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Improved design of transversally stiffened steel plate girders subjected to patch loading

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ABSTRACT

This article presents a mechanical formulation to estimate the strength of transversally stiffened steel plate girders subjected to patch loading, in this particular case, with closely space stiffeners. Steel plate girders with closely spaced stiffeners are occasionally found in bridge design and for such cases, the current EN1993-1-5 rules underestimate the strength of the webs to transverse forces. A FE-based parametric investigation is conducted to estimate the web strength to patch loading. The results are compared to the results obtained from classical beam theory in combination with the proposed formulation. A notional plate girder is analyzed to demonstrate the potential of the formulation for daily routine designs. Results indicate that the proposed formulation does a better job in predicting the web strength of transversely stiffened girders subjected to patch loading than the EN1993-1-5 specification, and thus yield a lighter and more economical design for these specific girder geometries.

1. Introduction

The incremental launching method as a constructive process of bridges has had a great boom since the second half of the twentieth century. It allows to significantly optimize time-constraints and to reduce auxiliary support elements. Bridges assembled with steel plate girders are ideal for this construction process due to their reduced weight and ease of maneuverability. Steel plate girders are built by assembling thin-walled elements in which the web slenderness ratio, defined as h_w/t_w, ranges from 80 (stocky) to 250 (slender). Because of the high slenderness ratios of the web, it is common practice to provide a considerable amount of transverse and/or longitudinal stiffening to avoid instability-related phenomena due to compressive, shear and concentrated forces, or their combination, during construction and/or service lifespan of the structure.

Launching minimizes the use of heavy equipment and implies that all cross-sections of the plate girder pass over temporary supports or piers and thus, concentrated forces act in both stiffened and unstiffened sections. Occasionally, t_w is governed by a temporary concentrated load during the launching operation.

An alternative to increasing the web thickness is to stiffen the web plate with equally spaced vertical stiffeners or a combination of vertical and longitudinal stiffeners. Vertical stiffeners are spaced a distance "a", ranging from $a/h_w = 1.0$ to $a/h_w = 4.0$. Engineering judgement suggests that the smaller the distance "a", the higher the buckling strength of the web plate. However, the EN1993-1-5 [1] design provision shows that for spacing less than $a/l_y = 1$, the predicted strength of the web reduces with the reduction of the spacing between vertical stiffeners (a), as shown in Fig. 1.

The ultimate strength of steel plate girders subjected to patch loading has been studied in depth for members with largely spaced stiffeners ($a/l_y > 1.0$) through mechanical models [2,3], critical buckling loads approaches [4,5], bending and shear interaction schemes [6–8] and more recently, bridge launching Structural Health Monitoring (SHM) applications have been implemented [9,10]. The case of closely spaced stiffeners has been studied to a lesser extent both experimentally and numerically, except for the work reported in Refs. [11,13] and the design formulation summarized in [12]. This formulation has been calibrated with experimental results with a satisfactory level of accuracy. However, as it will be explained later, the formulae provided in [12] is a function of the stresses in the flange of the plate girder (σ_f), which are obtained through a 3D model such as complex brick- or shell-based Finite Element (FE) simulations, thus reducing its practical application for daily routing designs. In this paper, practical applications of the formulation presented in [12] are proposed in which the stresses in the flange (σ_f) are calculated with the classical beam theory and compared to the results of a 3D shell-based FE-simulation. On the other hand, recent research in the field has been

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Nomenclature

h_w	clear web depth between flanges	λ_F	plate slenderness
t_w	web thickness	f_{yf}	flange yield stress
t_f	flange thickness	f_{yw}	web yield stress
t_s	transverse stiffener thickness	s_s	length of stiff bearing
b_f	flange width	F_{Rk}	characteristic design resistance to local buckling under transverse forces
a	length of a stiffened or unstiffened plate	N_{Ed}	design axial force
L_{eff}	effective length for resistance	F_{Ed}	design transverse force
l_y	effectively loaded length	V_{Ed}	design shear force
σ_f	longitudinal stresses in the flanges	M_{Ed}	design bending moment
k_F	buckling coefficient		
χ_F	reduction factor due to local buckling		

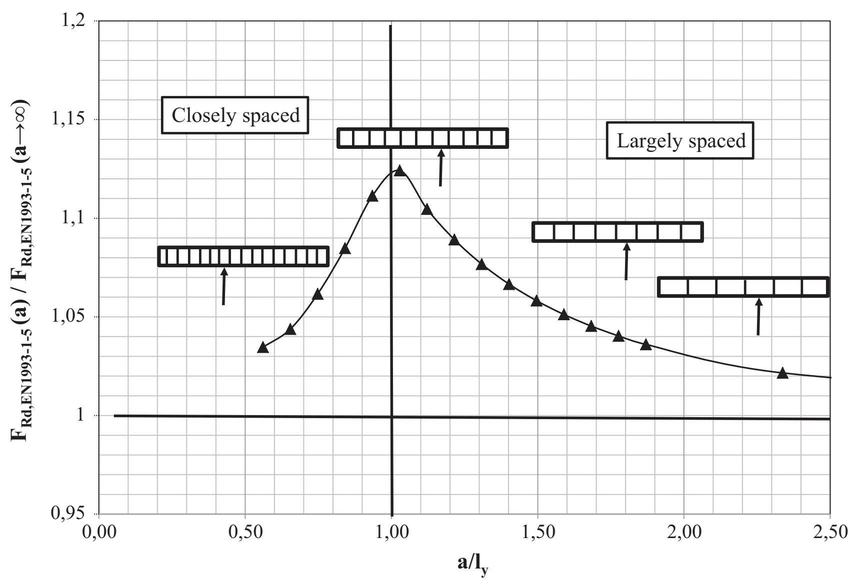

Fig. 1. EN1993-1-5 resistance to transverse forces as a function of a/l_y.

focused on longitudinally stiffened plates and eccentric concentrated loading [14–16].

2. Formulation of EN1993-1-5 to transverse forces

The prediction of the ultimate load carrying capacity of plate girders subjected to concentrated loads (F_{Rk}) is included in EN1993-1-5 in the same form as in other instability-related problems, i.e., the χ-λ approach Eqs. (1)(3). In this approach, the plastic strength F_y is partially reduced by χ_F (Eq. (3)). l_y is calculated from geometrical and material magnitudes (Eq. (2)). Note that the magnitude of l_y is limited to the distance "a". As a consequence, the ultimate load carrying capacity given by the F_{Rk} in EN1993-1-5 specification yields a reduction in the strength of the web of the plate girder as the spacing "a" between vertical stiffeners is reduced below l_y.

$$F_{Rk} = \chi_F \cdot F_y = \chi_F \cdot f_{yw} \cdot l_y \cdot t_w \leqslant \chi_F \cdot f_{yw} \cdot a \cdot t_w \quad (1)$$

$$l_y = S_s + 2 \cdot t_f \cdot (1 + \sqrt{m_1 + m_2}) = S_s + 2 \cdot t_f \cdot \left(1 + \sqrt{\frac{f_{yf} \cdot b_f}{f_{yw} \cdot t_w} + 0,02 \cdot \left(\frac{h_w}{t_f}\right)^2}\right) \leqslant a \quad (2)$$

$$\chi_F = \frac{0.5}{\bar{\lambda}_F} \quad \bar{\lambda}_F = \sqrt{\frac{F_y}{F_{cr}}} \quad F_{cr} = 0,9 \cdot k_f \cdot E \cdot \frac{t_w^3}{h_w} \quad (3)$$

It is important to point out that l_y has also been a subject of study within the core of European Committee of Standardization CEN/TC250/SC3. In future versions of EN1993-1-5, this magnitude will be changed to the one largely described in [17]. The described formulation will also be applicable if the new version of l_y is used.

3. Proposed design formulation

A solution to the problem of web instability in plate girders with closely spaced vertical stiffeners under patch loading can be found on a hinge mechanism, as proposed in Ref. [12]. The proposed model is based on an equation with two terms (Eq. (4)). The first term contains the web contribution given in the EN1993-1-5 specification for $l_y = a$ while the second term is a correction factor designated as ΔF_f.

$$F_{Rk,proposed} = F^*_{Rk} = F_{Rk(ly=a)} + \Delta F_f = \chi \cdot F_{y,(l_y=a)} + \Delta F_f = \chi \cdot f_{yw} \cdot a \cdot t_w + \Delta F_f \quad (4)$$