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Modified slenderness limits for bending resistance of longitudinally stiffened plate girders

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ABSTRACT

In this study, the slenderness limits for flanges and webs were examined to rationally evaluate the flange local buckling (FLB) strength of longitudinally stiffened I-girders. It is known that the bending resistance of a plate girder greatly increases when the web is longitudinally stiffened. This additional strength can be attributed to the fact that the stiffened web provides improved restraint to the rotation of the compression flanges as well as web bend-buckling strength. This study conducted a series of numerical analyses and it was found that the American Association of State Highway and Transportation Officials' (AASHTO's) load and resistance factor design (LRFD) requirements provide highly conservative estimates of the FLB strength of longitudinally stiffened plate girders, especially in noncompact sections. The reason is that the buckling coefficient and corresponding slenderness limit for a noncompact flange is determined based on the bending resistance of an unstiffened girder. Therefore, this study conducted a series of eigenvalue analyses in which the slenderness ratios of flanges and webs were considered. As a result, a buckling coefficient equation that reasonably reflects the interaction of the stiffened web and flange was derived. Based on the results of the analyses, this study proposed modified slenderness limits for the noncompact web and noncompact flange of a stiffened girder. It was verified that the bending resistance of longitudinally stiffened girders could be rationally estimated on the basis of the AASHTO LRFD specifications only by replacing the slenderness limits with the proposed formulas.

1. Introduction

As is widely known, it is economical to make the web as thin as possible when designing plate girders that are frequently used for bridge members, because the section design of the girders is usually governed by bending moments rather than shear forces. As the web section becomes more slender, however, stress redistribution from the web to the compression flange occurs due to the elastic buckling of the compressive portion of the web that is subject to bending, which ultimately leads to a considerable reduction in the bending strength of the plate girder [1,2]. To prevent such a reduction in the bending resistance of a plate girder with a slender web, longitudinal stiffeners could be applied to the webs. It has also been shown that the use of such longitudinal stiffeners provides an effective means of improving the buckling strength of webs under moment-shear interactions [3–5] or under concentrated loading such as patch loading [6,7], as well as improving the fatigue strength by controlling web breathing under repeated loadings [8].

During the past decades, many studies [9–14] have been conducted to determine the optimal location for longitudinal stiffeners to best improve the buckling strength of the webs. Based on the results of such research, it has usually been suggested by design specifications [15,16] that one-fifth (0.2) of the web depth from the compression flange would be the optimal location at which to install a longitudinal stiffener. Frank and Helwig [11] proposed a web buckling coefficient for a longitudinally stiffened web, which has been adopted by the AASHTO LRFD bridge design specifications [15]. In an attempt to determine the required stiffness for longitudinal stiffeners, Alinia and Moosavi [12] pointed out that the AASHTO LRFD specifications for the stiffness requirement are on the conservative side, as the aspect ratio of the web is >1.0.

Meanwhile, there have been few studies on the bending resistance of longitudinally stiffened plate girders. Cooper [2] conducted an experimental study of a built-up girder with a yield strength of 230 MPa, both with and without longitudinal stiffeners. The tests showed that an adequately proportioned longitudinal stiffener eliminates the bend-buckling loss in girders with a web slenderness of up to 400 to 450, so that the ultimate moment determined by the compression flange buckling strength can be attained. On the other hand, Cooper performed a manual calculation for these stiffened girder sections and showed that the application of a longitudinal stiffener to a web would not increase the lateral torsional buckling (LTB) strength.

It is well known that the bending resistance of a plate girder increases considerably when its web is longitudinally stiffened. The

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Nomenclature

D	depth of the web
D_c	depth of the web in compression in the elastic range
D_{cp}	depth of the web in compression at the plastic moment
d_s	distance between the longitudinal stiffener and inner surface of the compression flange
E	elasticity modulus of steel
F_{nc}	nominal flexural resistance of a compression flange
F_y	yield strength of steel
F_{yc}	yield strength of compression flange
F_{yr}	yield strength of compression flange including residual stress effect
I_y	second moment of inertia along the vertical axis
k	web buckling coefficient
k_c	buckling coefficient of compression flange
L_b	laterally unbraced length
L_p	unbraced length limit needed to achieve F_{yc}
L_r	unbraced length limit needed to achieve F_{yr}
M_{nc}	nominal flexural resistance based on compression flange
M_u	flexural resistance
R_b	web load-shedding factor
R_h	hybrid factor
R_{pc}	web plastification factor for compression flange
R_{pt}	web plastification factor for tension flange
s_{cf}	compressive residual stress of the flange
t_w	web thickness
λ_{pf}	limiting slenderness ratio for a compact flange
λ_{rf}	limiting slenderness ratio for a noncompact flange
$\lambda_{pw(Dcp)}$	limiting slenderness ratio for a compact web
λ_{rw}	limiting slenderness ratio for a noncompact web

enhancement in the bending strength can be attributed to the fact that the stiffened web provides improved rotational restraint to the compression flanges, as well as an additional resisting effect on web bend-buckling. This beneficial effect on the web buckling strength is well understood, and is adequately reflected in current design specifications [15,16]. However, the enhancement of rotational restraint for flanges due to web longitudinal stiffeners along the compression flange-web juncture is not yet well defined, even though the flange local buckling (FLB) resistance for a plate girder with a longitudinally stiffened web could be improved with this knowledge. To adequately estimate the flexural strength of a girder with a stiffened web, it is necessary to derive a reasonable formula for the flange buckling coefficient that considers the interaction between the stiffened web and the compression flange, because the coefficient is one of the key parameters affecting the evaluation of the bending resistance. To the best of our knowledge, there are few related research results. The Eurocode 3 [16] standards still regard the compression flange as being simply supported by the web, while AASHTO specifies using a buckling coefficient for a compression flange determined from bending tests on unstiffened girders [17].

Since the ultimate bending strength of a plate girder is determined by the smaller of the FLB strength and the LTB strength, this study conducted an analytical evaluation of the FLB and LTB strength of selected longitudinally stiffened girder models. Doubly and mono-symmetric sections that have a web with a slenderness that is close to the noncompact limit, as well as a noncompact or compact flange conforming to the AASHTO LRFD specifications, were considered. The flexural strengths determined from the numerical analyses were compared with the nominal strengths according to the AASHTO LRFD and Eurocode 3 standards, in order to identify any shortcomings in the design stipulations.

This study also conducted a series of the eigenvalue analyses by varying the slenderness ratios for the compression flange and the web. As a result, a buckling coefficient formula that more accurately reflects the interaction between the stiffened web and flange was derived. Based on these analysis results, new slenderness limits for the noncompact section of a stiffened web girder were proposed. It was verified that the bending resistance of longitudinally stiffened girders could be rationally estimated rationally estimated on the basis of the AASHTO LRFD specifications only by replacing the slenderness limits with the proposed formulas.

2. Current design stipulations

The design stipulations for a longitudinally stiffened plate girder, which are presented in the AASHTO LRFD specifications and the Eurocode 3 standards, are summarized in the following sections.

2.1. AASHTO LRFD specifications [15]

2.1.1. Web bend-buckling resistance

The nominal bend-buckling resistance of a web is based on the theoretical plate buckling resistance, as shown below:

$$F_{crw} = \frac{0.9kE}{\left(\frac{D}{t_w}\right)^2} \tag{1}$$

When one or more longitudinal stiffeners are provided, the following buckling coefficients [11] are suggested for use:

$$\frac{d_s}{D_c} \geq 0.4 : k = \frac{5.17}{(d_s/D)^2} \tag{2a}$$

$$\frac{d_s}{D_c} < 0.4 : k = \frac{11.64}{\left(\frac{D_c - d_s}{D}\right)^2} \tag{2b}$$

2.1.2. Limiting slenderness ratio for a noncompact web

AASHTO specifies the noncompact slenderness limit for a web λ_{rw} as follows, as derived from the theoretical plate buckling strength for webs without a longitudinal stiffener:

$$\frac{2D_c}{t_w} \leq \lambda_{rw} = 5.7\sqrt{\frac{E}{F_{yc}}} \tag{3}$$

The standard defines the slenderness of the web as $2D_c/t_w$, to consider a mono-symmetrical section in an unstiffened girder as being equivalent to a doubly symmetrical section with a web depth equal to $2D_c$.

For webs with one or more longitudinal stiffeners, the standard assumes that elastic buckling of the web does not occur prior to the yielding of the compression flange, when the slenderness ratio of the web (D/t_w) satisfies the following condition:

$$\frac{D}{t_w} \leq 0.95\sqrt{\frac{kE}{F_{yc}}} \tag{4}$$

where k is the web bend-buckling coefficient from Eqs. (2a) and (2b). Thus, AASHTO actually considers the noncompact slenderness limit for a stiffened web to be Eq. (4), although the standard does not clearly distinguish the limit for a stiffened web from that for an unstiffened web. In addition, it should be noted that the slenderness of a web is defined as being D/t_w because the bend-buckling coefficient equations