Tests on Plate Girders Containing Web Openings and Inclined Stiffeners


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Abstract
This paper presents the ultimate load behaviour of perforated steel plate girders with inclined stiffeners. Ten simply supported plate girders were tested to failure subjected to a single concentrated load applied at the centre of the girder span. The circular shape of web openings of various diameters, viz., 100 mm, 150 mm, 200 mm and 250 mm were located at the centre of every web panel in the girder specimens. The main focus of this study was to investigate the effects of different inclination angles of intermediate stiffeners on the post-buckling behaviour. The inclination angles of intermediate stiffeners measured from the bottom flange, viz., 90°, 75°, 60°, 45° and 30° were considered in the test series. Due to the effects of such inclinations, the variations of strength, failure characteristic and load-deflection response were investigated. Test results showed significant increases in the ultimate strength to the extent of 92% as the angle of the inclined stiffeners reduced.

Keywords: experiment, plate girder, inclined stiffener, web opening, post-buckling behaviour.

INTRODUCTION
Perforated plate girders are commonly used as a structural element in the construction of buildings, bridges, ships, and offshore applications for their advantage of enabling the passage of services such as pipelines and ducts beneath the web panel. The existence of web openings in steel plate girders will result in the decrease of the load carrying capacity, redistribution of stress and discontinuity of structure [1]. This type of construction method also reduces the clear floor height and improper systematic installation of services, hence affecting the cost-effectiveness [2].

In order to establish the design philosophy of the plated structures, many researchers had carried out studies on the design of steel plate girders with and without openings [3-8]. The purpose of intermediate stiffeners in a transverse direction in web panels is to prevent the torsion of top and bottom flanges. Determination of numbers, dimensions and positioning of longitudinal stiffeners were carried out by researchers [9-13] in order to enhance the performance of steel plate girders. Extensive studies on plate girders were carried out in the past [14-19]. Unfortunately, less work has been done on plate girders with inclined stiffeners.

In the conventional steel plate girders, vertical stiffeners are adopted to prevent the web panel from buckling and they do not carry any loads except at the point where the applied loads and stiffeners coincide. Intermediate stiffeners placement in a diagonal direction across each web panel forms a trussed girder which is able to carry a certain amount of loads and at the same time prevent the web from buckling [20]. Guarnieri [21] reported the advantage of inclined stiffeners in limiting the shear factor without requiring any additional longitudinal stiffeners. The use of inclined stiffeners in web panel forms an unequal diagonal length, both in the compression and tension flange; thus, the behaviour of web panels has become more complicated. Therefore, an experimental series on perforated plate girders with inclined stiffeners must be carried out to investigate the overall behaviour of such girders in order to evaluate the efficiency in terms of load carrying capacity, load-deflection behaviour and failure characteristic. Details of the test girder specimens, experimental set-up and loading procedure are outlined in this paper.

DETAILS OF TESTS
In this study, ten specimens of bare steel plate girders were loaded under a single concentrated load applied at the centre span of the girder in order to evaluate the ultimate strength capacity and observe the failure behaviour under the ultimate load. Each plate girder specimen comprised of a certain angle of inclined intermediate stiffeners, \( \theta \) measured from the bottom flange, viz., 90°, 75°, 60°, 45° and 30° and the diameter of web opening in a circular shape, \( \phi \). The test specimens are noted in the text as PG-90 Cr100, PG-90 Cr200, PG-75 Cr150, PG-75 Cr250, PG-60 Cr100, PG-60 Cr200, PG-45 Cr150, PG-45 Cr250, PG-30 Cr150 and PG-30 Cr250 in which, the notations 90, 75, 60, 45 and 30 refer to the angle of inclination of the stiffeners. In the notation of Cr100 for example, it refers to the circular opening that is equal to 100 mm or equivalent to 0.2d, where \( d \) is the web depth of the girder. Details of test girder specimens are summarised in Table 1. The typical geometry and notations of the specimens are shown in Figure 1 (a) – (c) in the elevation and cross sectional view, respectively.

Steel coupons were cut from the same stock of steel plate for the flange, stiffener and web. Preparation of the coupons in respect to the shape and dimensions was in accordance with ASTM A370-07a: Standard Test Methods and Definitions for Mechanical Testing of Steel Products”. Table 2 lists the average values of Young’s modulus \( E_{\text{avg}} \), yield stress \( f_{y \text{ (avg)} } \) at 0.2% plastic strain and ultimate stress, \( f_{u \text{ (avg)} } \) for flanges and webs, respectively.
Table 1: Details of test girders

<table>
<thead>
<tr>
<th>Girder</th>
<th>Diameter of web opening, $d_0$ (mm)</th>
<th>$d_0/d$</th>
<th>Angle of intermediate stiffeners, $\theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG-90-Cr100</td>
<td>100</td>
<td>0.2</td>
<td>90 (vertical)</td>
</tr>
<tr>
<td>PG-90-Cr200</td>
<td>200</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>PG-75-Cr150</td>
<td>150</td>
<td>0.3</td>
<td>75</td>
</tr>
<tr>
<td>PG-75-Cr250</td>
<td>250</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>PG-60-Cr100</td>
<td>100</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>PG-60-Cr200</td>
<td>200</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>PG-45-Cr150</td>
<td>150</td>
<td>0.3</td>
<td>45</td>
</tr>
<tr>
<td>PG-45-Cr250</td>
<td>250</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>PG-30-Cr150</td>
<td>150</td>
<td>0.3</td>
<td>30</td>
</tr>
<tr>
<td>PG-30-Cr250</td>
<td>250</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of steel material

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Young’s modulus, $E_{mod}$ (GPa)</th>
<th>Yield stress, $f_y$ (MPa) at 0.2% plastic strain</th>
<th>Ultimate stress, $f_u$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange and stiffener</td>
<td>205.5</td>
<td>295.1</td>
<td>424.8</td>
</tr>
<tr>
<td>Web</td>
<td>209.8</td>
<td>304.9</td>
<td>444.8</td>
</tr>
</tbody>
</table>

Figure 1: Elevation and cross-sections of a typical test girder

Specimen and Test Equipment

The test specimens were designed based on the tested specimen by Shanmugam and Baskar [22] by customising the configurations to compromise the available test facilities and to fulfil the objectives of this study. Test girders were fabricated using mild steel plates of grade 43A (equivalent to Grade S275) complying with code BS 4360: “Specification for weldable structural steels”: 1990. The plates for flanges, stiffeners and web for every test girder were prepared by the cutting process to require the dimension using a CNC plasma cutting equipment. The advantage of using this advanced equipment is it can avoid cutting the plates from adverse distortion and undesirable change of material properties.

After the plate cutting process, all flange, web and stiffener components were welded together with continuous fillet welds using a low temperature Metal Inert Gas (MIG) welding system to reduce the distortion due to welding. Since residual stresses were generated during the welding process, sufficient care was taken when welding the thin web plate by providing lateral supports at certain intervals to prevent large initial imperfections of the web including initial distortions, warping, twisting, dents and undulations. At the end of the welding process, stiffeners were welded accordingly on both sides of the web plate.

To investigate the behaviour of perforated plate girders with inclined intermediate stiffeners under shear load, an experimental setup had been developed. Based on the available local facility, the test girders were tested using a strain-gauging testing frame. A typical experimental setup is shown in Figure 2. An axial compression was applied at the centre span of a test girder by using a ENERPAC hydraulic jack and hand manual pump with the capacity of 500 kN. The hydraulic jack could transfer hydraulic energy to the load cell to measure the amount of load applied. Before carrying out the test, the load cell was calibrated by a certified testing company in accordance with the requirements of BS EN ISO 7500-1:2004. The purpose of the load cell calibration process was to ensure that the load cell will give an accurate reading during the loading test.

In the side and front views of the testing frame, a careful observation was carried out to ensure an axial compression load was applied to the neutral axis of the test specimen before the loading process. The test girder also needed to seat properly at both ends over the two sets of support system. At each support system, a steel circular shaft was placed at the top to allow displacement and rotation due to the reaction from both ends of the test specimen. At the bottom flange of the test girder, seven LVDT transducers were located at seven different locations to measure the vertical displacement during tests. Details of the location of LVDT transducer are given in Figure 3.

Test Procedure

All test girders were placed properly over two strong supports. The position of the girder had to be collinear for both the axial concentrated load and the neutral axis of the test girder. For safety reasons and to ensure the testing ran in a proper manner and all testing equipment readings were kept in the normal working level, the loading and unloading process was conducted up to five percent of the predicted ultimate load.
As the loading test started, the application of load was increased gradually by a predetermined increment to failure. After the critical buckling load was reached, the application of load was continued in order to investigate the post-buckling behavior. Buckling shapes due to tension field action were visible for each specimen during the test. The ultimate load and mode of failure for all specimens were recorded. The applied shear load was then removed when it dropped to a certain level beyond failure. In this study, the test procedures were similar for all girders.

Figure 2: Typical test set-up in the laboratory

TEST RESULTS AND DISCUSSION
In the test series, most of the test specimens had failed in a similar way. The purpose of the designed test specimens with influence of the intermediate inclined stiffeners and the presence of web openings was to evaluate the test specimens in terms of the ultimate load capacity, load-deflection behaviour and to observe the failure characteristic. Since the web thickness of test girders was very thin, it was possible for the web panel to buckle before yielding. The behaviour of the web panel could be divided into three stages; viz. pre-buckle, post-buckled and collapsed. The vertical deflection throughout the whole girder span can be seen as the load gradually increased.

![Diagram](image_url)

Figure 3: Locations of LVDT

Ultimate load capacity
The test specimens were loaded with a single shear load applied at the mid-span of the girders. From the test series, it was proven that the ultimate load was increased considerably as the intermediate inclined stiffeners angle measured from the bottom flange, \( \theta \) decreased. For instance, for the comparison of those test girders with circular size openings of \( d_o = 100 \) mm, the ultimate load capacity, \( P_u \) increased to the extent of 21% when the intermediate inclined stiffeners angle decreased from 90° (i.e. PG-90-Cr100) to 60° (i.e. PG-60-Cr100). The same observation had been made for those test girders with circular size openings of \( d_o = 250 \) mm, where the ultimate load capacity, \( P_u \) increased due to the extraordinary capacity of 92% when the intermediate inclined stiffeners angle decreased from 75° (i.e. PG-75-Cr250) to 30° (i.e. PG-30-Cr250). This showed the evidence that the intermediate inclined stiffeners improved the ultimate load capacity, \( P_u \) by restoring the loss of shear strength in the perforated test girders. The intermediate inclined stiffeners member could carry a certain amount of applied shear load through the distribution of forces as in truss members. As a result, the test girders with intermediate inclined stiffeners carried a larger shear load compared to the test girders with vertical intermediate stiffeners girders (i.e. PG-90-Cr100 and PG-90-Cr200). The presence of intermediate inclined stiffeners in a girder had established the web panel in a trapezoidal shape where the larger width of tension field was developed within the web panel that enabled the web to sustain a higher tensile force exerted within the panels compared to the rectangular ones.

In this experimental series, the presence of web openings showed the significant drops in the ultimate load capacity by reducing the tension bandwidth. The ultimate shear capacity, \( P_u \) in all test girders reduced when the size of the web openings were larger. For instance, the ultimate shear capacity, \( P_u \) of specimen PG-90-Cr200 was dropped to about 33% compared to specimen PG-90-Cr100 which had smaller web openings. The same result was found for specimen PG-60-Cr200, where the ultimate shear capacity, \( P_u \) also dropped about 31% compared to specimen PG-60-Cr100. This indicated the advantage of the application of inclined intermediate stiffeners as the stiffening element in the design of plate girders. Variations of ultimate load capacity, \( P_u \) of all test girders are summarize in Table 3.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate Load, ( P_u ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG-90-Cr100</td>
<td>187.7</td>
</tr>
<tr>
<td>PG-90-Cr200</td>
<td>126.4</td>
</tr>
<tr>
<td>PG-75-Cr150</td>
<td>169.5</td>
</tr>
<tr>
<td>PG-75-Cr250</td>
<td>124.4</td>
</tr>
<tr>
<td>PG-60-Cr100</td>
<td>226.2</td>
</tr>
<tr>
<td>PG-60-Cr200</td>
<td>157.5</td>
</tr>
<tr>
<td>PG-45-Cr150</td>
<td>221.7</td>
</tr>
<tr>
<td>PG-45-Cr250</td>
<td>180.3</td>
</tr>
<tr>
<td>PG-30-Cr150</td>
<td>304.4</td>
</tr>
<tr>
<td>PG-30-Cr250</td>
<td>238.7</td>
</tr>
</tbody>
</table>

Table 3: Comparison of ultimate loads

Load-deflection behaviour
Load-deflection curves of the girder specimens in the loading tests are plotted in Figure 4 (a) – (e). These figures show the effects of intermediate stiffeners angle on the overall behaviour of the perforated plate girders. The load was measured by using a load cell located at the top flange of the girder mid-span and the displacement was measured by using...
an LVDT transducer in a vertical direction located at the bottom of girder mid-span. The curves are primarily showing the bending behaviour of the test girders. It is obvious from the curves that the ultimate load capacity decreases due to the increase of the circular web openings size. Comparison of load-deflection plots for the selected girders was made to show the effects of inclined stiffeners, as shown in Figure 5 (a) – (d). It is evident from the figures that most of the curves show the same bending stiffness at the initial stages of loading and the trend continues further close to the ultimate load. It is also proof that the girders with a lower angle of inclined intermediate stiffeners can sustain larger loads compared to the girders with a higher angle of inclined intermediate stiffeners while considering same size of the web openings.

Figure 4: Comparison of load-deflection curves of perforated plate girders with intermediate inclined stiffeners angle: (a) 90°, (b) 75°, (c) 60°, (d) 45° and (e) 30°.
Failure characteristic
Loading was applied gradually at the mid-span of the test girders with a uniform rate. At the beginning of the loading procedure, all girders underwent positive bending and only marginal deflection was noticed at the mid-span. Once the diagonal-shape in the thin web was visible, it was the sign that the critical buckling load was reached. The initial formations of the tension field are shown in Figure 6 (a) – (j). Further increment of the applied loads in the post-buckling stage resulted in the web panel of the plate girder to deform in the out-of-plane. The increment of vertical displacement was larger compared to the elastic stage due to gradual loss in the flexural stiffness of the girder. The progress of web buckling as a result of tension field action was closely observed until the test girder reached the ultimate load. As the ultimate load was reached, the application of load was continued in order to investigate the collapse behaviour of the web panel. The applied load began to drop gradually which exhibited that the web panel had yielded, in which the web panel had suffered loss in shear capacity. In all cases, the test girders swayed to one side, either to the left or right, and deformation of web panels was evident, especially in the girders with large circular web openings associated with plastic hinges formed in the top and bottom flanges as shown in Figure 7 (a) – (j). These hinges were formed due to the vertical component of the pulling force from the tension field mechanism. From Figure 7 (a) – (j), it is clear that the girders with lower intermediate stiffeners angle have led to the formation of a larger angle of tension band in the web panels near to the point of the application of load. This occurred due to the reduced dimension of the web panel at the compression flange from which the tension field action was anchored to.
Figure 6: Formation of tension field band in all test girders
web panels

(e) Girder PG-60-Cr100
(f) Girder PG-60-Cr200
(g) Girder PG-45-Cr150
(h) Girder PG-45-Cr250

(i) Girder PG-30-Cr150
(j) Girder PG-45-Cr250

(a) Girder PG-90-Cr100
(b) Girder PG-90-Cr200
Figure 7: Collapse behaviour of all test girders
CONCLUSIONS
An experimental series of ten perforated steel plate girders with inclined intermediate stiffeners under shear load have been presented. The key finding of this study is the ultimate capacity of the test girders increased to the extent of 92% when the intermediate inclined stiffeners angles were reduced. It was evident that the significant contribution of intermediate inclined stiffeners in increasing the load carrying capacity had been observed by carrying some internal forces imposed to the web panels; hence, the loss in the load carrying capacity due to the presence of web openings of plate girders was restored. By introducing intermediate inclined stiffeners, trapezoidal shape web panel was formed at the end of the web panels, thus the tension bandwidth became larger compared to the ordinary girders with rectangular web panels. As a result, larger tension forces in the post-buckling stage can be carried out. It was noted that variations in load-deflection curves can be observed for all test girders. A sudden drop of applied load out. It was noted that variations in load-deflection curves presented. Results for the collapse behaviour have been presented for all the girders. In many cases, the girders swayed to one side with tremendous buckling at the web and top flanges. This study has provided some useful information and insights in terms of the ultimate load behaviour of plate girders having web openings and intermediate inclined stiffeners.

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REFERENCES

