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FINITE ELEMENT INVESTIGATION OF THIN-WEBBED PLATE GIRDERS WITH INCLINED STIFFENERS

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This paper is concerned with the ultimate load behavior of thin-webbed steel plate girders with inclined stiffeners. Non-linear analyses were carried out on the simply supported plate girders using a commercial finite element code, LUSAS. The girders are of practical size and subjected to a single concentrated load applied at the centre of gravity of the section. Effects of inclination degree of stiffeners and central web openings on the performance and behavior of such girders are investigated. Variations of ultimate strength, buckling characteristic and load-deflection response are obtained. The ultimate strength is found to increase significantly when the inclined stiffeners were provided to the girders, regardless the effect of openings in the web.

Keywords: Slender plate girder, Inclined web stiffener, Non-linear analysis, Ultimate load behavior.

1 INTRODUCTION

Plate girders are used in structural applications whenever the large commercially available rolled sections are still inadequate to carry high in-plane bending moments associated with large shearing forces over long spans. The slender webs in plate girders are prone to local and shear buckling at relatively low shear and thus, need be stiffened to increase the shear resistance of the web. Analysis and design of plate girders incorporate post-buckling reserve strength which resists applied loads considerably in excess of the initial buckling load. Once a web plate has lost its capacity, further increase in compressive load does not cause sudden collapse of the girder. The thin web sustains additional compressive stress through development of inclined tensile membrane field which anchors against the top and bottom flanges, resulting in formation of buckle patterns. Such load carrying mechanism contributes significantly to the ultimate capacity of plate girders. Provisions of intermediate transverse stiffeners at certain intervals, in addition to preventing the torsion of flanges, serve as boundaries for the development of tensile membrane in the thin web. Through many years, studies on ultimate load behaviour of transversely stiffened plate girders were extensive in order to establish the philosophy and design procedures (Basler and Thurlimann 1960, Rockey and Skaloud 1971, Porter *et al*. 1975, Narayanan and Adorisio 1983, Lee and Yoo 1998, Yoo and Lee 2006). Additionally, the stability of a web plate can also be enhanced by subdividing the individual panels with longitudinal stiffeners. Studies have been carried out in the past in order to determine the number, dimensions and positioning of the longitudinal stiffeners in a particular web panel for optimum performance of steel plate girders (Nishino and Okumura 1968, Rockey *et al*. 1978, Horne and Grayson 1983, Graciano and Edlund 2002, Alinia and Moosavi 2008). However, those dealing with inclined stiffeners are not many in the literature. Use of inclined stiffeners would result in unequal diagonal length and unequal subdivisions of web panels at the top compression and bottom tension flanges. Inclined stiffeners would also have the advantage of limiting the shear factor without requiring the expensive addition of longitudinal stiffeners (Guarnieri 1985). Therefore, there may be variations in the post-buckling strength and failure characteristic of plate girders due to effects of the inclination. Such variations are to be investigated in order to enhance understanding of the behaviour of stiffened plate girders. Non-linear finite element investigation on such girders has, therefore, been undertaken using a finite element package. Attention is focused on aspects such as inclination degree of the stiffeners as well as the web opening shape and size in order to highlight the benefits of using inclined stiffeners over the traditional vertical stiffeners.

2 FINITE ELEMENT MODELLING

Three-dimensional finite element models were developed by using LUSAS system. Non-linear analyses were carried out on 55 plate girder models having different degrees of inclined stiffeners and configurations of web openings. These girders are basically modified from girder SPG 1 tested in the past by Shanmugam and Baskar (2003) in order to suit the intentions of the study. Stiffeners were placed accordingly on both sides of the web plate, thus subdividing the thin web into four web panels. Vertical stiffeners are placed at the mid-span to prevent local buckling due to application of concentrated loads. Different angles of inclination viz., 30^o to 90^o in the increment of 15^o, are considered for the intermediate stiffeners in the girders. The basic dimensions were kept the same in all girders in order to have a constant span length, L = 4680 mm, depth of web panel, d = 750 mm, thickness of web, t = 3 mm, flange width, b_f = 200 mm, flange thickness, t_f = 20 mm and web slenderness ratio, d/t = 250. Details of the girders and the corresponding material properties are presented in Tables 1 and 2, respectively. The geometries of web, flanges and stiffeners were meshed with three-dimensional quadrilateral shell elements. Each of the elements consists of four corner and four intermediate nodes. The element formulation takes account of membrane, flexural and transverse shear deformations which are suitable in thin wall applications. The element comprises six degrees of freedom viz., translations and rotations with respect to global axes at each node.

In order to confirm the accuracy of the modeling, comparisons of results for the original girders have been made with the corresponding experimental ones. Regular finite element mesh with division size of 50 mm was adopted in all the analysis. It was chosen based on convergence studies carried out to determine the optimal element size that produces a relatively accurate solution in terms of strength and behavior within an acceptable computational time. Typical finite element meshes used for the analysis is depicted in Figure 1. The steel plate girders were modelled as isotropic elastic-perfectly plastic materials in both tension and compression, giving a uniaxial stress-strain relationship. All parameters needed to define this stress potential material model are listed in Table 2. These values are obtained from the experimental works reported by

Shanmugam and Baskar (2003). The non-linear properties are based on Von-Mises yield criterion which represents the ductile behavior of steel material that exhibits little volumetric strain.

Detailed boundary conditions were imposed to the finite element model to reflect simple i.e., pin and roller support conditions. At the pin support, the girder was restrained against the displacements in global *x*-, *y*- and *z*-directions but free to move along *z*-direction at the roller support. Nevertheless, rotations about all directions were allowed for in both types of support conditions. A vertical concentrated load was applied to the girder incrementally. In LUSAS, convergence criteria is based on force and displacement. An automatic load increment with Crisfield's arc length control was selected. Newton-Raphson solution strategy with a particular number of iterations was used to provide convergence at the end of each load increment within tolerance limits. Also, load step reduction with specified reduction factor and increase factor was allowed for. This procedure has a potential to step over a difficult point in the analysis so that the solution can proceed to lead to convergence. Termination of analysis was, however, limited to the default criteria.

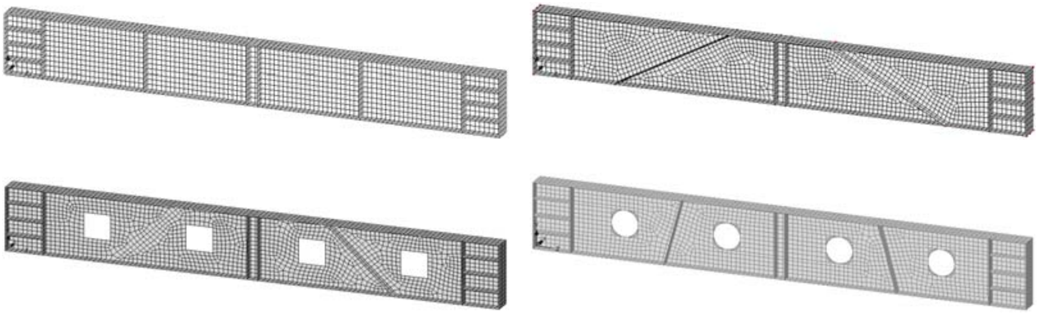

Figure 1. Typical finite element meshes.

3 RESULTS AND DISCUSSION

Ultimate loads obtained from the numerical analyses, P_u along with the ratio P_u / P_{u0} are listed in Table 1 in which, P_{u0} is the ultimate load obtained for plate girder stiffened vertically (90°) and without web openings. For the unperforated girders, it is clear from the table that the ultimate load increased significantly when the inclined stiffeners were used in place of the vertical stiffeners. For example, the ultimate load carrying capacity has been improved by 12% and 38% when the stiffeners were made inclined by 60° and 30°, respectively. In the girders with centrally located square web openings, the ultimate strength shows 56% reduction when the size of openings were enlarged from 0.1*d* to 0.5*d* for the girder with intermediate vertical stiffener, whilst those with inclined stiffeners, the percentage drop from 52% (75° inclination) to the extent of 39% (30° inclination). Moreover, the load carrying capacity of the girder with 30° inclined stiffeners remained unaffected even though the opening size as large as 0.4*d* was introduced in the web panel. These portray the advantage of using inclined stiffeners as stiffening element for the thin webs. Variations of ultimate strength for the girders containing circular web openings, however, exhibit similar pattern as those having square.

Figure 2 shows the typical predicted deformed shapes of the girders at failure load. In all the girders, after reaching the elastic critical load, the web panels started to buckle along the diagonal parallel to the tensile direction, indicating the formation of tension field. Further loading in the post-buckling stage was resisted by tensile membrane action, leading to increase in out-of-plane deformation of the web due to shear. At this stage, the increase in applied load gives rise to the corresponding vertical displacement larger compared to that in the elastic phase. Formation of plastic hinges in the top and bottom flanges can be observed in the figure. The stiffeners at the support were strong enough to anchor the horizontal and vertical components of the diagonal tensile force. Hinges that formed in the flanges were caused by the vertical component of the pulling force from the tension field. The central portion of the girder between the internal hinges remained straight and horizontal instead of being curved in elevation as in the normal beam behaviour.

The accuracy of the models has been ascertained through comparison with the available experimental results at the initial stages of modelling particularly the original girder with intermediate vertical stiffeners and without web openings, hence it is assumed that predictions for other models with inclined intermediate stiffeners are considerably correct. However, further experimental and analytical works on such girders as well as design recommendations are essential in order to understand the mechanisms clearly and add significantly to the knowledge of the related fields.

Table 1. Details of plate girders considered for finite element modelling.

Girder	**Inclination angle of stiffeners, θ (degree)**	**Web opening shape**	**Diameter of web opening, d_0 (mm)**	**Ultimate load, P_u (kN)**	P_u / P_{u0}
A90D0	90	NA	NA	442	1.00
A75D0	75			467	1.06
A60D0	60			494	1.12
A45D0	45			533	1.21
A30D0	30			610	1.38
A90D1S	90	Square	0.1*d*	416	0.94
A90D2S			0.2*d*	362	0.82
A90D3S			0.3*d*	338	0.76
A90D4S			0.4*d*	248	0.56
A90D5S			0.5*d*	182	0.41
A75D1S	75	Square	0.1*d*	436	0.99
A75D2S			0.2*d*	377	0.85
A75D3S			0.3*d*	354	0.80
A75D4S			0.4*d*	262	0.59
A75D5S			0.5*d*	208	0.47
A60D1S	60	Square	0.1*d*	464	1.05
A60D2S			0.2*d*	400	0.90
A60D3S			0.3*d*	358	0.81
A60D4S			0.4*d*	290	0.66
A60D5S			0.5*d*	216	0.49
A45D1S	45	Square	0.1*d*	509	1.15
A45D2S			0.2*d*	445	1.01
A45D3S			0.3*d*	372	0.84

A45D4S			0.4*d*	310	0.70
A45D5S			0.5*d*	243	0.55
A30D1S	30	Square	0.1*d*	606	1.37
A30D2S			0.2*d*	585	1.32
A30D3S			0.3*d*	524	1.19
A30D4S			0.4*d*	442	1.00
A30D5S			0.5*d*	364	0.82
A90D1C	90	Circular	0.1*d*	424	0.96
A90D2C			0.2*d*	380	0.86
A90D3C			0.3*d*	332	0.75
A90D4C			0.4*d*	334	0.76
A90D5C			0.5*d*	244	0.55
A75D1C	75	Circular	0.1*d*	444	1.00
A75D2C			0.2*d*	396	0.90
A75D3C			0.3*d*	344	0.78
A75D4C			0.4*d*	320	0.72
A75D5C			0.5*d*	264	0.60
A60D1C	60	Circular	0.1*d*	472	1.07
A60D2C			0.2*d*	422	0.95
A60D3C			0.3*d*	370	0.84
A60D4C			0.4*d*	320	0.72
A60D5C			0.5*d*	290	0.66
A45D1C	45	Circular	0.1*d*	512	1.16
A45D2C			0.2*d*	472	1.07
A45D3C			0.3*d*	414	0.94
A45D4C			0.4*d*	358	0.81
A45D5C			0.5*d*	342	0.77
A30D1C	30	Circular	0.1*d*	608	1.38
A30D2C			0.2*d*	596	1.35
A30D3C			0.3*d*	568	1.29
A30D4C			0.4*d*	512	1.16
A30D5C			0.5*d*	458	1.04

Table 2. Material properties of plate girders used for finite element modelling.

Girder	**Young's modulus, E_s (GPa)**	**Yield stress, $f_{y\,(avg)}$ (MPa)**	**Ultimate stress, $f_{u\,(avg)}$ (MPa)**
All	200	277	423

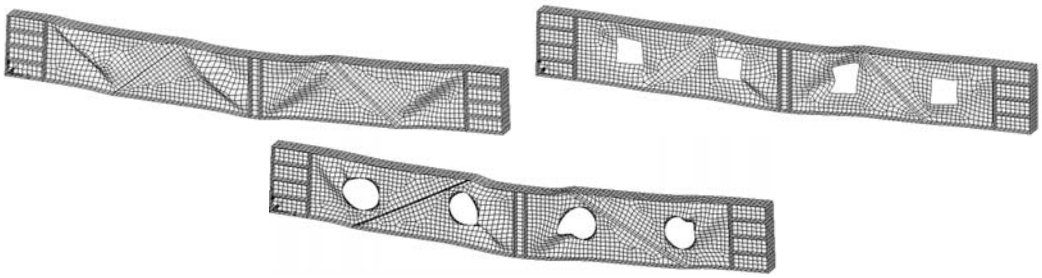

Figure 2. Typical deformation at failure.

3 CONCLUSIONS

Non-linear finite element analysis has been carried out on simply supported thin-webbed steel plate girders with inclined intermediate stiffeners. Results have shown the variations of ultimate strength and behavior at failure. Different degrees of inclination angles of the stiffeners, sizes of web openings and shapes of web openings are accounted for in this numerical study. It can be concluded from the findings that inclination degree of the stiffeners affect significantly the load carrying capacity of the girders. This preliminary study has provided some general insights regarding the ultimate load behavior of plate girders having inclined stiffeners and therefore, further experimental investigations and detailed analytical works are strongly recommended.

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