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Design recommendations for stainless steel I-sections under concentrated transverse loading

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ABSTRACT

Recent investigations have highlighted the need for improved provisions for determining the resistance of stainless steel I-sections under concentrated transverse loading. Such provisions, which reflect the particular characteristics of the material, have been developed and are described herein. A review of the existing European design formulae for members under concentrated transverse loading is firstly presented. Then a series of parametric studies, based on validated finite element models are described covering I-sections with a range of web slenderness values and different stainless steel grades. On the basis of the numerical results, together with existing experimental data, revised design equations are presented and assessed through reliability analysis performed in accordance with Annex D of EN 1990. The new provisions yield enhanced ultimate load predictions and are expected to be included in the next revision of EN 1993-1-4.

1. Introduction

Structural steel members are often subjected to concentrated transverse loads; examples include runway beams subjected to wheel loads, columns in beam-to-column connections and bridge girders during their launching phase, as illustrated in Fig. 1(a–c). In these cases, the possibility of web bearing failure needs to be assessed. Bearing failure has been extensively studied for carbon steel I-beams [1–5] and design specifications are broadly available [6,7]. Owing to the nonlinear stress-strain properties of stainless steel, the structural response differs from that of structural carbon steel. In strength governed scenarios, the significant strain hardening can lead to capacity benefits, while in stability governed scenarios, the early onset of nonlinearity in the stress-strain behaviour can lead to reduced capacities [8]. Previous design recommendations made by Zhao et al. [9] for the design of stainless steel hollow section members under combined axial and bending moment achieved gains of about 20% on average (greater in strength governed scenarios) over existing carbon steel design rules. Similarly to the case of members under combined loading, members under concentrated transverse loading also feature both strength and stability dominated failure modes, depending on the cross-section proportions and loading conditions; recent experimental and numerical studies on austenitic stainless steel beams [10–13] have shown that the current EN 1993-1-4 [14] design provisions are generally rather conservative. The primary aim of this paper is therefore to develop improved rules for the design of stainless steel beams under concentrated transverse loading, suitable for inclusion in the next revision of EN 1993-1-4.

In this paper, three stainless steel grades – austenitic, duplex and ferritic and three concentrated loading types are investigated herein: (i) Type (a) – internal one-flange (IOF) loading where failure occurs beneath a single concentrated load away from the beam end, (ii) Type (b) – internal two-flange (ITF) loading where failure occurs between two concentrated loads applied at opposite flanges away from the beam end and (iii) Type (c) – end-one-flange (EOF) loading where failure occurs beneath a concentrated load near the beam end, as shown in Table 1. Design provisions for each of the loading conditions and material grades are developed, and their reliability is assessed in accordance with Annex D of EN 1990 [15].

2. Review of existing design methods and experimental data

In this section, existing design methods for determining the resistance of hot-rolled and welded steel and stainless steel members under concentrated transverse loading are reviewed. A summary of existing experimental data on welded stainless steel sections under concentrated transverse loading is then presented.

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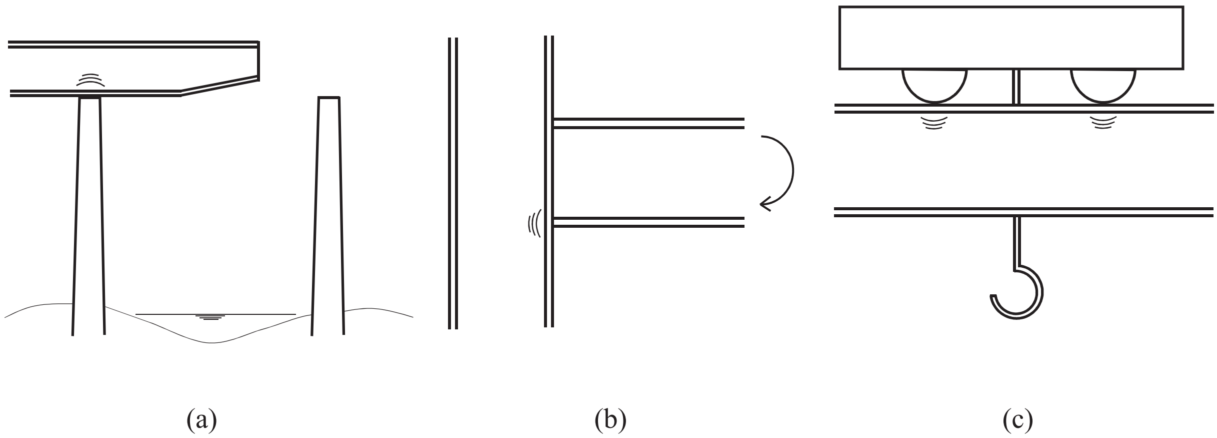
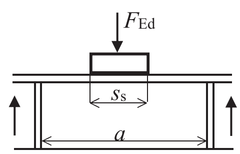
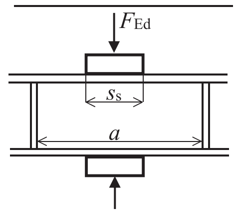
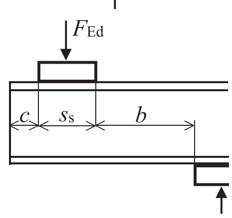


Fig. 1. Practical cases susceptible to web bearing failure.

Table 1
Types of concentrated transverse loading investigated.

Loading type [6]	Common description	Diagram
Type (a)	Internal One-Flange (IOF)	
Type (b)	Internal Two-Flange (ITF)	
Type (c)	End One-Flange (EOF)	

2.1. ENV 1993-1-1 (1992)

The prediction of the resistance of a hot-rolled or welded steel member to concentrated transverse loading in Eurocode 3 has evolved from the ENV pre-standard [16] to the final European standard [6]. In ENV 1993-1-1 [16], the design resistance was dictated by the critical of web crippling, web crushing and web buckling. The resistance formulae for both web crushing and web crippling were devised based on a four-hinge plastic mechanism proposed by Roberts and Rockey [17,18] whereas the web buckling resistance formula was based on idealising the web as a column. These design rules were later reformulated to align with the design approach adopted for other buckling problems in Eurocode 3 [1].

2.2. EN 1993-1-5 (2006)

The current European design provisions for the resistance of carbon steel members to concentrated transverse loading are set out in EN 1993-1-5. Originally proposed by Lagerqvist and Johansson [1], the design resistance to local failure under concentrated transverse loading F_{Rd} is presented as a function of the web yield strength f_{yw}, the web thickness t_w, an effective length L_{eff} and the partial safety factor γ_{M1}, as shown in Eq. (1):

$$f_{Rd} = \frac{f_{yw} L_{eff} t_w}{\gamma_{M1}} \tag{1}$$

The effective length $L_{eff} = \chi_F L_y$ is given by the product of the reduction factor χ_F and the effective loaded length, denoted l_y in general and $l_{y,a}$, $l_{y,b}$ or $l_{y,c}$ for loading Type (a), Type (b) or Type (c) respectively, as given by Eqs. (2)–(5), where s_s is the bearing length, t_f is the flange thickness, b_f is the flange width, f_{yf} is the flange yield strength, h_w is the web height and $m_{2,a}$, $m_{2,b}$ and $m_{2,c}$ are the m_2 factors for loading Types (a) and (b) and loading Type (c), respectively.

$$l_{y,a} = l_{y,b} = l_{y,1}, \quad l_{y,c} = \min(l_{y,1}, l_{y,2}, l_{y,3}) \tag{2}$$

where

$$\begin{aligned} l_{y,1} &= s_s + 2t_f\left(1 + \sqrt{m_1 + m_2}\right) \leqslant a, \\ l_{y,2} &= l_e + t_f\sqrt{\frac{m_1}{2} + \left(\frac{l_e}{t_f}\right)^2 + m_2} \quad \text{and} \\ l_{y,3} &= l_e + t_f\sqrt{m_1 + m_2} \end{aligned} \tag{3}$$

in which

$$l_e = \frac{k_F E t_w^2}{2 f_{yw} h_w} \leqslant s_s + c \tag{4}$$

and

$$m_1 = \frac{f_{yf} b_f}{f_{yw} t_w} \quad \text{and}$$

$$m_{2,a} = m_{2,b} = m_{2,c} = \left| \begin{array}{l} 0.02\left(\frac{h_w}{t_f}\right)^2 \mathit{for}\ \bar{\lambda}_F > 0.5 \\ 0\ \mathit{for}\ \bar{\lambda}_F \leqslant 0.5 \end{array} \right. \tag{5}$$

The method adopted for the determination of the effective loaded length for Type (a) and Type (b) loading, $l_{y,a}$ and $l_{y,b}$ respectively, is based on the four-hinge plastic mechanism model proposed by Roberts and Rockey [17], whereas the effective loaded length $l_{y,c}$ for Type (c) loading is based on different plastic mechanisms proposed by Voss [19] and modified by Lagerqvist [20].

The reduction factor χ_F, determined from Eq. (6) is a function of the slenderness parameter $\bar{\lambda}_F$, which is equal to the square root of the ratio of the plastic load, given by Eq. (8), to the elastic buckling load F_{cr} of the member under concentrated force.

$$\chi_F = \frac{0.5}{\bar{\lambda}_F} \leqslant 1.0 \tag{6}$$

$$\bar{\lambda}_F = \sqrt{\frac{F_y}{F_{cr}}} \tag{7}$$