Optimization of Plate Girder cross-section by effective spacing of transverse stiffeners

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Abstract: This paper discusses about the spacing of the transverse stiffeners in a plate girder so as to achieve most cost effective cross-section. A comparison between the two methods of analysis of plate girders—Simple Post Critical method and Tension Field method--- is made and the increase in the efficiencies of the cross section is made. As a conclusion, a value of 'c/d' ratio is arrived at, at which the efficiency of the cross section is maximum, where 'c' is the spacing between the stiffeners and 'd' is the depth of the plate girder. Moreover, this ratio of 'c/d' remains constant for any combination of flanges, web, spans and loadings.

Key words: Plate Girders, stiffeners, c/d ratio, spacing.

INTRODUCTION

Steel is a costly resource and its use needs to be done judiciously. In huge industrial set-ups where frequency of repetitive use of similar elements is high, optimization of elements can result in huge savings.

Plate girder is a structural element widely used in engineering and much effort has been made to rightly proportion the various elements of the cross section like flanges and web. However, the design of stiffeners and their spacing is usually not paid as much attention. In this work, an attempt is made to arrive at the most effective spacing of the stiffeners by utilizing the c/d ratio without compromising on the other design parameters.

PROBLEM STATEMENT

A number of plate girders for different proportions of web, flanges, depths and loads were designed with both Simple Post Critical method and Tension Field method and compared for increase in the load carrying capacities of the cross section. At a certain ratio of c/d an increase in the capacities of the plate girder sections was observed if designed by tension field method. Since tension field method utilizes the post buckling strength of the section, the percentage increase in capacities over the simple post critical method was noted for various combinations of spans, loads and element sizes.

METHODOLOGY

This study attempts to find the most effective spacing of stiffeners by taking the post buckling strength of the plate girder into account.

The modes of failure of a plate girder are by yielding of the tension flange and buckling of the compression flange. Plate girders depend on the post-buckling strength of the webs. As the web begins to buckle, the web loses its ability to resist the diagonal compression. The diagonal compression is then transferred to the transverse stiffeners and the flanges. The vertical component of the compression is supported by the stiffeners and the flanges resist the horizontal component. The web resists only the diagonal tension and this behavior of the web is called the Tension Field Action.

For a web panel subjected to Shear the IS 800 2007 says:

The factored design shear force, V, in a beam due to external actions shall satisfy $V \leq V_d$

Where,

V_d = Design Strength = V_n / γ_{mo}

Where, γ_{mo} = Partial Safety factor against shear failure

The nominal shear strength of a cross section, V_n, may be governed by Plastic Shear Resistance (Cl.8.4.1) or strength of the web as governed by Shear Buckling (Cl.8.4.2)

The nominal Plastic Shear resistance under pure shear is given by:

$V_n = V_p$

Where,

$$V_p = \frac{A_v . f_{yw}}{\sqrt{3}}$$
$$= A_v . 250 / \sqrt{3}$$
$$= 144.37 . A_v$$

Where,

A_v = Shear area of the web
f_{yw} = Yield Strength of the web

Resistance to Shear Buckling
Resistance to shear buckling shall be verified as specified:

when $d/t_w > 67 \, \varepsilon$ for web without stiffeners
$67 \, \varepsilon \, \sqrt{(K_v/5.35)}$ for web with stiffeners

Where,

K_v = Shear Buckling Co-efficient (Cl. 8.4.2.2)
$\varepsilon = \sqrt{(250/f_y)}$

Shear Buckling Resistance methods:

The Nominal Shear Strength, V_n, of webs, with or without stiffeners, as governed by buckling may be evaluated by one of the following methods:

    a) Simple Post Critical Method.

    b) Tension Field Method.

a) Simple Post Critical Method:

The Simple Post Critical Method, based on the shear buckling strength can be used for the webs of I-Section girders, with or without intermediate transverse stiffeners, provided that the web has transverse stiffeners at the supports. The Nominal Shear Strength is given by:

$$V_n = V_{cr}$$

Where,

    $V_{cr} =$ Shear force corresponding to shear Buckling

        $= A_v . \tau_b$

Where,

    $\tau_b =$ Shear stress corresponding to web buckling, determined as follows:

1) when $\lambda_w < 0.8$

    $\tau_b = f_{yw}/\sqrt{3}$

2) when $0.8 < \lambda_w < 1.2$

    $\tau_b = [1-0.8(\lambda_w - 0.8)] f_{yw}/\sqrt{3}$

3) when $\lambda_w > 1.2$

    $\tau_b = f_{yw}/\sqrt{3}.\lambda_w^2$

Where,

    $\lambda_w =$ Non dimensional web slenderness ratio for shear buckling stress given by

    $= \sqrt{(f_{yw}/\sqrt{3}. \tau_{cr.e})}$

Where,

    $\tau_{cr.e} =$ Elastic critical shear stress of web

$$= \frac{K_v . \pi^2 . E}{(12(1-\mu^2)[d/t_w]^2}$$

Where,

    $\mu =$ Poisson's ratio

    $\underline{K_v} = 5.35$ when transverse stiffeners are provided only at supports

    $= 4.0 + 5.35/(c/d)^2$ for $c/d < 1.0$

    $= 5.35 + 4.0 /(c/d)^2$ for $c/d \geq 1.0$

Where,

    'c' and 'd' are spacing of the transverse stiffeners and depth of the web respectively.

b) Tension Field Method:

After the web buckles along the direction of the principal compressive stress, a new load mechanism develops along the principal tensile direction, called as the Tension field action.

This mechanism resists any further increase in the shear load.

This tensile field is constituted by the portion of the plate in the principal tensile direction and anchored at the boundaries along the top and bottom flanges and the stiffener members on either side of the web.

At this stage, the total stress in the web plate is composed of the applied critical shear stress, $\tau_{cr.e}$, when the web buckled, and the post buckled membrane tensile stress, ft., due to tension filed action.

On further increase of loads, the tensile membrane stress in the web plate applies greater pull on the flanges.

Porter et al. (1975) suggested that a tension field consists of a single band and has been proved experimentally and theoretically, that plate girders fail when a section of the web plate yields and plastic hinges are formed in the flanges, thereby permitting a shear mechanism to occur.
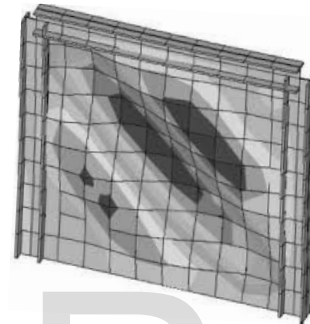

Fig 1: Formation of tension field

In Tension Field method, the Nominal Shear Resistance, Vn is given by, $V_n = V_{tf}$

Where,

    $V_{tf} = [A_v . t_b + 0.9.wtf.t_w.f_v.\sin \emptyset] < V_p$

    $\tau_b =$ Buckling strength as per 8.4.2.2a

Where,

    $f_v =$ Yield strength of Tension field

    $= [f_{yw}^2.-3.t_b^2+\Psi^2]^{0.5}- \Psi$

    $\Psi = 1.5.t_b.\sin2\emptyset$

    $\emptyset =$ Inclination of Tension field$= \tan^{-1}(d/c)$

    $W_{tf} =$ Width of the tension field

    $= d.\cos\emptyset+(c-s_c-s_t).\sin\emptyset$

    $f_{yw} =$ Yield Stress of the web

    $s_c, s_t =$ Anchorage length of the tension field along the Compression and Tension flanges respectively,

    $= 2/\sin\emptyset.[M_{fr}/f_{yw}.t_w]^{0.5} <c$

Where,

    $M_{fr} =$ Reduced Plastic Moment capacity of the respective flange plate (Disregarding any edge stiffener) after accounting for Axial force, N_f in the flange, due to overall bending and any external axial force in the cross section.

    $= 0.25.b_f.t_f^2.f_{yf}.[1-\{N_f/(b_f.t_f.f_{yf}/g_{mo})\}^2]$

Where,

    $b_f, t_f =$ width and thickness of relevant flange respectively.

    $f_{yf} =$ Yield stress of flange.

By observing the above two methods, we see that the tension field method utilizes the post buckling strength of the web, which depends on the width of the tension field, its anchorage with the flanges and the stiffeners and the collapse mechanism formed after the web buckles.

In other words, the tension field method utilizes the cross section of the plate girder more efficiently by considering the post buckling strength of the web.

If the two methods are compared for different 'c/d' ratios, it is observed that the efficiencies of the cross-section under the tension field method increases up to a certain limit, after which it takes a dip.

This maximum efficiency has a 'c/d' ratio which remains constant.

CONCLUSION

The tension field method takes into consideration the post buckling strength of the section which the simple post critical method ignores. This additional strength helps in more economical sections of the plate girder.

The tension field attaches itself between the flanges and the transverse stiffeners, inclined at an angle. The angle of inclination of the tension field has an influence of the spacing between stiffeners and the depth of the section.

As seen in the attached sheet, it is observed that if the same section of the plate girder is designed with both these methods, there is increase in the Nominal Shear Resistance, V_{tf} of the tension field method over the Nominal Shear Strength, V_{cr} of the simple post critical method. This increase in the capacity goes on increasing after which it takes a dip. The value of c/d ratio after which the efficiency of the section starts decreasing is observed to remain constant for any combinations of spans, loadings and sizes of plate girder elements.

It is seen that at a 'c/d' ratio of 1.23, the efficiency of the plate girder is the most optimum.

Therefore, it can be concluded that with a 'c/d' ratio of 1.23, the steel as a resource is most efficiently used.

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	Example 1	Example 2	Example 3	Example 4	Example 5	Example 6	Example 7	Example 8	Example 9	Example 10	Example 11
Span	30 m	30 m	10 m	15 m	15 m	20 m	25 m	25 m	27 m	16 m	23 m
Load	50 Kn/m	100 Kn/m	75 Kn/m	75 Kn/m	56.5 Kn/m	80 Kn/m	100 Kn/m	135 Kn/m	200 Kn/m	55 Kn/m	120 Kn/m
Moment	5625 Kn-m	11250 Kn-m	937.5 Kn-m	2109 Kn-m	1589 Kn-m	4000 Kn-m	7813 Kn-m	10547 Kn-m	18225 Kn-m	1760 Kn-m	7935 Kn-m
Af	16500 mm2	24750 mm2	4583 mm2	8438 mm2	6992 mm2	12571 mm2	20221 mm2	24424 mm2	36450 mm2	7040 mm2	20538 mm2
tf	35 mm	40 mm	20 mm	25 mm	25 mm	30 mm	35 mm	40 mm	50 mm	25 mm	35 mm
bf	675	725	120	425	290	510	675	700	950	150	825
d	1500 mm	2000 mm	900 mm	1100 mm	1000 mm	1400 mm	1700 mm	1900 mm	2200 mm	1100 mm	1700 mm
tw	10 mm	12 mm	6 mm	8 mm	6 mm	8 mm	10 mm	12 mm	16 mm	6 mm	10 mm
d/tw	150 mm	166.7 mm	150.0 mm	137.5 mm	166.7 mm	175.0 mm	170.0 mm	158.3 mm	137.5 mm	183.3 mm	170.0 mm
nu	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
ε	1	1	1	1	1	1	1	1	1	1	1

c/d ratio at which there is percentage increase in values of Vtf of Tension field method over Vcr of Simple post critical method after which the values start reversing:

1.22	1.229	1.25	1.23	1.22	1.22	1.22	1.23	1.24	1.25	1.22

Average value of c/d at which the spacing is most economical=   **1.23**