OPEN ACCESS

International
Journal
Of Modern Engineering Research (IJMER)

Effect of Imperfection on Shear Behaviour of Hybrid Plate Girder

Ajeesh S S[1], Sreekumar S.[2]

[1, 2] (Ajeesh S.S, M.Tech student, Professor, Department of Civil Engineering, College of Engineering Trivandrum, Kerala)

Abstract: *The influence of initial imperfection of plates on the shear resistance of hybrid plate girder fabricated using slender plate elements is studied. Nonlinear finite element analysis was performed to compute the ultimate shear strength of hybrid girder. Imperfection analysis was performed by varying the magnitude of imperfection on web panel of hybrid plate girder to compare the variation in ultimate shear strength. The study was also done by varying the yield strength and slenderness ratio of web panel. The result of the study indicates that the ultimate shear strength of hybrid plate girder decreases with increase in the magnitude of initial imperfection. The effect of imperfection on shear strength was significantly high for plate girder with low web slenderness ratio and high yield strength of web panel. The maximum lateral as well as the vertical deflection at ultimate strength state of the model increases with increase in magnitude of imperfection.*

Keywords: *buckling, finite element analysis, hybrid, imperfection, nonlinear, steel plate girder, ultimate shear strength, web panel.*

I. Introduction

Usage of high strength steel is now prominent in the steel design and construction industry, which necessitate making of hybrid structures with thin walled slender sections. The low strength-weight ratio is one of the main advantages of such structures, consequently considerable economy and material savings can be achieved. On the other hand, these structures are more susceptible to deformations due to instability related issues. Buckling of slender members is the main kind of stability loss affecting the shear resistance of thin walled steel structures. In the process of fabrication, particularly welding, initial imperfections may occur to some extent in thin plate components of steel structural members. Hybrid plate girders have different grades of steel for flanges and web panel. Usually the flanges of the girder are fabricated using high strength steel and comparatively low strength steel is used for the web panel.

Lee and Yoo[1] conducted finite element analysis to study the effect of imperfections on shear strength of plate girder. The effect of web slenderness ratio on imperfection was also discussed. Hassanein[2] compared the effect of imperfection on shear strength by varying flange width to web depth ratio, flange to web thickness ratio, and web slenderness ratio of stainless steel plate girders. Chacon et al.[3] performed finite element analysis on the patch load resistance of hybrid plate girder by incorporating the effect of initial imperfection. Kala et al.[4] conducted finite element analysis to study the effect of initial imperfections on the load carrying capacity of plate girder. The effect of the shape of initial curvature and the magnitude of initial curvature were considered in the analytical study. Alinia et al.[5] analysed a number of full scale plate girders to determine their shear failure mechanism characteristics. Gheitasi and Alina[6] studied the post bucking behaviour of slender unstiffened shear plates of stainless steel and aluminium girders. Numerical investigation was conducted by Zhou et al.[7] on the shear behaviour of aluminium alloy pate girders. Studies related to the effect of imperfection on shear resistance of hybrid plate girder are scarce.

The effect of initial imperfection in the web panel of hybrid plate girder is analysed in the present study. The analytical work presented here is mainly concentrated on the variation in magnitude of imperfection of web panel (d/100000 to d/10) on shear strength of hybrid plate girder where 'd' is the depth of plate girder Although the design codes limit the maximum imperfection to d/100, sufficient data was not available on imperfection analysis for plate girders fabricated using high strength steel and hence the imperfection magnitude was increased upto d/10. The study was extended by varying the web slenderness ratio as well as the yield strength of web panel. Nonlinear buckling analysis was performed to compare the effect of imperfection on ultimate shear strength of hybrid plate girder.

II. Shear resistance of hybrid girder

The web panel of plate girder is usually slender in cross section and susceptible to buckling phenomenon. There are two important contributions to the shear resistance of transversely stiffened plate girders:

- Shear buckling resistance of web panel
- Shear postbuckling resistance of web panel.

Web buckling due to shear is essentially a local buckling phenomenon. The elastic buckling stress (τ_{cr}) of a rectangular web plate (width c, depth d and thickness t_w) was given by Timoshenko and Gere[8] as

$$\tau_{cr} = k \frac{\pi^2 E}{12\left(1-\mu^2\right)\left(\frac{d}{t_w}\right)^2} \qquad (1)$$

Where E=Young's modulus of elasticity, μ=Poisson's ratio and k=web shear buckling coefficient.

The web shear buckling coefficient 'k' is a key factor influencing the shear strength of plate girder. The real boundary condition of the web–flange juncture is still unknown. The boundary of web panel is assumed to be simply supported in order to find the value of shear buckling coefficient in theoretical formulations. The shear buckling coefficient for simply supported edge condition is given by

$$k = 4 + \frac{5.35}{\left(c/d\right)^2} \qquad \text{for } c/d<1 \qquad (2)$$

$$k = 5.35 + \frac{4}{\left(c/d\right)^2} \qquad \text{for } c/d\geq 1 \qquad (3)$$

The nominal shear resistance of a plate girder can be calculated using any of the two methods proposed in IS 800:2007[9]- simple post critical method or tension field method. Both these methods consider the buckling of web panel as the governing failure criterion of the plate girder under shear load. The simple post critical method can be applied to both stiffened and unstiffened girders, provided that the web has transverse stiffeners at the supports. The nominal shear strength by this method is given by

$$V_n = A_v \tau_b \qquad (4)$$

Where A_v is the shear area and τ_b is the shear stress corresponding to web buckling.

The nonlinear shear stress and normal stress interaction that takes place from the onset of elastic shear buckling to the ultimate strength state contributes to postbuckling shear strength. For transversely stiffened girders, where the stiffener spacing lies within the range $1.0 \le c/d \le 3.0$,the tension field method utilizes the post buckling shear resistance of the girder. This reserve strength arises from the development of "tension field action" within the girder. Once the web panel of plate girder has buckled in shear, it loses its resistance to carry additional compressive stresses.

In the post buckling range, a new load carrying mechanism is developed, where by any additional shear load is carried by an inclined tensile membrane stress field. This tension field anchors against the top and bottom flanges and against the transverse stiffeners on either side of the web panel. The resistance offered by the web plate is analogous to that of the diagonal tie bars in a truss. The shear strength of plate girder (V_{tf}) according to tension field method is given by

$$V_{tf} = \left[A_v \tau_b + 0.9 w_{tf} t_w f_v \sin\phi\right] \leq V_p \qquad (5)$$

$$\boldsymbol{V_p = \frac{A_v f_{yw}}{\sqrt{3}}} \qquad (6)$$

Where V_p = plastic shear resistance of girder, w_{tf} = width of tension field, t_w = thickness of web panel, f_v = yield strength of tension field, φ = inclination of tension field and f_{yw} = yield strength of web panel.

In order to study the variation of yield strength of web panel on shear strength, a hybrid factor (HF) was introduced in the analytical study as given by

$$HF = f_{yf}/f_{yw} \qquad (7)$$

Where f_{yf} is the yield strength of flange plate and f_{yw} is the yield strength of web panel.

III. Imperfection analysis

Nonlinear finite element analysis was performed using the program ANSYS to study the effect of imperfection on hybrid plate girder. Structural steel conforming to the Indian Standard IS 2062[10] was chosen for modelling the girder by incorporating both geometrical and material nonlinearities. Thickness of the flange (t_f = 30 mm), depth of the web (t_w = 700 mm), and breadth of flange (b_f = 200 mm) were maintained constant for all finite element models. Modelling was done by adopting high strength steel for flanges (f_{yf}= 450 N/mm^2) and varying the material properties of web panel (f_{yw}= 250, 300, 350, 410 and 450 N/mm^2). The material nonlinearity was modelled using ideal elasto-plastic assumption. The material relationship was modelled as von Mises material with isotropic hardening law. Young's modulus of 2x10^5 N/mm2 and Poisson's ratio 0.3 were used for the analysis.

Finite element modelling of plate girder was performed using shell element having six degrees of freedom: translations in the x, y, and z directions, and rotations about the x, y, and z axes. Simply supported end condition was adopted for the model and concentrated force was applied on the mid span of the girder to calculate the shear strength of girder. The imperfections were introduced in one of the web panel using scaled first eigen buckling mode (Chacon et al.[3]). The finite element model used to study the effect of imperfection is shown in Fig.1.

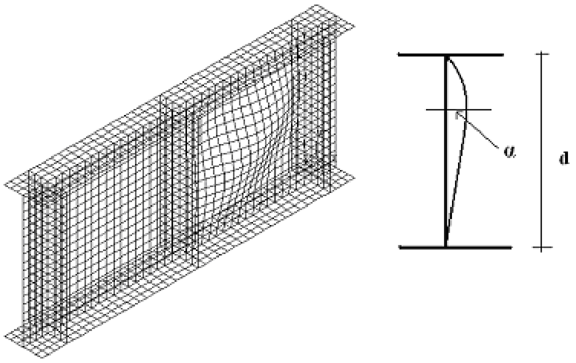

Fig.1 Finite element model with initial imperfection

The validation of the analytical procedure was done by analyzing a stainless steel plate girder problem reported in literature (Estrada et al [11]). Both critical shear buckling strength (V_{cr}) and ultimate shear strength (V_u) were computed using finite element method. The results of finite element analysis were comparable with the analytical and experimental results available (Table 1.). The error in the estimation of results using finite element method was less than 5%.

Table 1 Comparison of FEM results with experimental results

Girder	Present study		Analytical study by Estrada et al.[11]		Experimental study by Estrada et al.[11]	
	V_{cr} (kN)	V_u (kN)	V_{cr} (kN)	V_u (kN)	V_{cr} (kN)	V_u (kN)
nr700ad15	145	307	148.39	319.22	150	309.21
nr500ad25	177.5	232.8	178.62	231.37	175	228.05

In the present study, the ultimate shear strengths of 75 models were compared by varying the magnitude of imperfection (α), web slenderness ratio (d/t_w) and hybrid factor (HF) of the girder.

IV. Results and discussion

The results of finite element analysis used for comparison of ultimate shear strength are summarised in Table 2. The effect of imperfection on ultimate shear strength was compared by varying the magnitude of imperfection and thickness of web panel. Three web slenderness ratios were incorporated in the analysis by setting the thickness of web panel t_w=6, 7 and 8 mm. The variation in hybrid factor was achieved by increasing the yield strength of web panel. Nonlinear buckling analysis was performed by incorporating material and geometric nonlinearity to compute the ultimate shear resistance of hybrid girder.

Table 2 Effect of imperfection on ultimate shear strength

Finite Element Model	d/t_w	t_f/t_w	b_f/t_w	Magnitude of imperfection (α)	Ultimate shear strength (kN)				
					$V_{u,FEM}$ (HF=1.8)	$V_{u,FEM}$ (HF=1.5)	$V_{u,FEM}$ (HF=1.29)	$V_{u,FEM}$ (HF=1.1)	$V_{u,FEM}$ (HF=1)
1	117	5	33	d/100000	599.89	676.31	751.56	842.43	901.63
2	117	5	33	d/10000	588.47	669.67	749.77	841.58	900.93
3	117	5	33	d/1000	568.21	655.73	738.96	834.03	894.77
4	117	5	33	d/100	576.87	659.23	742.58	842.15	907.69
5	117	5	33	d/10	562.8	634.07	703.06	783.69	836.52
6	100	4.2	28	d/100000	730.44	855.62	963.14	1058.78	1117.48
7	100	4.2	28	d/10000	717.06	843.04	946.1	1056.26	1127.46
8	100	4.2	28	d/1000	694.68	811.6	918	1037.1	1113.06
9	100	4.2	28	d/100	662.22	764.92	867.44	989.16	1068.9
10	100	4.2	28	d/10	638.32	723.86	807.54	905.94	970.48
11	88	3.8	25	d/100000	858.92	1007.28	1153.74	1321.1	1415.78
12	88	3.8	25	d/10000	837.94	988.48	1135.78	1301.64	1386.54
13	88	3.8	25	d/1000	810.66	959.24	1100.46	1250.54	1342.48
14	88	3.8	25	d/100	742.2	873.94	1001.18	1148.66	1243.76
15	88	3.8	25	d/10	714.56	816.9	917.92	1037.18	1115.4

As the magnitude of imperfection (α) increases from d/100000 to d/10, the ultimate shear strength of hybrid plate girder decreases. The maximum variation in ultimate shear strength with increase in imperfection magnitude was 7% for low values of web slenderness ratio (d/t_w = 117). The percentage decrease in ultimate shear strength becomes 21% for d/t_w = 88. Also the imperfection of web panel significantly reduces the load carrying capacity of plate girder with high web yield strength. The effect of imperfection becomes significant for low values of web slenderness ratio (d/t_w = 88) and hybrid factor (HF = 1).

The maximum lateral deflection of the web panel due to increase in load for various imperfection values is shown in Fig.2. An increase in lateral deflection of web panel is observed with increment in imperfection magnitude for all the hybrid plate girder models considered in the present study. For imperfection magnitude (α) less than d/1000, the percentage variation in maximum lateral deflection of web panel is less than 40%. A variation of 90% is observed in maximum lateral deflection, as the imperfection magnitude increases from d/1000 to d/100. For the model with α=d/10, the load-deflection graph loses its linearity at low load values compared to other imperfection magnitudes. The lateral deflection of the web panel gives a clear indication of the strength reduction in web panel with increase in imperfection magnitude.

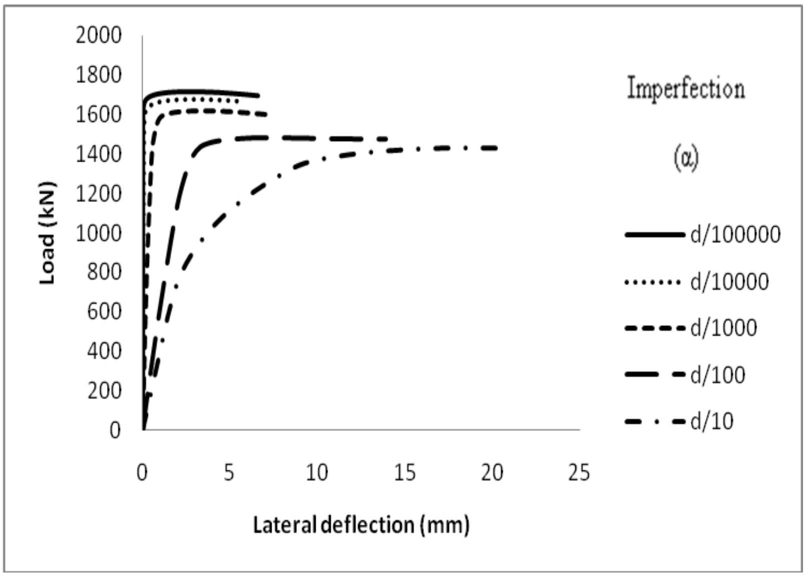

Fig.2 Plot of load versus maximum lateral deflection

(d/t_w=88, HF=1.8)

The vertical deflection of the plate girder model with increase in loading is compared for various imperfection magnitudes as shown in Fig.3. The load-deflection plots of the models were almost similar with increase in imperfection α upto d/100. The load deflection curve was linear for almost 80% of the maximum load for imperfection magnitude α≤d/100. The variation in magnitude of maximum vertical deflection of the girder was less than 70% with increase in α upto d/100. The vertical deflection of girder with α=d/10 was 110% greater than other imperfection magnitudes for highest load level. The highest imperfection factor suggested in most of the international welding standards is d/100.

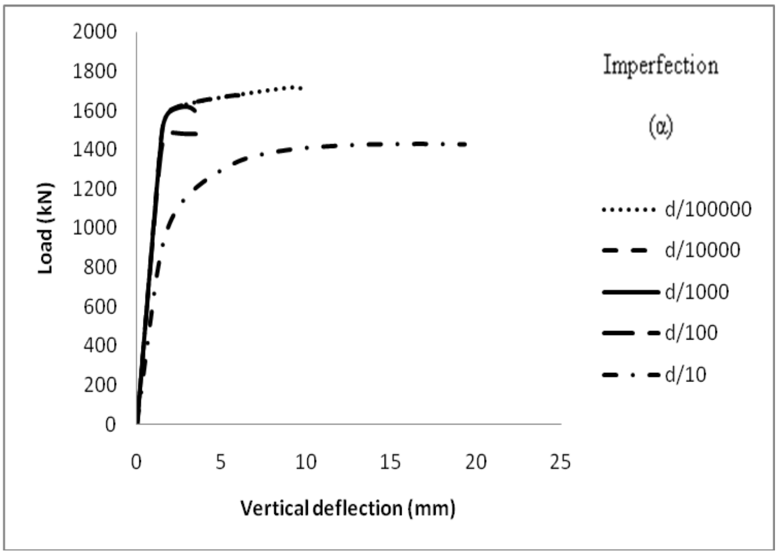

Fig.3 Plot of load versus vertical deflection (d/t_w=88, HF=1.8)

The von Mises stress distribution of the model (d/t_w=88, HF=1.8) for various imperfection values are compared in Fig.4. For all imperfections, the maximum von Mises stress values is observed in the flanges and this gives a clear indication of the contribution of flange plate in ultimate shear strength of the model. The von Mises stress in web panel also reaches the yield strength of web (250 MPa) at ultimate strength state for all imperfections. For imperfection magnitude d/100000, the von Mises stress in flanges reaches the yield strength of flange plate (450 MPa) at the point of loading in flange plate. For α=d/10, wide spreading of the maximum von Mises stress is observed in compression flange near the loading point. In the stress distributions, there is a clear indication of gradual development of tension yield band in the web panel at higher values of imperfections. Similar stress distributions were also obtained for other values of d/t_w (100 and 117) with various hybrid factors considered. As depth of girder and width and thickness of flange are taken as constant for all models considered, it is clear that the ratio of thickness of flange to web does not affect the mechanism of failure for all imperfections.

V. Conclusion

The main conclusions of the imperfection analysis of hybrid plate girder are listed below:

1. The imperfection on web panel significantly affects the shear load carrying capacity of hybrid plate girder and as the magnitude of imperfection increases, the ultimate shear strength of girder decreases.
2. The web slenderness ratio and yield strength of web panel are the two main factors which influences the ultimate shear strength of girder with imperfections in web panel. The percentage reduction in shear strength was 21% for low values of web slenderness ratio and hybrid factor of girder (d/t_w=88, HF=1).
3. The maximum lateral deflection as well as the vertical deflection of plate girder model increases with increase in imperfection magnitude from d/100000 to d/10.
4. As the magnitude of initial imperfection increases, the von Mises stress distribution in the web panel reaches the yield strength at relatively low value of applied loading.

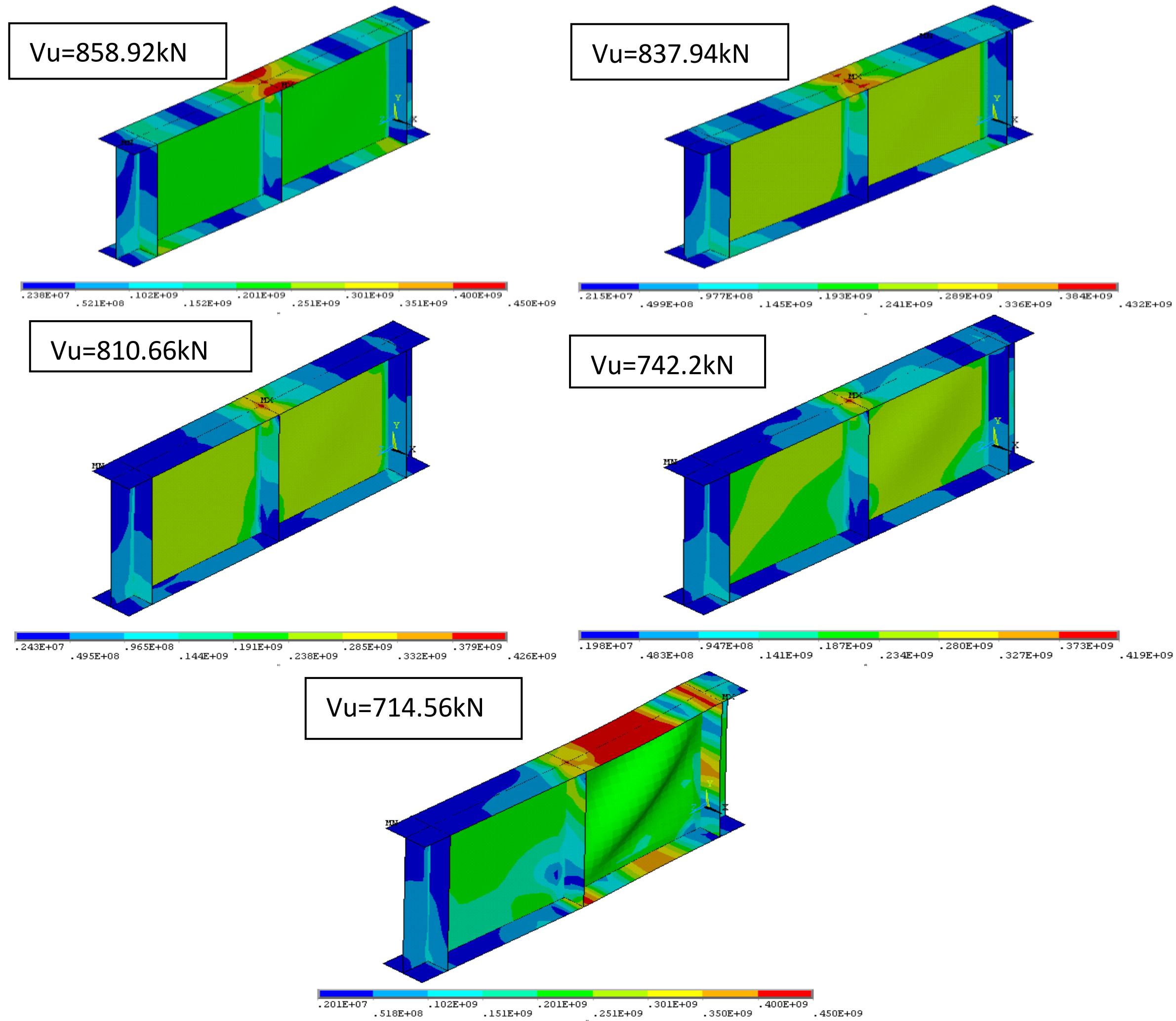

Fig.4 Von Mises stress distribution at ultimate stage for various imperfections (d/t_w=88, HF=1.8); (a) d/100000, (b) d/10000, (c) d/1000, (d) d/100, (e) d/10

REFERENCES

[1.] Lee, S. C., and Yoo, C. H. (1998), 'Strength of plate girder web panels under pure shear', Journal of Structural Engineering, 124, pp. 184–194.

[2.] Hassanein, M. F. (2010), 'Imperfection analysis of austenitic stainless steel plate girders failing by shear', Engineering Structures, 32, pp. 704–713.

[3.] Chacon, R., Mirambell, E., and Real, E. (2010), 'Hybrid steel plate girders subjected to patch loading, Part 1: Numerical study', Journal of Constructional Steel Research, 66, pp. 695–708.

[4.] Kala, Z., Kala, J., Melcher, J., Skaloud, M., and Omishore, A. (2009), 'Imperfections in steel plated structures – should we straighten their plate elements?', NSCC-2009, pp.552-555.

[5.] Alinia, M.M, Marvam Shakiba, and Habashi, H.R. (2009), 'Shear failure characteristics of steel plate girders', Thin-Walled Structures, 47,12, pp.1498-1506.

[6.] Gheitase, A., and Alinia, M.M. (2010), 'Slenderness classification of unstiffened metal plates under shear loading', Thin-Walled Structures, 48,7, pp.508-518.

[7.] Zhou, F., Young, B., and Lam, H.C. (2012), 'Welded aluminum alloy plate girders subjected to shear force', Advanced Steel Construction, 8, 1, pp.71-94.

[8.] Timoshenko, S. P., and Gere, J. M. (1961), Theory of elastic stability (2^{nd} ed), Newyork: McGraw-Hill.

[9.] IS 800:2007, 'Code of practice for general construction in steel', BIS, New Delhi-110002.

[10.] IS 2062:2006, 'Indian Standard hot rolled low, medium and high tensile structural steel', BIS, New Delhi-110002.

[11.] Estrada, I., Real, E., and Mirambell, E. (2007), 'General behavior and effect of rigid and non-rigid end post in stainless steel plate girders loaded in shear. Part I: Experimental study', Journal of Constructional Steel Research, 63, pp. 970–984.