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Shear design recommendations for stainless steel plate girders

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A B S T R A C T

The behaviour and design of stainless steel plate girders loaded in shear is investigated in this paper. A review of existing methods for the design of stainless steel plate girders, including codified provisions, is first presented. A database of thirty-four experiments carried out on austenitic, duplex and lean duplex stainless steel plate girders is then reported, and used to assess the current shear resistance design equations from Eurocode 3: Part 1.4 and Eurocode 3: Part 1.5 and the recent proposals from the literature. The comparisons clearly indicate that the design provisions of Eurocode 3: Part 1.4 are conservative and that improved results can be achieved by applying Eurocode 3: Part 1.5 and the proposed expressions of Estrada et al. However, yet further improvements are possible and, based on the available structural performance data, revised design expressions for the calculation of the ultimate shear capacity of stainless steel plate girders suitable for incorporation into future revisions of Eurocode 3: Part 1.4 have been proposed and statistically verified. Unlike the current provisions of Eurocode 3: Part 1.4, the design rules proposed herein differentiate between rigid and non-rigid end posts, and, offer enhancements in shear buckling capacity of around 10%.

1. Introduction

Plate girders are widely used in the construction industry especially in bridge applications, as transfer beams and shear walls in buildings and in offshore structures, owing to their ability to withstand heavy loads over long spans. For material efficiency, plate girder webs are often of slender proportions, making them susceptible to a form of instability known as shear buckling. This type of failure has been extensively studied over the past few decades in carbon steel plate girders and a range of design methods have been established. A more limited number of studies has been devoted to stainless steel plate girders, and current design provisions are known to be conservative.

Hence, the aims of this paper are to study the shear response of stainless steel plate girders, to collate and examine available structural performance data, to review existing design methods and to develop and statistically verify revised design expressions suitable for inclusion in international design codes. A total of thirty-four experiments carried out on stainless steel plate girders of austenitic, duplex and lean duplex grades, with web panel aspect ratios varying between 1.0 and 4.0 and with rigid and non-rigid end posts, were first collected and used to evaluate the shear resistance design equations of EN 1993-1-4 (2006) [1]. Next, a comparative analysis of other design methods including EN 1993-1-5 (2006) [2] and the proposed design expressions of Estrada et al. [3] has been performed. Finally, based on the available experimental data, revised design expressions for the calculation of the ultimate shear capacity of stainless steel plate girders are proposed and a reliability analysis in accordance with EN 1990 (2002) [4] was carried out to confirm their applicability.

2. Literature review

2.1. Introduction

In this section, an overview of the available laboratory test data on stainless steel plate girders is presented and existing design methods and proposals for assessing the shear buckling resistance of plate girders are briefly reviewed. The design methods discussed are the tension field method and the rotated stress field method.

2.2. Overview of previous experimental studies

The first experimental investigation of stainless steel plate girders was carried out by Carvalho et al. [5]. The results of this study served as the basis for the first codified provisions for determining the ultimate shear resistance of stainless steel beams set out in

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ENV 1993-1-4 (1996) [6]. Following the introduction of ENV 1993-1-4 (1996) [6], experimental studies were carried out by Olsson [7], Real et al. [8] and Estrada et al. [9], all of which highlighted deficiencies in the existing design methods. The main objectives of these investigations were to develop a better understanding of the behaviour of stainless steel plate girders under shear and to propose design expressions capable of predicting accurately the shear resistance of stainless steel plate girders. Most recently, a detailed experimental and numerical study of lean duplex stainless steel plate girders was conducted [10], bringing the total pool of laboratory test data to 34. Further numerical studies were also reported by Hassanein [11,12]. The findings of these studies are discussed in Section 4 of this paper, while the experimental data are used to verify a revised design treatment.

2.3. Overview of theoretical models for predicting shear buckling resistance

The earliest attempt to estimate the shear resistance of slender plate girders was made by Basler et al. [13,14]. According to Basler, once shear buckling had occurred in a plate girder web, a theoretical tension field would extend over the whole depth of the web and the shear resistance could be expressed as the sum of the buckling and postbuckling resistances of the web but with no flange contribution. Although there were limitations [15,16] to the Basler theory, the basic tension field concept was able to represent observed physical behaviour and was further developed by Rockey et al. [17,18]. A drawback to the tension field approach lies in its inability to predict accurately the shear buckling resistance of plate girders with widely spread transverse web stiffeners. A solution, termed the rotated stress field method [7], was proposed by Höglund [19,20]. This method was able to represent the postbuckling shear strength of both stiffened and unstiffened webs.

The rotated stress field method assumes that, prior to buckling, the web is in a state of pure shear stress and the principal planes are inclined at an angle $\varphi = 45°$ to the horizontal. However, once buckling has occurred, it is assumed that the principal compressive stress, remains equal to the shear buckling stress τ_{cr}, and that further increases in load are resisted by an increase in the tensile stress. This causes the major principal plane to rotate towards the horizontal, and the ultimate resistance is said to be reached when the von Mises yield criterion [7] is met. A detailed description of the rotated stress field theory can be found in [21].

3. Current and proposed design methods

3.1. Introduction

In this section, the design methods for assessing the shear buckling resistance of plate girders in Eurocode 3 are reviewed, including the evolution from the ENV prestandard to final EN standard. The provisions for both carbon steel and stainless steel, as well as proposed changes to the latter, are considered.

3.2. Carbon steel design provisions

3.2.1. ENV 1993-1-1 (1992)

Two methods were provided in ENV 1993-1-1 (1992) [22] for determining the design shear resistance of carbon steel plate girders: (1) the simple post critical method and (2) the tension field method. The first design method was developed by Dubas [23] based on the rotated stress field theory, and applied to plate girders with and without transverse stiffeners. The design shear resistance ignored any flange contribution, and was later found by Höglund [21] and Davies and Griffith [24], to be unduly conservative. The second method, the tension field method, was found to be only appropriate for transversely stiffened webs with web panel aspect ratios ranging between 1.0 and 3.0 [25]. Furthermore, numerical studies by Presta et al. [26] showed that the forces in the transverse stiffeners implied by the tension field method were inaccurate. Limitations in both methods given in ENV 1993-1-1 (1992) [22], lead to revised design rules being provided upon conversion to the EN standards, at which point the design provisions for shear buckling were also moved to Part 1.5 of the code.

3.2.2. EN 1993-1-5 (2006)

The rotated stress field method developed by Höglund [19,20] forms the basis of the shear design rules given in EN 1993-1-5 (2006) [2]. In the EN 1993-1-5 (2006) [2] provisions, ultimate shear resistance $V_{b,Rd}$ is given by Eq. (1) and expressed as the sum of the web shear buckling resistance $V_{bw,Rd}$ (Eq. (2)) and the flange contribution (Eq. (3)) $V_{bf,Rd}$.

$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leqslant \frac{\eta f_{yw} h_w t_w}{\sqrt{3}\gamma_{M1}} \tag{1}$$

where f_{yw} is the yield strength of the web, f_{yf} is the yield strength of the flanges, η is a parameter that approximates the influence of strain hardening, h_w is the depth of the web, t_w is the thickness of the web, b_f is overall the flange width, t_f is the flange thickness, and γ_{M1} is a partial safety factor.

The web contribution $V_{bw,Rd}$ is given by

$$V_{bw,Rd} = \frac{\chi_w f_{yw} h_w t_w}{\sqrt{3}\gamma_{M1}} \tag{2}$$

where χ_w is the web shear buckling reduction factor. The flange contribution $V_{bf,Rd}$ is given by:

$$V_{bf,Rd} = \left(\frac{b_f t_f^2 f_{yf}}{c\gamma_{M1}}\right)\left(1 - \left(\frac{M_{Ed}}{M_{f,Rd}}\right)^2\right) \tag{3}$$

in which M_{Ed} is the coexistent design bending moment, $M_{f,Rd}$ is the moment resistance of the cross-section considering only the flanges and the distance c, which defines the location of the plastic hinges that form in the flanges, is given by:

$$c = \left(0.25 + \frac{1.6 b_f t_f^2 f_{yf}}{t_w h_w^2 f_{yw}}\right) a \tag{4}$$

where a is the spacing of the transverse stiffeners.

3.3. Stainless steel design provisions

3.3.1. ENV 1993-1-4 (1996)

At the time of the development of ENV 1993-1-4 (1996) [6], the only experimental research into the shear resistance of stainless steel members was that carried out by Carvalho et al. [5]. Carvalho et al. [5] performed a series of three point bending tests on cold-formed austenitic and ferritic stainless steel sections. The obtained results were used in the formulation of the design provisions of ENV 1993-1-4 (1996) [6], which were based on the simple post critical method of ENV 1993-1-1 (1992) [22], but with modifications to reflect the material nonlinearity of stainless steel. Subsequent experimental studies on stainless steel plate girders [3,7–9] showed that the ENV 1993-1-4 (1996) [6] provisions were conservative, raised questions of the quality of the earlier test data [5] and emphasised the need to consider the flange contribution to the shear buckling capacity.

3.3.2. EN 1993-1-4 (2006)

Following the adoption of the simple post critical method in ENV 1993-1-4 (1996) [6], Olsson [7] performed an experimental