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SHEAR STRENGTH OF PERFORATED PLATE GIRDERS WITH INCLINED STIFFENERS

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A series of experimental tests on perforated steel plate girders with inclined stiffeners is presented herein. Ten simply supported girders of practical size were tested for failure under a single concentrated load applied at the center of gravity of the section. Circular web openings of various diameters were introduced at the middle panels of the girders. Effects of different inclination angles of intermediate stiffeners on the ultimate load behavior are the main focus of the present study. Five different angles, measured from the bottom flange, were considered in the tests, viz., 90^o, 75^o, 60^o, 45^o, and 30^o. Variations of strength, failure characteristic, and load-deflection response have been observed. The ultimate strength was found to increase considerably from 21% to 92% as the angle of inclined stiffeners reduced from 90^o to 30^o.

Keywords: Plate girder, Inclined stiffener, Web opening, Ultimate load behavior, Post-buckling strength.

1 INTRODUCTION

The use of plate girders in civil engineering construction has found increasing popularity in railroad bridges and industrial buildings. Studies on plated structures were carried out by many scholars since decades ago in order to establish the design philosophy of plated structures and other forms of thin-walled structures (Basler and Thurlimann 1960, Rockey and Skaloud 1971, Porter *et al.* 1975, Lee and Yoo 1998, Horne and Grayson 1983, Alinia and Moosavi 2008). It is common to allow ducts and services pass through the plate girders by providing openings in the web. (Hagen *et al.* 2009) and (Hagen and Larsen 2009), for instance, carried out some analyses and proposed simple design calculations to determine the shear capacity of steel girders having large web openings. In addition, (Shanmugam *et al.* 2002) investigate the ultimate load behavior of plate girders containing central web openings of rectangular and circular shapes. This form of structural member results in reduced floor height, systematic installation of pipes or ducts, and cost-effectiveness, but at the same time, causes penalty on the shear strength of the girders depending on the parameter of the openings.

It has long been known that vertical stiffeners, except those at load points, do not carry any load and serve only to prevent the web from buckling. By placing the intermediate stiffeners diagonally across each panel, a trussed girder is formed and the stiffeners thereby carrying a portion of the load in addition to performing in an efficient manner, their given tasks of preventing buckling. Inclined stiffeners would also have the advantage of limiting the shear factor without requiring additional longitudinal stiffeners (Guarnieri 1985). However, the use of inclined stiffeners causes unequal diagonal length and unequal subdivisions of web panels at the top compression and bottom tension flanges thus, results in a complex behavior of the panels and complicates the analysis. Also, far too little attention has been paid to study inclined stiffeners in the plated structures as found in the literature.

Therefore, there is a necessity to get a clear picture of the behavior of such girders through physical observations in order to enhance the understanding of the elastic and inelastic responses under loading. An experimental investigation on plate girders having different angles of inclined stiffeners has, therefore, been undertaken. Details of the girders and experimental procedures are described in this paper. Attention was focused on the variations of ultimate capacity, load-deflection behavior, and failure characteristics. This paper will demonstrate the potential application of inclined stiffeners in plate girders containing web openings in which a definite increase in the efficiency of plate girders can be obtained over the conventional ones.

2 EXPERIMENTAL PROGRAM

Tests were conducted on ten perforated steel plate girder specimens of practical size containing inclined stiffeners. The specimens are basically same in dimensions such as span length, L = 2410 mm, depth of web panel, d = 500 mm, thickness of web, t_w = 2 mm, width of flange, b = 100 mm, thickness of flange, t_f = 10 mm, and the web slenderness ratio, d/t_w = 250. The differences between all specimens are the angle of inclination of the intermediate web stiffeners which varies from 90^o to 30^o in the increment of 15^o and the diameter of web openings, d_0 which varies from $0.2d_0$ to $0.5d_0$. 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 angles of inclination of the stiffeners. Notation Cr100, for example, indicates 100 mm diameter of circular opening. A typical test girder is shown in Figure 1.

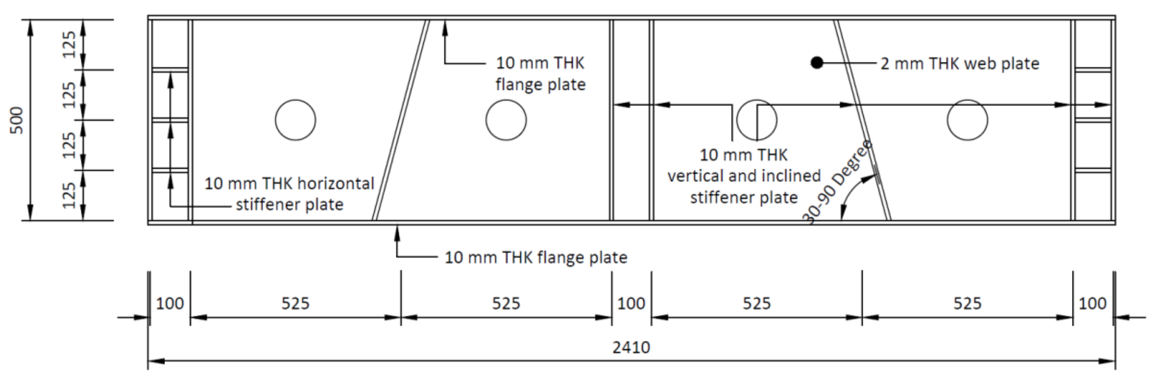

Figure 1. Typical details of the test girder.

Mild steel plates of grade S275 were chosen in the fabrication of the plate girder specimens. The simply supported girder was placed over the strong support system mounted to the test frame. It is very important to ensure the correct positioning of the test specimen in such a way that the midpoint of the girder is in line with the centre line of the hydraulic jack. Seven LVDT transducers were placed at seven selected points below the bottom flange of the girder to measure the vertical deflection during the testing program. Experimental data such as increment of loads and deflections were recorded using an appropriate data acquisition system. Figure 2 shows a typical test set-up.

Prior to testing, all specimens were loaded about 10 percent of the expected ultimate load and then unloaded in order to ensure the specimens are properly seated on the support system. This procedure also helps to check the functionality of the strain gauges and transducers used in the test. Then, the application of load will be increased gradually by a predetermined increment to failure. After the ultimate 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 are similar for all girders.

Figure 2. Typical view of the test set-up.

3 TEST RESULTS AND DISCUSSION

3.1 Ultimate Load Capacity

All of the girders were tested for failure under shear load applied at the mid-span. The ultimate loads obtained from the experiments, P_u are tabulated in Table 1. The test specimens were designed so that they could be used to determine the influence of inclined stiffeners and the effect of openings in the web panels. Figure 5(a) compares the behavior of girders of PG-75-Cr150 and PG-75-Cr250 which have the same inclination angle of intermediate stiffeners but different circular opening size. The results show a substantial decrease in the ultimate strength about 27% when the circular opening size increases. Figure 5(b) shows the behavior of girders of PG-75-Cr250, PG-45-Cr250, and PG-30-Cr250 which have the same opening size but different inclination angle of intermediate stiffeners. It is evident from the results that the ultimate load of the girder with the same size of web opening is increased by 92% when the angle of intermediate stiffeners is reduced from 75^o (i.e., PG-75-Cr250) to 30^o (i.e., PG-30-Cr250). Same findings were found where the ultimate load capacity of girder PG-60-Cr100 increased about 21% compared to girder PG-90-Cr100 and the ultimate load capacity of girder PG-60-Cr200 increased about 25% compared to girder PG-90-Cr200. These indicate that the intermediate inclined stiffeners carry some of the applied load through the distribution of forces as in truss members. However, it can also be observed that the ultimate loads of girders with the same angle of stiffeners inclination decrease when the web opening is larger.

3.2 Load-Deflection Behavior

Figure 5(a – b) shows the comparisons of load-deflection response of the girders by considering the influences of the inclination angle of stiffeners and web opening size. Both curves represent mid-span deflection plotted against the applied load. The curves primarily show the bending behavior of the girders. A sudden drop of the applied load can be observed in almost girders after reaching the maximum capacity, indicating the yielding of web material. It is evident from the figures that the two curves correlate well especially at the initial stages of loading.

Table 1. Ultimate loads.

Specimen	**Ultimate Load, P_u (kN)**
PG-90-Cr100	187.7
PG-90-Cr200	126.4
PG-75-Cr150	169.5
PG-75-Cr250	124.4
PG-60-Cr100	226.2
PG-60-Cr200	157.5
PG-45-Cr150	221.7
PG-45-Cr250	180.3
PG-30-Cr150	304.4
PG-30-Cr250	238.7

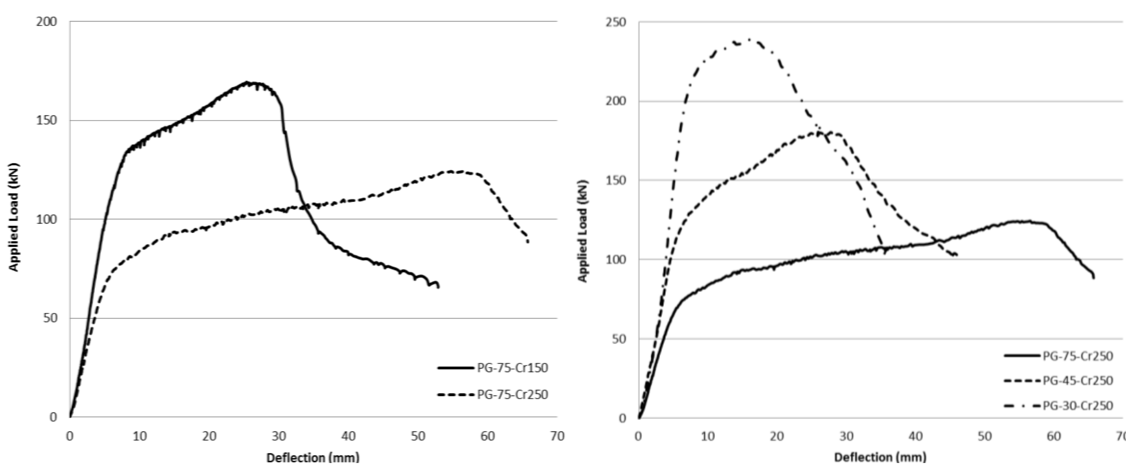

Figure 5. Comparisons of load-deflection behavior.

3.3 Failure Characteristic

All of the girders exhibited almost identical behavior at failure load. After reaching the elastic buckling load, all web panels started to develop diagonal-shaped bucklings as shown in Figure 6. Further increment in load beyond this stage was resisted by the web tension field action which, from then on, caused an increase in out-of-plane deformation of the diagonal buckling. Upon attaining the ultimate load, plastic hinges were formed in the compression and tension flanges, and the deformation of the girders was obvious, particularly those having large web openings.

Beyond this point, the girder swayed to one side as presented in Figure 7 and a gradual drop in the applied force occurred. This indicates that the girder has totally lost its capacity and the web material started yielding. All of the girders appeared to have this similar ductile failure characteristic.

Figure 6. Typical deformation of webs at critical buckling load.

Figure 7. Typical deformation of girder at failure.

4 CONCLUSIONS

Ten perforated steel plate girders with different inclination angles of intermediate stiffeners were tested for failure under shear load at mid-span. The following conclusions were made based on the experimental results. It is clear from the experimental results, with the same size of web openings, the ultimate strength increased when the angles of intermediate stiffeners were reduced. This finding shows the significant contribution of inclined stiffeners in carrying some percentages of forces. Appreciable variations may be observed in the load-deflection responses. The curves show a sudden drop in the applied force soon after attaining the ultimate point. Corresponding curves obtained from the non-linear finite element analysis are superimposed for comparison, only to find that the two curves correlate with each other well especially at the initial stages of loading. Overall, this study has provided some insights regarding the ultimate load behavior of plate girders having inclined stiffeners and therefore, further detailed analytical works and design recommendations are strongly suggested.

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