Hybrid Design of Longitudinal Plate Girder

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Abstract — **Design and construction of steel structures utilizing hybrid plate girder with different grades of steel for web and flanges is now increasingly important in construction industry. The behaviour of web panel under shear loading is one of the major factors influencing the design of plate girder. The present analytical study using finite element method is mainly concentrated on the shear behaviour of hybrid plate girders under varying parameters such as aspect ratio, slenderness ratio, ratio of flange to web thickness and yield strength of web panel. The main objective of the work is to study the behaviour of hybrid plate girder subjected to center point load using Simple Post Critical Method and Tension Field Method specified as per IS 800: 2007 and compare it with the analytical results. It was observed that the results were closely matching with the tension field method. Accordingly a strength reduction factor for ultimate shear strength prediction by tension field method of IS 800:2007 was proposed.**

Keywords—hybrid plate girder, shear stress ,aspect ratio web slenderness ratio.

I. INTRODUCTION

Design and construction of steel structures utilizing hybrid plate girder with different grades of steel for web and flanges is now increasingly important in construction industry. The behaviour of web panel under shear loading is one of the major factors influencing the design of plate girder. The present analytical study using finite element method is mainly concentrated on the shear behaviour of hybrid plate girders under varying parameters such as aspect ratio, slenderness ratio and yield strength of web panel.

A plate girder is a beam built up from the plate elements to achieve more efficient arrangement of material than it is possible with rolled steel beams. Plate girders are economical where spans are long enough to allow saving in cost by proportioning for the particular requirements. Plate girders may be riveted, bolted or welded [9]. They are deep structural members subjected to transverse loads. They are used in building constructions and also in bridges as shown in Fig 1.1. The plate girders are economically and efficiently used for spans upto about 45m in building construction. The depth of plate girder may range up to 5m or more, 1.5m to 2.5m depths are very common.

Stiffeners, plates or angles, may be attached to the girder web by welding or bolting to increase the buckling resistance of the web. Stiffeners are also required to transfer the concentrated forces of applied loads and reactions to the web without producing local buckling. Splices are required for webs and flanges when full lengths of plates are not available from the mills or when shorter lengths are more readily fabricated. Splices provide the necessary continuity required in the web and flanges.

A plate girder is basically an I-beam built up from plates using riveting or welding. It is a deep flexural member that can carry loads which cannot be economically carried by rolled beams. Standard rolled sections may be adequate for many of the usual structures; but in situations where the load is heavier and the span is also large, the designer has the following choices.

- Use two or more regularly available sections, side-by-side.
- Use a cover-plated beam; i.e. weld a plate of adequate thickness to increase the bending resistance of the flange.
- Use a fabricated plate girder, wherein the designer has the freedom (within limits) to choose the size of web and flanges, or
- Use a steel truss or a steel-concrete-composite truss.

Among the options available, the first is usually uneconomical and does not satisfy deflection limitation. The second option is advantageous where the rolled section is marginally inadequate. Therefore the real choice lies between the plate girder and the truss girder. Plate girders have a moment resisting capacity in between rolled I sections and truss girders [5]. Truss girders involve higher cost of fabrication and erection, problems of vibration and impact, and require higher vertical clearance. For short spans (< 10 m) plate girders are uneconomical due to increase in connection cost and rolled I sections are the preferred choice.

As stated earlier, plate girders are deep flexural members used to carry loads that cannot be carried economically by rolled beams. Plate girders provide maximum flexibility and economy. In the design of a plate girder the designer has freedom of choosing the component parts of convenient size, but has to provide connections between the web and the flanges. Instances where large loads and large spans occur are: gantry girders provided in industrial buildings to carry the rails for large capacity overhead traveling crane, deep girders provided in power plant buildings to support bunkers, railway bridges and many other applications in industrial and residential buildings. Plate girders offer a unique flexibility in fabrication and the cross section can be made uniform or non uniform along the length. It is possible for putting the exact amount of steel required at each section along the length of the girder by changing the flange areas and keeping the same depth of the girder [11]. In other words, it can be shaped to match the bending moment curve itself. Thus a plate girder offers limitless possibilities to the creativity of the engineer.

The main objective of the work is to study the behaviour of hybrid plate girder subjected to center point load using simple post critical method and tension field method specified as per IS 800: 2007.Also an attempt is made to investigate the performance of the hybrid plate girder with various parameters. The parameters are aspect ratio, slenderness ratio and yield strength of web panel. Another objective is to develop an analytical model of the hybrid plate girder using ANSYS and compare the analytical results obtained with code results. This report makes it possible for an extended study of hybrid plate girders with varying web types. This study can also help a designer in choosing a hybrid plate girder for practical use, as it is found to be more economical, ensures more strength and reduces the weight of the girder.

II. DESIGN OF PLATE GIRDER ACCORDING TO IS 800:2007

Design and construction of steel structures utilizing hybrid plate girder with different grades of steel for web and flanges is now increasingly important in construction industry. It was found that the use of hybrid plate girders is cost-effective compared to ordinary plate girders. It ensures more strength to the girder and also reduces the weight of the girder. The ultimate shear strength of the hybrid plate girder was computed using Simple Post Critical Method and Tension Field Method and the results were compared. It was done by varying the material properties of the web panel (TABLE I). The selected grades were confirming to the Indian Standard IS 2062 and the various structural steel grades adopted were E 250, E 300, E350, E 410, and E 450[13].

TABLE I
MATERIAL PROPERTIES OF STRUCTURAL STEEL

Group	Yield Stress (MPa)			Young's Modulus (MPa)	Poisson's Ratio
	Web	*Flange*	*Stiffener*		
I	250	450	450	2 x 10^5	0.30
II	300	450	450	2 x 10^5	0.30
III	350	450	450	2 x 10^5	0.30
IV	410	450	450	2 x 10^5	0.30
V	450	450	450	2 x 10^5	0.30

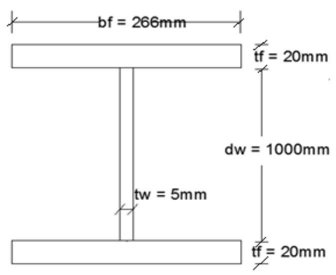


Fig 1. Section geometry

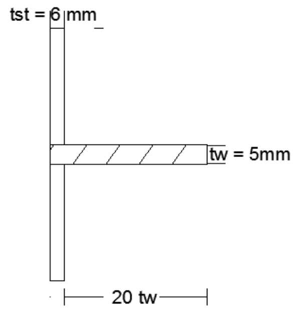


Fig 2. Area of the Effective Section for End Stiffener

A. *Design results*

TABLE II
SHEAR BUCKLING RESISTANCE USING SIMPLE POST CRITICAL METHOD AND TENSION FIELD METHOD

Group	Ultimate Shear Strength (kN)		% increase
	Simple Post Critical Method	*Tension Field Method*	
I	143.33	270.27	88.56
II	172.00	284.78	65.56
III	200.66	299.22	49.11
IV	235.06	316.47	34.63
V	258.00	327.94	27.11

The graph shows the variation in shear buckling resistance using Simple Post Critical Method and Tension Field Method. It is observed that tension field method gives a higher value for shear buckling resistance when compared with simple post critical method.

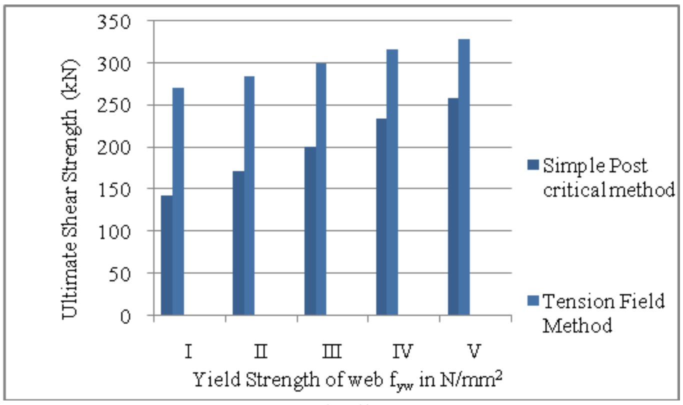


Fig 4. Behaviour of stiffened plate girder

B. *Shear buckling resistance using simple post critical method and tension field method for varying aspect ratio (c/d)*

Table III and IV shows the variation of shear buckling resistance using Simple Post Critical Method for varying aspect ratio (c/d). Table V and VI shows the variation of shear buckling resistance using Tension Field Method for varying web slenderness ratio (d/t_w).

TABLE III
SHEAR BUCKLING RESISTANCE USING SIMPLE POST CRITICAL METHOD FOR VARYING ASPECT RATIO (C/D)

Aspect Ratio (c/d)	Group 1	Group 2	Group 3	Group 4	Group 5
	E 250	*E 300*	*E 350*	*E 410*	*E 450*
	$V_{cr}(kN)$	$V_{cr}(kN)$	$V_{cr}(kN)$	$V_{cr}(kN)$	$V_{cr}(kN)$
2.0	143.33	172.00	200.66	235.06	258.00
2.2	139.41	167.30	195.18	228.64	250.95
2.4	136.43	163.72	191.01	223.75	245.58
2.6	134.11	160.94	187.76	219.95	241.41
2.8	132.27	158.73	185.19	216.93	238.10

TABLE IV
SHEAR BUCKLING RESISTANCE USING TENSION FIELD METHOD FOR VARYING ASPECT RATIO (c/d)

Aspect Ratio (c/d)	Group 1	Group 2	Group 3	Group 4	Group 5
	E 250	*E 300*	*E 350*	*E 410*	*E 450*
	$V_{tf}(kN)$	$V_{tf}(kN)$	$V_{tf}(kN)$	$V_{tf}(kN)$	$V_{tf}(kN)$
2.0	270.27	284.78	299.22	316.47	327.92
2.2	296.83	318.16	339.36	364.69	381.54
2.4	316.22	342.38	368.36	399.40	420.04
2.6	330.31	359.87	389.21	424.25	447.54
2.8	340.47	372.37	404.03	441.82	466.94

TABLE V
SHEAR BUCKLING RESISTANCE USING SIMPLE POST CRITICAL METHOD FOR VARYING WEB SLENDERNESS RATIO (D/T_W)

WebSlenderness Ratio (d/t_w)	Group 1	Group 2	Group 3	Group 4	Group 5
	E 250	*E 300*	*E 350*	*E 410*	*E 450*
	V_{cr} (kN)	V_{cr} (kN)	V_{cr} (kN)	V_{cr} (kN)	V_{cr} (kN)
200	143.33	172.00	200.66	235.06	258.00
140	292.51	351.02	409.52	479.73	526.53
100	573.33	688.00	802.67	940.27	1032.00
87.5	748.84	898.61	1048.38	1228.11	1347.00

TABLE VI
SHEAR BUCKLING RESISTANCE USING TENSION FIELD METHOD FOR VARYING WEB SLENDERNESS RATIO (D/T_W)

WebSlenderness Ratio (d/t_w)	Group 1	Group 2	Group 3	Group 4	Group 5
	E 250	*E 300*	*E 350*	*E 410*	*E 450*
	V_{cr} (kN)	V_{cr} (kN)	V_{cr} (kN)	V_{cr} (kN)	V_{cr} (kN)
200	156.32	182.01	200.89	210.45	245.00
140	156.32	182.02	200.90	210.45	245.00
100	156.31	182.02	200.90	210.50	245.00
87.5	156.30	182.02	200.91	210.50	245.00

III. FINITE ELEMENT MODELLING

A. Element used –SHELL 181

SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. (If the membrane option is used, the element has translational degrees of freedom only). The degenerate triangular option should only be used as filler elements in mesh generation.SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported. SHELL181 accounts for follower (load stiffness) effects of distributed pressures. SHELL181 may be used for layered applications for modeling laminated composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first order shear deformation theory.

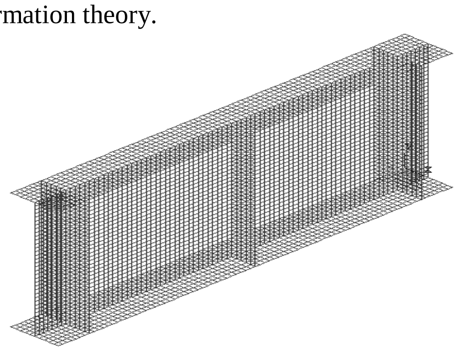


Fig 5. Finite element model of plate girder

B. Analytical results

Comparison of Deflections

Analytical modelling of plate girders is carried out using ANSYS. Plate girders without any intermediate stiffeners, with intermediate stiffeners (transverse) are modelled. The maximum deflection that the plate girders modelled undergoes is noted for a span of 30 m and a concentrated load of 100 kN. It was observed that deflection for plate girder with stiffener is less than that without stiffener.

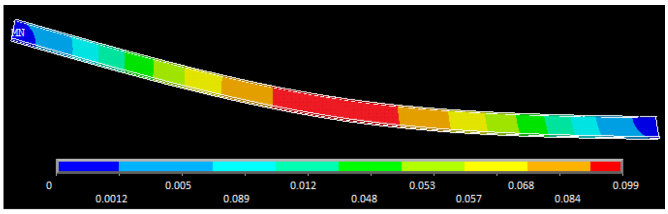


Fig 6. Deflection diagram of a Plate girder without Stiffeners

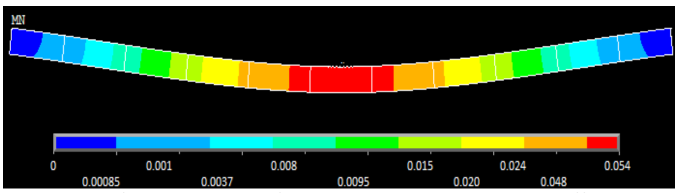


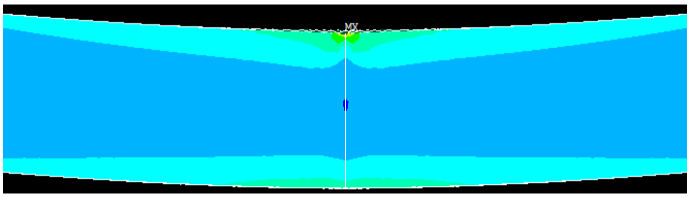
Fig 7. Deflection diagram of a Plate girder with Transverse Stiffeners

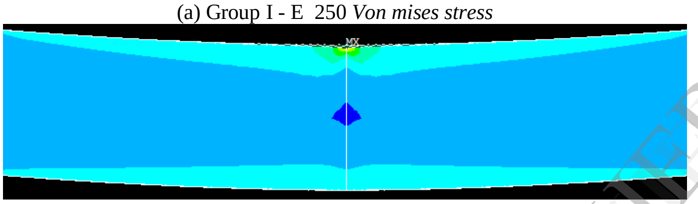
TABLE VII
COMPARISON OF DEFLECTIONS

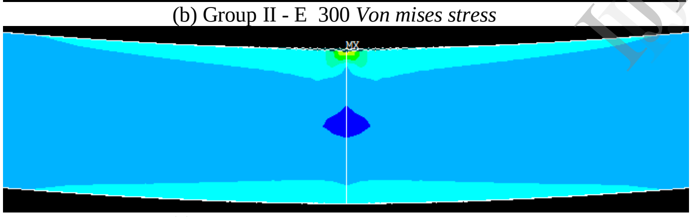
Stiffener Type	Deflection(mm)
Without Stiffener	0.099
With Transverse Stiffener	0.054

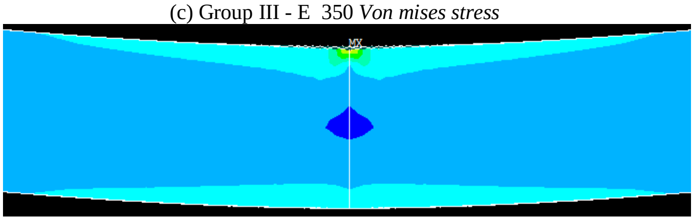
Variation in shear strength with aspect ratio

The aspect ratio (c/d) variation in plate girder web panel was obtained by adjusting the width (c) of the web panel keeping depth (d) as constant. The ultimate shear strength was compared using finite element analysis as shown in Table VIII. The effect of aspect ratio on shear strength was also compared by varying the yield stress of web panel.[6] The variation in ultimate shear strength with aspect ratio for varying web yield strength is shown in Fig.10.


(a) Group I - E 250 *Von mises stress*


(b) Group II - E 300 *Von mises stress*


(c) Group III - E 350 *Von mises stress*


(d) Group IV - E 410 *Von mises stress*

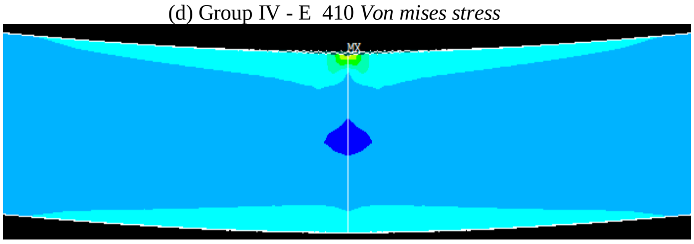

(e) Group V - E 450 *Von mises stress*

Fig 8: Stress variations at mid span for aspect ratio - 2.8

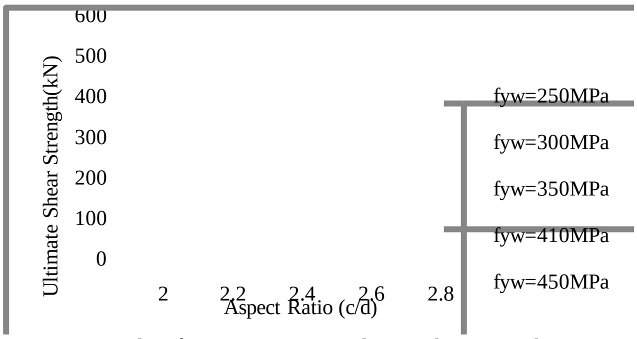
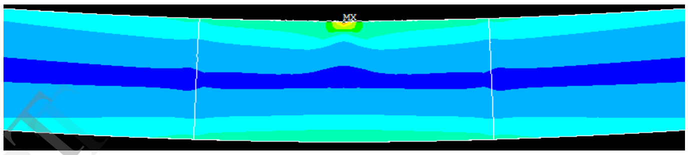
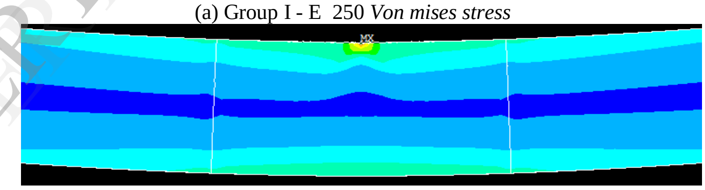


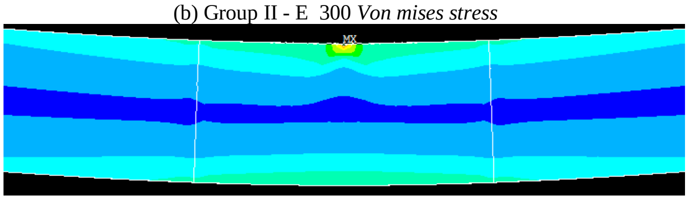
Fig.10: Plot of aspect ratio versus ultimate shear strength

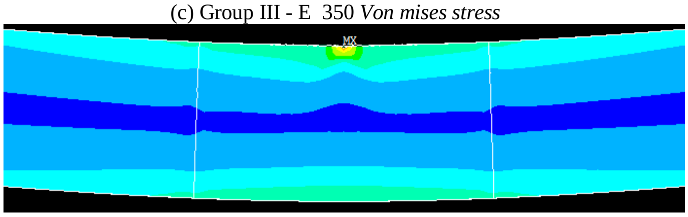
Variation in shear strength with web slenderness ratio

Variation of slenderness ratio (d/t_w) in hybrid plate girder was achieved by varying the thickness of web panel (t_w), keeping depth (d) as constant. [5]The variation in ultimate shear strength (V_u) was monitored corresponding to varying slenderness ratio as shown in Table IX. The strength calculation was done for different yield strengths of web panel as shown in Fig. 11. As the slenderness ratio of web panel increases, ultimate shear strength of hybrid plate girder decreases.


(a) Group I - E 250 *Von mises stress*


(b) Group II - E 300 *Von mises stress*


(c) Group III - E 350 *Von mises stress*


(d) Group IV - E 410 *Von mises stress*

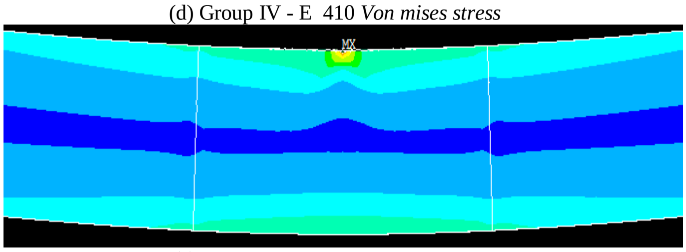

(e) Group V - E 450 *Von mises stress*

Fig 9: Stress variations at mid span for web slenderness ratio – 100

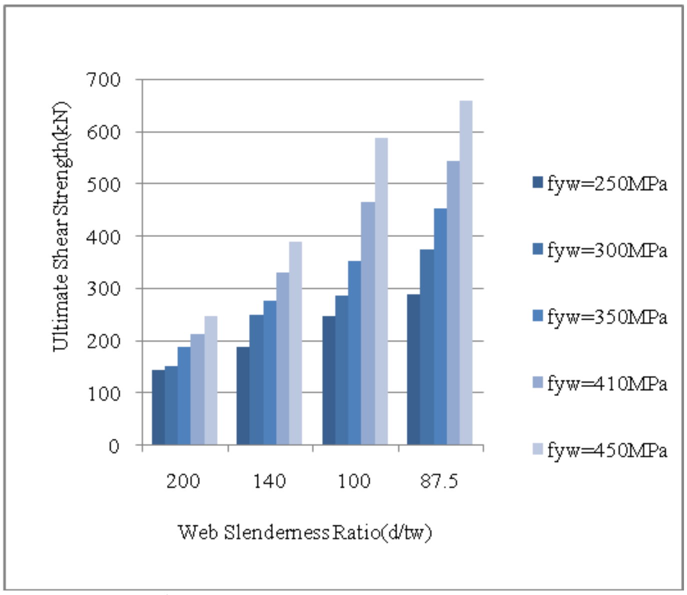


Fig.11:Plot of web slenderness ratio versus ultimate shear strength

IV. RESULTS AND DISCUSSIONS

A. Comparison of results with theoretical predictions

The ultimate shear strength computed using finite element method was compared with tension field method and Simple Post Critical Method provided by IS 800:2007. All these methods assume the formation of tension field at ultimate strength state. The comparison of finite element results of models considered in the present study with theoretical predictions is shown in Table VIII and Table XI.

The maximum variation in the strength prediction by two methods was less than 30%. The Simple Post Critical Method provided closer prediction to finite element method than tension field method and the results were matching with finite element method for low web yield strength. The finite element results were also comparable with tension field method and Simple Post Critical Method for aspect ratio 2.0, 2.2, 2.4, 2.6 and 2.8 for all grades of steel compared in the present study. The strength prediction by the two methods provided by IS 800:2007 was closer to finite element results for aspect ratio 2.4 and 2.6 and web slenderness ratio 200 as shown in table VIII and table IX.

The tension field method of IS 800:2007 provided upper bound results to finite element method and two methods provided by IS 800:2007 compared in the present study.[2] The variation in the strength prediction of finite element method and tension field method increases with increase in yield strength of web panel. Also the tension field method provided upper bound results for low values of web slenderness ratio. The tension field prediction (V_{tf}) by IS 800:2007 was compared with ultimate shear strength ($V_{u,fem}$)using finite element method.

TABLE VIII
Comparison of shear strength for various aspect ratio

Aspect Ratio (c/d)	f_{yf}/f_{yw}	Ultimate Shear Strength (kN)		
		Finite Element results	IS 800:2007	
			Tension Field Method	*Simple Post Critical Method*
2.0	1.80	184.65	270.27	143.33
2.2	1.80	232.23	296.83	139.41
2.4	1.80	328.52	316.22	136.43
2.6	1.80	353.87	330.31	134.11
2.8	1.80	381.13	340.47	132.27
2.0	1.50	200.57	284.78	172.00
2.2	1.50	243.223	318.16	167.30
2.4	1.50	379.125	342.38	163.72
2.6	1.50	381.173	359.87	160.94
2.8	1.50	388.236	372.37	158.73
2.0	1.30	230.365	299.22	200.66
2.2	1.30	265.654	339.36	195.18
2.4	1.30	384.336	368.36	191.01
2.6	1.30	395.26	389.21	187.76
2.8	1.30	452.37	404.03	185.19
2.0	1.10	256.365	316.47	235.06
2.2	1.10	283.654	364.69	228.64
2.4	1.10	392.092	399.40	223.75
2.6	1.10	409.25	424.25	219.95
2.8	1.10	473.25	441.82	216.93
2.0	1.00	266.365	327.92	258.00
2.2	1.00	292.654	381.54	250.95
2.4	1.00	400.325	420.04	245.58
2.6	1.00	450.388	447.54	241.41
2.8	1.00	485.89	466.94	238.10

TABLE IX
Comparison of shear strength for various web slenderness ratio

web slenderness ratio (d/t_w)	f_{yf}/f_{yw}	Ultimate Shear Strength (kN)		
		Analytical result	IS 800:2007	
			Tension Field Method	*Simple Post Critical Method*
200	1.80	144.059	156.32	143.33
140	1.80	189.57	156.32	292.51
100	1.80	247.59	156.31	573.33
87.5	1.80	287.95	156.30	748.84
200	1.50	151.173	182.01	172.00
140	1.50	248.733	182.02	351.02
100	1.50	286.54	182.02	688.00
87.5	1.50	375.59	182.02	898.61
200	1.30	189.35	200.89	200.66
140	1.30	275.63	200.90	409.52
100	1.30	352.71	200.90	802.67
87.5	1.30	452.68	200.91	1048.38
200	1.10	212.024	210.45	235.06
140	1.10	329.522	210.45	479.73
100	1.10	463.825	210.50	940.27
87.5	1.10	544.059	210.50	1228.11
200	1.00	248.325	245.00	258.00
140	1.00	389.540	245.00	526.53
100	1.00	587.325	245.00	1032.00
87.5	1.00	658.257	245.00	1347.00

All the cases, provided upper bound strength prediction using tension field method (V_{tf}) of IS 800:2007 compared to finite element method. Based on the finite element analysis, a strength reduction factor (RF) was proposed using regression analysis in order to modify the tension field stress (V_{tf}) such that

$$V_{tf,new} = V_{tf} \times RF \quad (1)$$

The comparison of tension field stress incorporating strength reduction factor ($V_{tf,new}$) with finite element results ($V_{u,fem}$) is shown in Fig.12. A reasonably better prediction was obtained by including RF in tension field method.

$$RF = (f_{yw}/f_{yf})^{0.655} \times (c/d)^{-0.252} \times (d/t_w)^{-0.332} \times (t_f/t_w)^{0.722} \times (b_f/t_f)^{-0.087}$$

$$\text{for } 1 \leq c/d \leq 2.5 \quad (2)$$

$$RF = 0.33 \times (f_{yw}/f_{yf}) - 0.13 \times (c/d) + 0.569$$

$$\text{for } c/d > 2.5 \quad (3)$$

TABLE X
VARIATION IN TENSION FIELD METHOD INCLUDING RF FROM FEM RESULTS

Group	Yield stress for web (MPa)	Ultimate Shear Strength (kN)		
		Simple Post Critical Method	*Tension Field Method*	*Analytical result*
I	250	143.33	154.58	184.65
II	300	172	185.62	200.57
III	350	200.66	220.47	230.365
IV	410	235.06	248.81	256.365
V	450	258	257.45	266.365

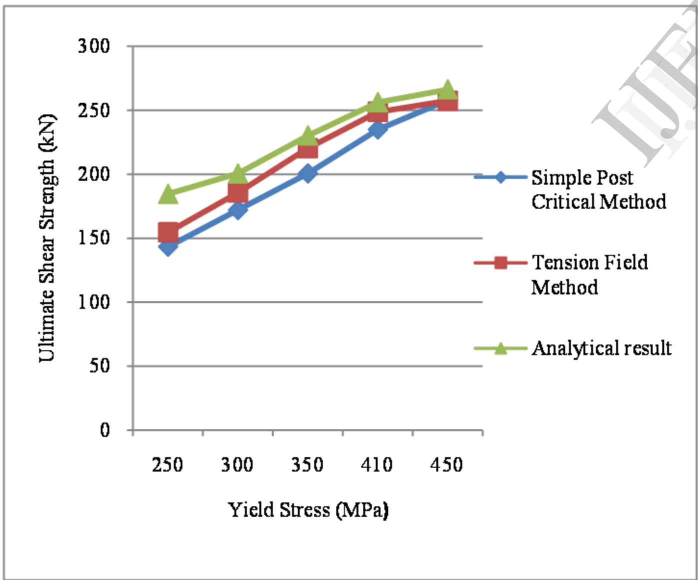


Fig. 12: Variation in Tension Field Method including RF from FEM results

V. CONCLUSIONS

Tension field method gives a higher value for shear buckling resistance than that of simple post critical method. It is also found that for a constant aspect ratio, the shear buckling resistance increases proportionally with the increase in grade of steel used for web of plate girder. It can also be concluded that variation in slenderness ratio (d/t_w) does not influence the shear buckling resistance when calculated using tension field method. Analytical models of plate girders without any stiffeners and with only transverse stiffeners are developed using ANSYS for comparing the deflections. It is found that Plate girders with transverse stiffeners undergo less deflection compared to that without intermediate stiffeners.Comparative study of analytical and code results are obtained.A reduction factor (RF) for ultimate shear strength prediction of IS 800:2007 (tension field method) was proposed using regression analysis.

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