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Ultimate Load Behaviour of Perforated Steel Plate Girders with Inclined Stiffeners

Kelakuan Beban Muktamad Galang Plat Keluli Berlubang dengan Pengukuh Condong

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ABSTRACT

This paper is concerned with the ultimate load behaviour of perforated thin-webbed steel plate girders with inclined web stiffeners. Non-linear modelling and analyses were carried out on simply supported plate girders using a commercial finite element software, 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 behaviour of such girders are investigated. Variations of ultimate strength, failure characteristic and load-deflection response are obtained from the analyses. The load carrying capacity is found to increase significantly when the inclined intermediate stiffeners were provided to the girders; to the extent of 38% for the unperforated girders whilst 45% for those having web openings. Reduction of shear strength due to presence of web openings may also be improved from 56% in the girders stiffened vertically to only 24% in the girders provided with inclined stiffeners of 30*^{o}.

Keywords: Slender girder; web opening; inclined stiffener; non-linear analysis; ultimate load behaviour

ABSTRAK

Kertas ini adalah tentang kelakuan beban muktamad galang plat keluli berweb nipis yang berlubang dengan pengukuh web condong. Permodelan dan analisis tidak linear telah dijalankan ke atas galang plat tersokong mudah dengan menggunakan perisian komersil unsur terhingga, LUSAS. *Saiz galang-galang tersebut adalah praktikal dan dikenakan beban tumpu tunggal pada pusat graviti keratan. Kesan-kesan seperti darjah kecondongan pengukuh dan bukaan web terhadap prestasi dan kelakuan galang terbabit dikaji. Pelbagai variasi kekuatan muktamad, ciri kegagalan dan respons beban-pesongan diperolehi daripada analisis. Kapasiti tanggungan beban oleh galang didapati meningkat dengan signifikan apabila pengukuh condong digunakan; sehingga 38% untuk galang tanpa bukaan sementara 45% untuk galang dengan bukaan web. Pengurangan kekuatan ricih yang disebabkan oleh bukaan web dapat ditambah baik daripada 56% bagi galang terkukuh menegak kepada hanya 24% bagi galang dengan pengukuh condong 30*^{o}.

Kata kunci: Galang langsing; bukaan web; pengukuh condong; analisis tidak linear; kelakuan beban muktamad

INTRODUCTION

Plate girders are employed in structural applications whenever the largest 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 of strength which resists applied forces 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 membrane which anchors against the top and bottom flanges, resulting in formation of buckle patterns. Such load carrying mechanism is called tension field action that 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 slender web. Through many years, studies on the ultimate load behaviour of transversely stiffened plate girders were extensive in order to establish the philosophy and design procedures (Basler & Thurlimann 1960, Rockey & Skaloud 1971, Porter et al. 1975, Narayanan & Adorisio 1983, Lee & Yoo 1998, Yoo & Lee 2006). In addition, 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 & Okumura 1968, Rockey et al. 1978, Horne & Grayson 1983, Graciano & Edlund 2002, Alinia & Moosavi 2008). However, those dealing with inclined stiffeners are not many and seem to require more attention.

Plate girders with web openings have found increasing popularity in civil engineering constructions due to their beneficial characteristics of providing spaces for services, inspection and periodic maintenance. This form of construction 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 parameters of the openings. The loss of strength can be restored by reinforcing the openings using steel flats or bars which is costly and complicate the fabrication process (Lian & Shanmugam 2003).

Use of inclined stiffeners 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 need 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 angle of the stiffeners as well as the web opening shape and size in order to highlight the benefits of using inclined stiffeners over the conventional vertical stiffeners. Details of the numerical modelling are reported herein along with the results obtained.

FINITE ELEMENT ANALYSIS

FINITE ELEMENT MODEL

Three-dimensional finite element models were developed by using LUSAS package. 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 the girder SPG 1 tested in the past by Shanmugam and Baskar (2003) in order to suit the intentions and objectives 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 premature failure due to local buckling. Different angles of inclination, θ viz., 30^o to 90^o in the increment of 15^o, are considered for the intermediate stiffeners in the girders. Two shapes of centrally located web openings viz., square and circular having diameter, d_0 of 0.1d, 0.2d, 0.3d, 0.4d and 0.5d, are accounted for in this study. 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_w = 3 mm, flange width, b_f = 200 mm, flange thickness, t_f = 20 mm and web slenderness ratio, d/t = 250. Details of the models developed for verification and for the present study, and the corresponding material properties are presented in Tables 1 and 2, respectively.

ELEMENT

Various types of elements are available in the LUSAS element library. Proper selection of elements is important as they dictate the behaviour of the model. 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 for thin wall applications. A consistent formulation of the tangent stiffness makes this element particularly effective in geometrically non-linear treatment. The quadrilateral elements use an assumed strain field to define transverse shear which ensures that the element does not lock when it is thin. The element comprises six degrees of freedom viz., translations and rotations with respect to global axes at each node.

MESH

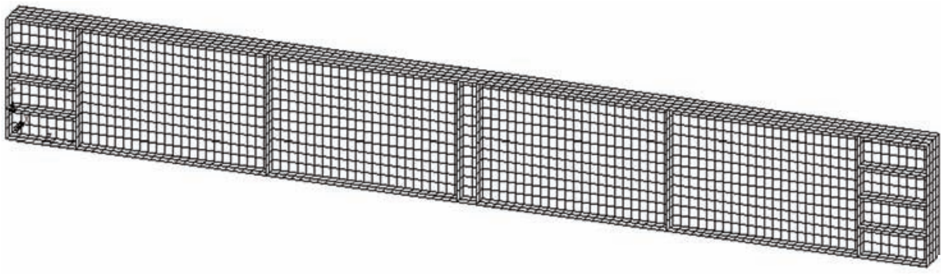
In order to confirm the accuracy of the modelling, comparisons of results for the original girders have been made with the corresponding experimental values. Regular finite element mesh with division size of 50 × 50 mm was adopted in all the analysis. It was chosen largely based on convergence studies carried out to determine the optimal element size that produces a relatively accurate solution in terms of strength and behaviour within an acceptable computational time. However, irregular mesh was allowed for at the web surfaces due to effect of inclination of the intermediate stiffeners. A typical finite element model is displayed in Figure 1.

TABLE 1. Details of plate girders tested by other researchers

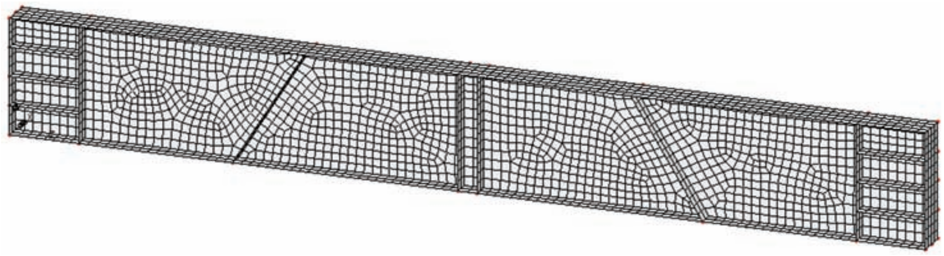
Girder	Inclination angle of stiffeners, θ	Shape of web openings	Diameter of web openings, d_0 (mm)	Modulus of elasticity, E_s (GPa)	Average yield stress, $f_{y\,(avg)}$ (MPa)
SPG 1 (Shanmugam & Baskar 2003)	90^o	NA	NA	200	277
NCP 10 (Narayanan & Der Avanessian 1983)	90^o	Rectangular	$b_0 \times d_0$ (300 × 240)	200	243
CP 4 (Narayanan & Rockey 1981)	90^o	Circular	0.5d	200	251

TABLE 2. Details of plate girders in the present study

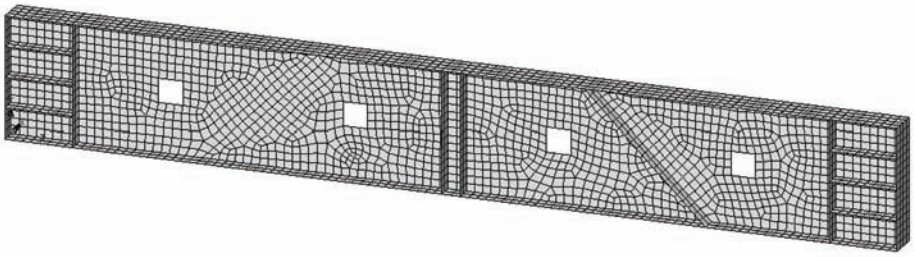
Girder	Inclination angle of stiffeners, θ	Shape of web openings	Diameter of web openings, d_0 (mm)	Modulus of elasticity, E_s (GPa)	Average yield stress, $f_{y\,(avg)}$ (MPa)
A90D0	90^o	NA	NA	200	275
A75D0	75^o				
A60D0	60^o				
A45D0	45^o				
A30D0	30^o				
A90D1S	90^o	Square	0.1*d*	200	275
A90D2S			0.2*d*		
A90D3S			0.3*d*		
A90D4S			0.4*d*		
A90D5S			0.5*d*		
A75D1S	75^o	Square	0.1*d*	200	275
A75D2S			0.2*d*		
A75D3S			0.3*d*		
A75D4S			0.4*d*		
A75D5S			0.5*d*		
A60D1S	60^o	Square	0.1*d*	200	275
A60D2S			0.2*d*		
A60D3S			0.3*d*		
A60D4S			0.4*d*		
A60D5S			0.5*d*		
A45D1S	45^o	Square	0.1*d*	200	275
A45D2S			0.2*d*		
A45D3S			0.3*d*		
A45D4S			0.4*d*		
A45D5S			0.5*d*		
A30D1S	30^o	Square	0.1*d*	200	275
A30D2S			0.2*d*		
A30D3S			0.3*d*		
A30D4S			0.4*d*		
A30D5S			0.5*d*		
A90D1C	90^o	Circular	0.1*d*	200	275
A90D2C			0.2*d*		
A90D3C			0.3*d*		
A90D4C			0.4*d*		
A90D5C			0.5*d*		
A75D1C	75^o	Circular	0.1*d*	200	275
A75D2C			0.2*d*		
A75D3C			0.3*d*		
A75D4C			0.4*d*		
A75D5C			0.5*d*		
A60D1C	60^o	Circular	0.1*d*	200	275
A60D2C			0.2*d*		
A60D3C			0.3*d*		
A60D4C			0.4*d*		
A60D5C			0.5*d*		
A45D1C	45^o	Circular	0.1*d*	200	275
A45D2C			0.2*d*		
A45D3C			0.3*d*		
A45D4C			0.4*d*		
A45D5C			0.5*d*		
A30D1C	30^o	Circular	0.1*d*	200	275
A30D2C			0.2*d*		
A30D3C			0.3*d*		
A30D4C			0.4*d*		
A30D5C			0.5*d*		



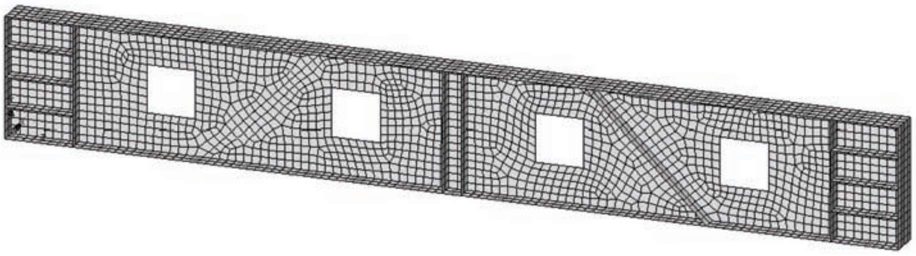
(a) Girder A90D0



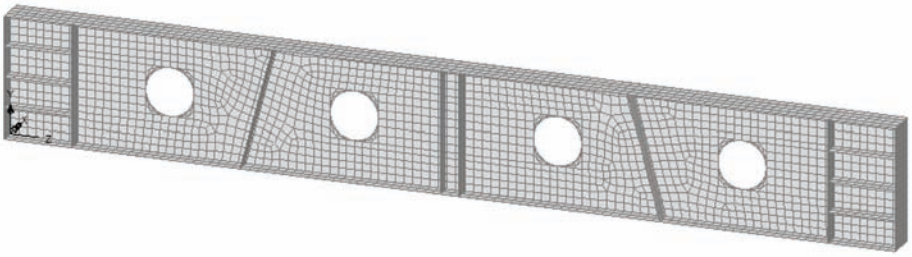
(b) Girder A60D0



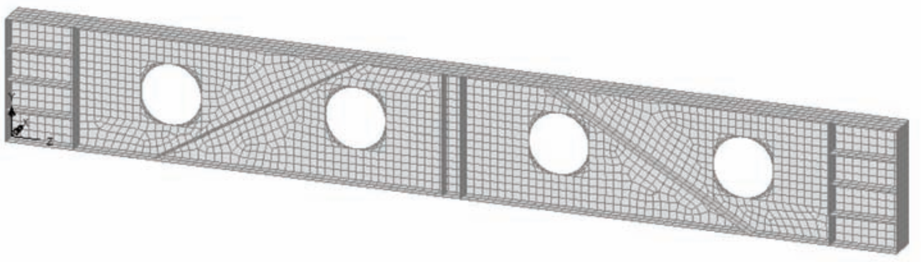
(c) Girder A45D2S



(d) Girder A45D5S



(e) Girder A75D4C



(f) Girder A30D5C

FIGURE 1. Typical finite element meshes

MATERIAL MODEL

The steel plate girders were modelled as isotropic elastic-perfectly plastic materials, giving a uniaxial stress-strain relationship as shown in Figure 2. Parameters needed to define this stress potential material model are listed in Table 1. These values are taken from experimental works reported by earlier researchers (Shanmugam & Baskar 2003, Narayanan & Der Avanessian 1983, Narayanan & Rockey 1981). The non-linear properties are based on Von-Mises yield criterion which represents the ductile behaviour of steel material that exhibits little volumetric strain.

BOUNDARY CONDITION AND LOADING

Detailed boundary conditions were imposed to the finite element model to reflect simple support conditions i.e., pin and roller. 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, the convergence criterion is based on force and displacement. An automatic load increment with Crisfield's arc length control was selected. Newton-Raphson solution strategy with a specified 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.

INITIAL IMPERFECTION

Generally, plates used in thin-walled applications are not perfectly flat but may have small initial imperfections. These initial imperfections can take the form of non-uniformity or local variations in the physical properties of the material, deviations in shape and load eccentricities (Alinia et al. 2009). Residual compressive stresses in a slender plate induced by uneven cooling after rolling or welding cause it to premature buckling. A perfectly flat and undeformed model may be stiff and basically yields different response compared to the one having imperfect geometry.

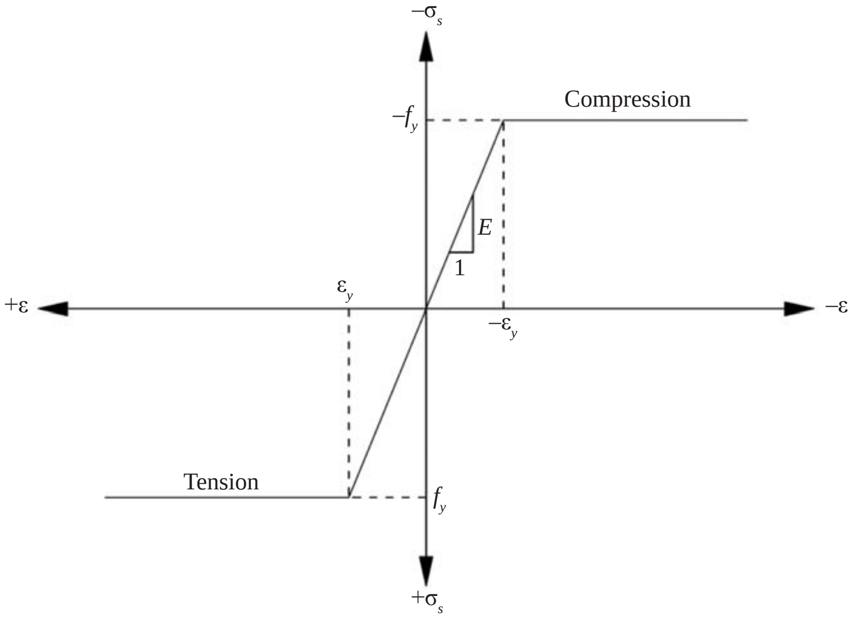


FIGURE 2. Uniaxial stress-strain relationship for steel material

Initial imperfections can be initiated in several ways in the modelling. One method is by manually defining the appropriate geometry during pre-processing stage. Alternatively, according to Chen and Jia (2010) and Basher et al. (2011), an imperfection model can be built into the initial model by loading the results file from buckling analysis in which, the deformed mesh is considered as initially imperfect geometry of the girder. The latter technique was adopted in the present study as it is more feasible as far as geometric modelling is concerned. The buckling analysis predicts the possible deformed shapes due to structural instability. The subspace iteration algorithm available in LUSAS facilities was employed for solving the associated eigenvalue problems. Different deformed shapes or eigenvectors obtained from the buckling analysis were attempted for further non-linear analysis. From extensive trials, a mode shape from the first extracted eigenvalue was assumed as the imperfection model since it has provided satisfactory results as far as ultimate load behaviour is concerned.

RESULTS AND DISCUSSION

ULTIMATE LOAD CAPACITY AND ACCURACY OF MODEL

It is imperative to validate the models before carrying out further analysis. The assessment of the accuracy was made through comparisons between the finite element predictions and the corresponding experimental results for the girders SPG 1 (Shanmugam & Baskar 2003), NCP 10 (Narayanan & Der Avanessian 1983) and CP 4 (Narayanan & Rockey 1981). Finite element analysis provided a detailed output from which the ultimate loads and deformation behaviour can be extracted. Finite element results for ultimate load, $P_{u,}$ is tabulated in Table 3 along with the corresponding experimental values, $P_{u, exp}$. It is apparent from the ratio $P_{u,}$ / $P_{u, exp}$ that the finite element and experimental values are relatively close within acceptable level of accuracy, i.e., ±10%. Thus, it can be concluded that the proposed finite element model is capable of predicting the ultimate strength of steel plate girders with good approximation.

Ultimate loads obtained from the numerical analyses, P_u along with the ratio P_u / P_{u0} are listed in Table 4 in which, P_{u0} is the ultimate load obtained for plate girder stiffened

TABLE 3. Verification of numerical model

Girder	LUSAS	Experiment	$\frac{P_u}{P_{u, exp}}$
	P_u(kN)	$P_{u, exp}$ (kN)	
SPG 1 (Shanmugam & Baskar 2003)	470	488	0.96
NCP 10 (Narayanan & Der Avanessian 1983)	130	143.6	0.91
CP 4 (Narayanan & Rockey 1981)	86	86	1.00

TABLE 4. Comparison of ultimate loads

Girder	P_u (kN)	$\frac{P_u}{P_{u, exp}}$
A90D0	442 (P_{u0})	1.00
A75D0	467	1.06
A60D0	494	1.12
A45D0	533	1.21
A30D0	610	1.38
A90D1S	416	0.94
A90D2S	362	0.82
A90D3S	338	0.76
A90D4S	248	0.56
A90D5S	182	0.41
A75D1S	436	0.99
A75D2S	377	0.85
A75D3S	354	0.80
A75D4S	262	0.59
A75D5S	208	0.47
A60D1S	464	1.05
A60D2S	400	0.90
A60D3S	358	0.81
A60D4S	290	0.66
A60D5S	216	0.49
A45D1S	509	1.15
A45D2S	445	1.01
A45D3S	372	0.84
A45D4S	310	0.70
A45D5S	243	0.55
A30D1S	606	1.37
A30D2S	585	1.32
A30D3S	524	1.19
A30D4S	442	1.00
A30D5S	364	0.82
A90D1C	424	0.96
A90D2C	380	0.86
A90D3C	332	0.75
A90D4C	334	0.76
A90D5C	244	0.55
A75D1C	444	1.00
A75D2C	396	0.90
A75D3C	344	0.78
A75D4C	320	0.72
A75D5C	264	0.60
A60D1C	472	1.07
A60D2C	422	0.95
A60D3C	370	0.84
A60D4C	320	0.72
A60D5C	290	0.66
A45D1C	512	1.16
A45D2C	472	1.07
A45D3C	414	0.94
A45D4C	358	0.81
A45D5C	342	0.77
A30D1C	608	1.38
A30D2C	596	1.35
A30D3C	568	1.29
A30D4C	512	1.16
A30D5C	458	1.04

vertically (θ = 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% (θ = 75°) to only 39% (θ = 30°). This indicates the effectiveness of inclined stiffeners as alternative element to restore the loss of strength in the perforated girders. 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 thin webs. Variations of ultimate strength for the girders containing circular web openings, however, exhibit similar pattern as those having square web openings.

Figure 3 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 typical plastic hinges in the top and bottom flanges can be observed in Figure 4. 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.

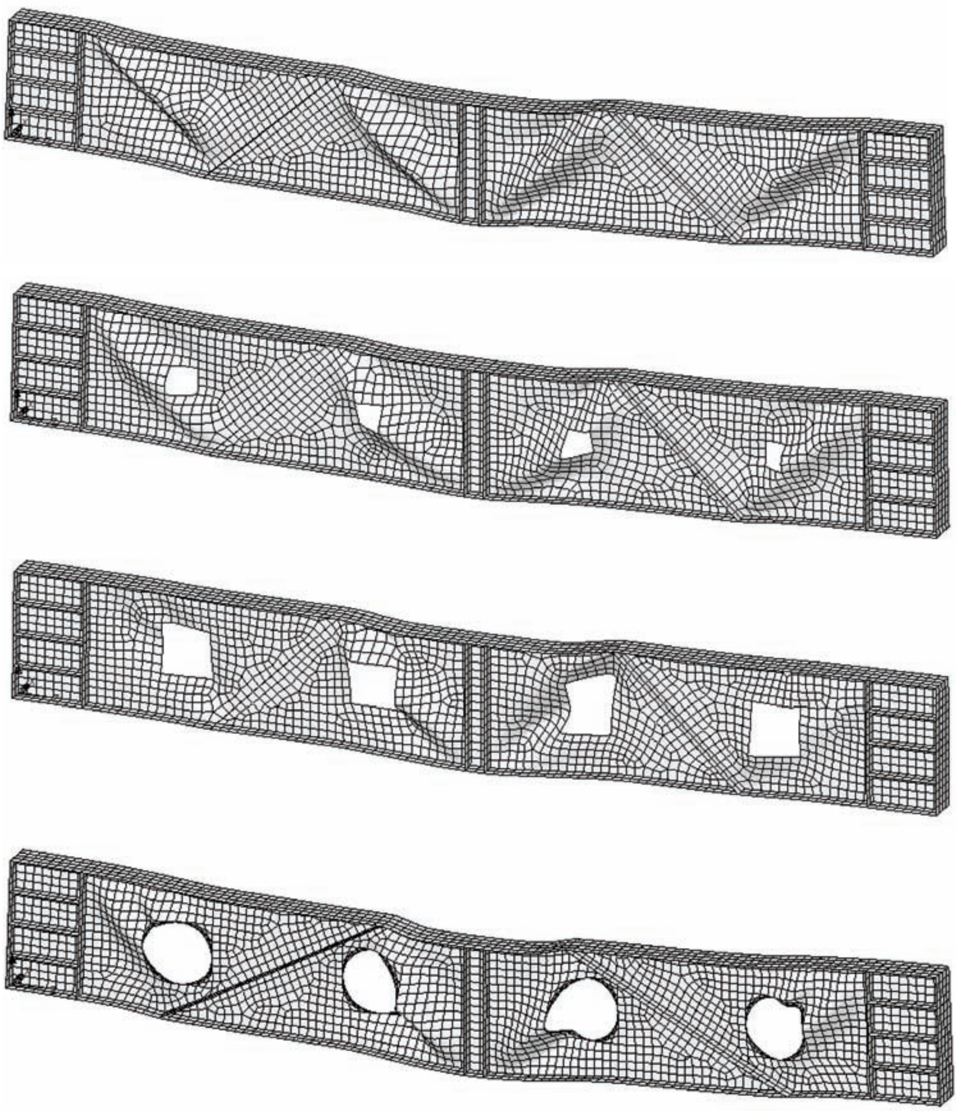


FIGURE 3. Typical deformation of girders at failure

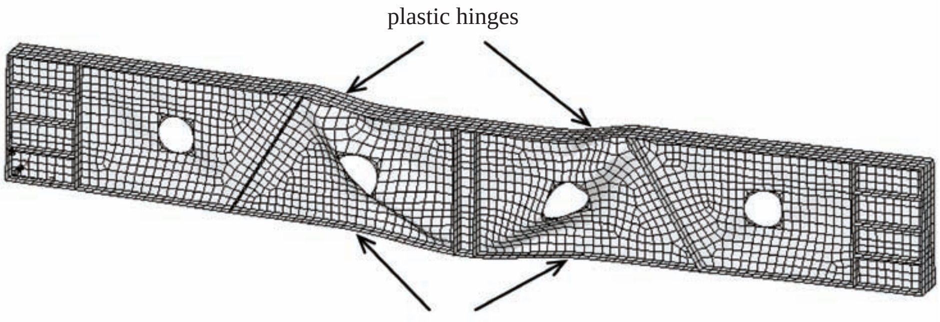


FIGURE 4. Typical formation of plastic hinges

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 as well as design recommendations are essential in order to understand the mechanisms clearly and add significantly to knowledge of the related fields.

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 behaviour 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 use of inclined stiffeners affects significantly the load carrying capacity of plate girders. This preliminary study has, therefore, provided some general insights regarding the ultimate load behaviour of plate girders having inclined stiffeners and thus, further analysis on stiffeners with inclination angle lower than 30^o may be looked into. In addition, experimental investigations and detailed theoretical works are strongly recommended.

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