear of the web plate, and stiffeners before full welding was made. After that, the constant gut welding was accomplished with E43 electrodes. Openings were then recognized by marking and cutout from the web plates using cut sawing. Tensile test coupons were tested under tension accord with ASTM A36 descriptions. The mean yield stress and modulus of elasticity for the steel were 250 MPa and 200,000 MPa, correspondingly. To detect the structural behaviour of the beams at every stage of loading a dialing gauge with the correctness is 0.01 mm, was used. During each load step, the measurement of corresponding vertical displacements (deflection) at the beam mid-span and lateral web deformation had been checked.

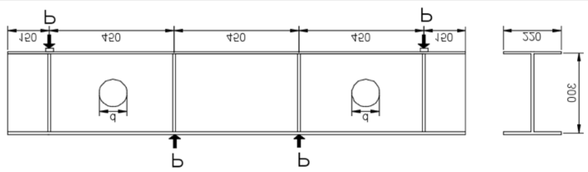
In this study, all girders were tested under two concentrated static loading as simply supported. The load had increased slightly up to collapse. The load had applied using Torsee's Universal Testing Machine with a capacity of 200 tons. Figure 2 showed the test setup. The load was applied using a stiff steel spreader beam. The inner two point loads were applied over two transverse steel plates, which covered the entire width of the specimen. Steel rollers were placed between the spreader beam on steel plates which will present the support reaction loads. In both bearings, the rotation and movement along the longitudinal axis has been allowed.

Table 1. Tested plate girders dimensions

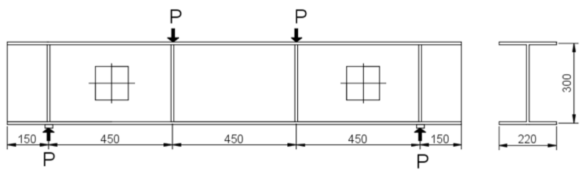
group	Shape of opening	Girders	d	d/h
Control	----	GO	----	----
A	Circle	GC1	100	0.33
		GC2	150	0.5
B	Square	GS1	100	0.33
		GS2	150	0.5
C	Rectangle	GR1	50x150	0.17
		GR2	100x150	0.33



a) plate girder has rectangular opening in the web



b) plate girder has circular openings in the web



c) plate girder has square openings in the web

Figure 1. Dimensions of plate girders

Figure 2. Test setup.

3. Finite element analysis

ANSYS Version 12.0 [9] was adopted to generate the finite element (FE) models. The same material properties which were got from the experimental work were used in this analysis. Von Mises yield criterion and bilinear isotropic material model were adopted to represent the nonlinearity of the steel. The support and loading conditions of experimental girders are computer-generated by preventive the appropriate degrees of freedom. SHELL181 element was used to model the webs, flanges and stiffeners. It is acceptable to analyze thin to relatively thick shell assemblies, and it has a four-nodal element with six DOF at each node: interpretations in the x, y and z axes. The boundary conditions where applied at the plane of symmetry and location of supports and loadings. To represent the symmetry, nodes on the plane of symmetry must be constrained in the perpendicular direction. Therefore, the displacement is equal to zero in the x-direction for all nodes at the plane, as shown in Figure 3. The supports were modeled by constraint one line of nodes in the y-direction to allow the plate girder to rotate at the support.

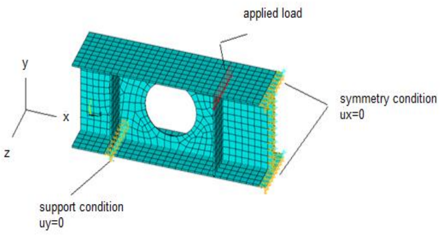


Figure 3. Typical finite element mesh, boundary conditions and applied load.

4. Results and discussion

Table 2 summarized the results for both experimental and FEA and Figure 4 explains the typical specimens after failure.

Table 2. The girders result (experimental and FEA).

Series	Girders	Experimental Critical load P_{cr} (kN)	P_{cro}/P_{crs}	τ_{cr1} / τ_{cre}	τ_{cr2} / τ_{cre}	Analytical ultimate load $P_{cr.FE}$ (kN)	$P_{cr.FE}$ / P_{cr}
Control	GO	110	----	1.2	1.3	125	1.17
A	GC1	90	0.82	1.1	1.2	96	1.06

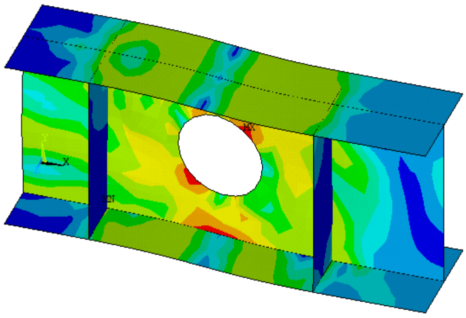
	GC2	77	0.7	1.1	1.22	82	1.07
B	GS1	80	0.73	1.12	1.21	87	1.08
	GS2	66	0.6	1.23	1.32	75	1.14
C	GR1	70	0.64	1.25	1.34	77	1.10
	GR2	58	0.53	1.34	1.4	70	1.20

- P_{crs} is the critical load of the solid web girder.
- P_{cro} is the critical load of girders with opening web.
- τ_{cre} is the experimental shear stress.
- τ_{cr1} is the shear stress using equations (1) and (1:a).
- τ_{cr2} is the shear stress using equations (1) and (1:b).

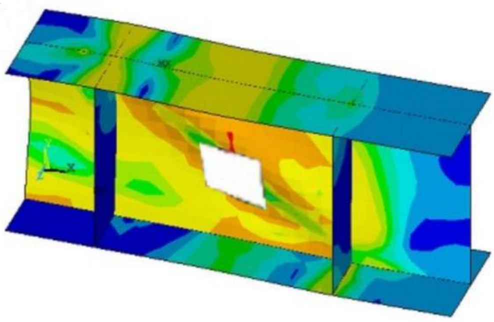
GC1

GS1

GR1



GC1



GS1

Figure 4. Specimens after failure (theoretically by FEM and experimentally)

A comparison was made of the experimental and finite element results as explained in Table 2 and Figure 4. The FE shows the ability to give accurate results for the buckling and ultimate load.

The experimental shear stress (τ_e) specimens are given in Table 2 and are compared with corresponding stresses from equation [1] by using (K_s) from equation (1: a) and (1: b). it is noticed that the results from the cases of simply boundaries are closed to the experimental.

Figure 5, and girders with small web opening (d_o=100 mm) circular and both square and rectangular (50x100), note that the buckling occurred approximately along the transverse of the web and the maximum stress located along the transverse of buckling. The plastic hinge is pointed close to the meeting line between the web and the flanges.

The shear buckling has occurred along with a line that made approximately 45 degrees with the flange and through the hole with large circular, square and rectangular web opening (d_o=100, 150 and 100x150 mm), Figure 4. The plastic hinge created near to the perpendicular center line of the web. This means that the hinge place is interconnected to the size of hole in the web.

For the girders with the opening web, it can be noticed that the stresses for the webs with square and rectangle openings are concentrated above and below the holes and through edges of the openings. Therefore, the corners of square holes should be bends to reduce or to eliminate as much as possible the stress concentration. From Table 2, it can be noted that the buckling load decreases when we cut off a part of the web, and it decreases further when the size of hole increases. The decreases occur due to reduce the strength of web to resistance a bulking. Figure 5 illustrates the typical load mid span deflection for the selected girders, GO, GC2, GS2 and GR2.

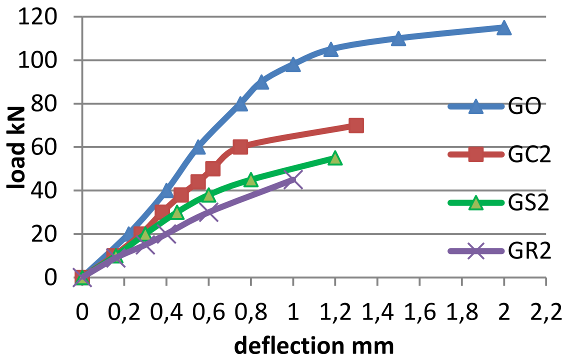


Figure 5. Load-deflection curves of GO, GC2, GS2 and GR2

From this figure, the curves remain approximately linear till signs of the critical buckling load shows, after this stage, post-buckling stage happens. At this stage, the curves behave nonlinearly, and developing the tension through web could achieved by upgrading the load. The panel reaches the ultimate failure load by adopting plastic hinges on base and upper flanges. For girders with large size of opening web, the tension cannot be achieved effectively due to erasing big area from the web. Thus, the ultimate load of those girders will be excluding than that of girder GO. That is due to the stress concentrated at ends of the square and rectangular holes which leads to buckle the web early and forming final collapse of the panel.

5. Parametric study

A parametric study on panel covering central area with circular, square and rectangular openings of the girders are investigated by using the FEA. similar material properties applied for all models. Figure 6 shows the variation of τ_{cr}/τ_y verse web slenderness ratio (h/t_w) for circular, square and rectangular hole for web panel width ratio 1.5 with different size and shape of hole. It is clear that the τ_{cr}/τ_y ratio decreases when the hole size increase from ratio h/t_w=0.33 to 0.5. Lower values for girders with rectangular hole are obtained, particularly for high value of slenderness ratio.

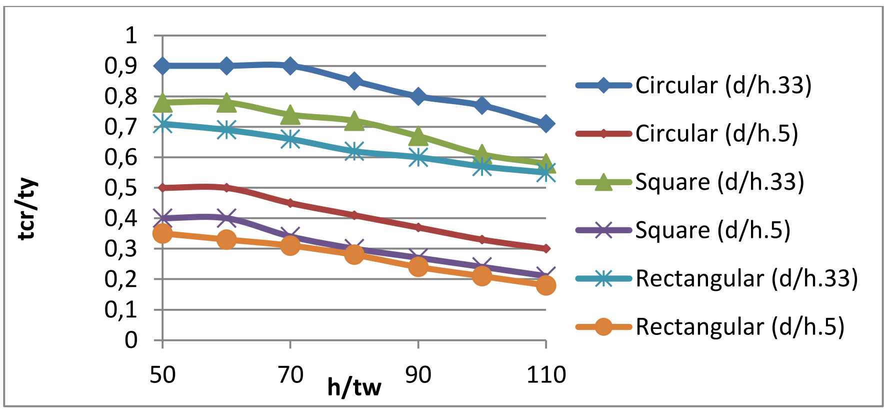


Figure 6. τ_{cr}/τ_y verse h/tw diagram for different shape and size of hole of s/h=1.5

To study the behaviour of the web panel width of girders, different ratios of s/h (2.5 and 3.5) are adopted, as shown in Figures 7 and Figures 8. When comparing those curves with curves in figure 9 it is clear that the curves are similar, but lower values of critical shear stress are obtained for s/h=2.5 and

3.5, particularly for high value of slenderness ratio h/tw. However, the critical shear stress is less sensitive to the variation of the panel width ratio than that of the web slenderness ratio. This may be occurring due to the fact that increasing the height of the web contributes to increase the slenderness of panel more than the effect of increasing the width.

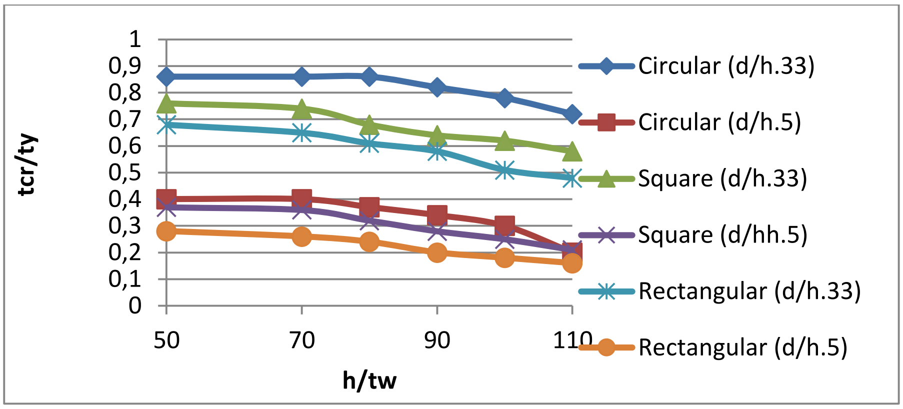


Figure 7. τ_{cr}/τ_y verse h/tw diagram for different shape and size of hole of s/h=2.5

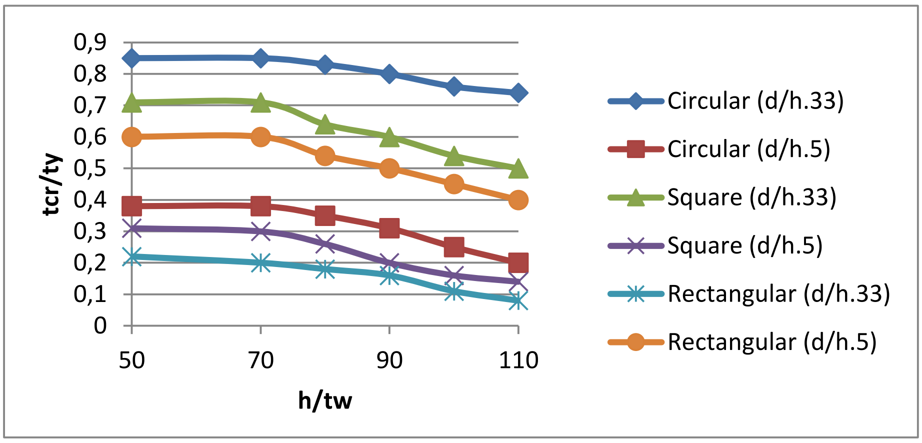


Figure 8. τ_{cr}/τ_y verse h/tw diagram for different shape and size of hole of s/h=3.5

6. Conclusions

The stability and the behaviour of the girders with web openings under to two-point loads were studied to provide some new insights into the response of the plate girders. The following conclusions are reached.

1. The buckling load occurs approximately along the transverse of the web and the plastic hinge forms at a point nearby the meeting line between the web and the flanges.
2. Shear stresses decreased for the web with openings especially with rectangular opening webs.
3. The analytical results by equation [1] are approximately closed with the experimental results. This can be achieved when the boundary conditions are assumed to simply supports for all edges of the plate.
4. Lower values of critical shear stress can be obtained for the plate girder with rectangular hole particularly for the cases with high value of slenderness ratio. And the shear stress decreases when the hole size increases.
5. Shear stresses decrease with the increase of the webs width to height ratio, mainly for the high

value of slenderness web.

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Acknowledgments

Open Web Girders, Stresses, Buckling, Experimental Work, Finite Element Analysis, Parametric Study, Plate Girder.