Journal of Constructional Steel Research 66 (2010) 709–715

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

# Hybrid steel plate girders subjected to patch loading, Part 2: Design proposal

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ARTICLE INFO

*Article history:*
Received 23 March 2009
Accepted 6 December 2009

*Keywords:*
Patch loading
Hybrid girders

ABSTRACT

The resistance of plate girders subjected to patch loading has been studied thoroughly for the case of homogenous girders. The particular case of hybrid girders has been generally treated identically than for homogenous specimens. In this paper, the current EN1993-1-5 formulation is evaluated and some peculiarities concerning the treatment of hybrid girders subjected to patch loading are pinpointed. It is numerically demonstrated that the moment capacity of the flanges does not play any role in the resistance of plate girders to patch loading as predicted in EN1993-1-5. Accordingly, a design proposal which corrects the current EN1993-1-5 formulation is presented at the end of the paper.

## 1. Introduction

The collapse behavior of patch loaded homogenous plate girders has been widely studied through experimental, theoretical and numerical analyses [1–3]. As a result, design rules are nowadays enriched with safe predictions of the resistance of plate girders subjected to concentrated forces. Researchers have proposed several expressions of the elastic critical loads and physical models which, referring to these expressions, accurately reproduce the limit state of the plates at ultimate load. The majority of these approaches agree with a vast number of experimental results obtained from various sources. However, it has been pinpointed that the vast majority of these studies dealt only with the resistance of homogenous plate girders. For the particular case of hybrid girders, scarce studies have been found. In a companion paper [4], the need for completing the existing database with hybrid specimens has been discussed. In order to fulfill this gap, a total amount of 192 steel plate girders have been numerically simulated (three-quarters of the database correspond to hybrid specimens). Pairs of values of ultimate and critical loads are available for each simulation. The structural response of such specimens has been studied by means of load–deflection as well as load–stress plots.

The numerical database presented in the companion paper includes homogeneous and hybrid steel plate girders in which the flanges present a high cross-sectional area compared to the cross-sectional area of the web. In this paper, a statistical appraisal of such results is presented. Section 3 focuses entirely on the influence of $f_{yf}/f_{yw}$ on the resistance of plate girders assembled with flanges having such proportions when subjected to patch loading.

It is well known, however, that, for a given total web depth, the usage of a hybrid alternative on plate girders enables the designers to provide flanges with smaller cross-sectional area than equivalent homogenous girders for the same level of performance.

Consequently, the flange plates may happen to be more slender than the in the case of homogeneous girders. Therefore, the conclusions presented in Section 3 are verified for the case of steel plate girders presenting these latter proportions. A second parametric numerical study is developed for the sake of verification. Finally, further checks of the proposal are performed in Section 5 by using a third parametric numerical study in which the influence of the flange width is assessed.

With the results obtained, it is observed that a modification of the current formulation of the EN1993-1-5 verification of steel girders subjected to patch loading is needed. The current formulation gives unsound results for the particular case of hybrid steel plate girders subjected to patch loading. In this paper, a modification of the effectively loaded length $l_y$ is proposed. With such modification, the theoretical predictions are more consistent, and accordingly on the safety side. Validity limits for such proposal are also given at the end of the paper.

## 2. Review of the earlier work

The current formulation of EN1993-1-5 [5] defines the patch loading resistance $F_{\mathrm{Rd,EN1993-1-5}}$ as Eq. (1):

$$F_{\mathrm{Rd,EN1993-1-5}} = \frac{\chi_F \cdot F_y}{\gamma_{M1}} = \frac{\chi_F \cdot f_{yw} \cdot t_w \cdot l_y}{\gamma_{M1}} \leq \frac{\chi_F \cdot f_{yw} \cdot t_w \cdot a}{\gamma_{M1}}. \quad (1)$$

The ultimate load capacity is understood as a plastic resistance $F_y$ partially reduced by a coefficient which takes instability into account. The plastic resistance is calculated in a yield-prone area $t_w \cdot l_y$. This area is limited to the physical value $t_w \cdot a$, in which $a$ is the distance between transverse stiffeners. The effectively loaded

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doi:10.1016/j.jcsr.2009.12.004

## Notations

| | |
|---|---|
| $h_w$ | Clear web depth between flanges |
| $a$ | Width of web panel (distance between transverse stiffeners) |
| $s_s$ | Length of stiff bearing |
| $t_f$ | Thickness of the flanges |
| $t_w$ | Thickness of the web |
| $t_s$ | Thickness of the transverse stiffeners |
| $f_{yf}$ | Flange yield strength |
| $f_{yw}$ | Web yield strength |
| $f_{ys}$ | Stiffener yield strength |
| $l_y$ | Effective loaded length |
| $\chi_F$ | Reduction factor due to local buckling |
| $F_y$ | Plastic resistance |
| $F_{cr}$ | Critical buckling load |
| $E$ | Young's modulus |
| $\lambda_F$ | Slenderness |
| $\gamma_{M1}$ | Partial factor |
| $F_{Rd}$ | Design resistance to transverse forces |
| $F_{u,num}$ | Predicted resistance to transverse forces according to numerical results |

length $l_y$ has been quite a topic of study among researchers of the patch loading phenomena. Roberts [6] defined $l_y$ by means of Eq. (2). This definition comes as a result of applying the virtual work principle to a four-hinge mechanism developed on the web-to-flange junctures of patch loaded girders together with yield lines on the web (web folding).

$$l_y = s_s + 2 \cdot t_f \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}}}. \tag{2}$$

The same author proposed a slight modification [7] of this equation resulting in Eq. (3). The model was tuned to take into account the load spread through the flange.

$$l_y = s_s + 2 \cdot t_f \left(1 + \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}}}\right). \tag{3}$$

Subsequently, Lagerqvist proposed a four-hinged model, which is currently used in the definition of the plastic resistance in EN1993-1-5, that includes a part of the web in the moment resistance of the outer plastic hinges [2]. As a result, $l_y$ happens to present an additional term $m_2$ (Eqs. (4) and (5)).

$$l_y = s_s + 2 \cdot t_f \left(1 + \sqrt{m_1 + m_2}\right) \tag{4}$$

$$m_1 = \frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}} \qquad m_2 = 0.02 \cdot \left(\frac{h_w}{t_f}\right)^2. \tag{5}$$

The latter term $m_2$ was subsequently questioned by Davaine [8] for the case of slender girders. The author observed the effectively loaded length $l_y$ numerically. This length was understood as the distance between the observed plastic hinges within the flanges at advanced load levels. These observations were compared to the design provisions given by EN1993-1-5. The author claimed that if $m_2$ was suppressed from the current formulation, the accuracy of the formulation would be increased. Correspondingly, Gozzi [9] carried out investigations focused on the relevance of $m_2$. This relevance was studied on girders with a web slenderness $h_w/t_w$ ranging from 150 to 500. Numerical values of $l_y$ were inferred from the performed simulations. Preliminary conclusions demonstrated that $m_2$ could be suppressed for the case of slender girders. Accordingly, the effectively loaded length has been claimed back to Eq. (6).

$$l_y = s_s + 2 \cdot t_f \left(1 + \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}}}\right). \tag{6}$$

**Table 1**
Effectively loaded length $l_y$ according to several authors.

| Researcher | Equation | Terms |
|---|---|---|
| Roberts [6] | $l_y = S_s + 2 \cdot t_f \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}}}$ | $m_1$ |
| Roberts et al. [7] | $l_y = S_s + 2 \cdot t_f \left(1 + \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}}}\right)$ | $m_1$ |
| Lagerqvist et al. [2] | $l_y = S_s + 2 \cdot t_f \left(1 + \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}} + 0.02 \cdot \left(\frac{h_w}{t_f}\right)^2}\right)$ | $m_1$; $m_2$ |
| Davaine [8]<br>Gozzi [9] | $l_y = S_s + 2 \cdot t_f \left(1 + \sqrt{\frac{b_f \cdot f_{yf}}{t_w \cdot f_{yw}}}\right)$ | $m_1$[a] |

[a] Studies performed upon slender girders.

Table 1 summarizes the different shapes of the effectively loaded length according to the aforementioned authors. In all cases, the term $m_1$ is included whereas $m_2$ is alternatively considered or dismissed.

The numerical studies on hybrid steel plate girders subjected to patch loading presented in the companion paper [4] have shown an additional outlandish peculiarity worth being assessed. For girders with largely spaced transversal stiffeners ($l_y < a$, see Eq. (1)), the contribution of the ratio $f_{yf}/f_{yw}$ to the patch loading resistance seems negligible. The current formulation of EN1993-1-5 takes this ratio into account in such a way that the greater the ratio $f_{yf}/f_{yw}$, the higher the ultimate load capacity of the girders. Presently, the term $m_1$ is a monotonically increasing function of $f_{yf}/f_{yw}$. The results obtained suggest that $m_1$ should be modified to some extent since numerical observations do not show the same trend. Noticeably, $m_1$ consists of two factors: the $f_{yf}/f_{yw}$ ratio, which takes the mechanical properties of the plates into account, and the $b_f/t_w$ ratio, which accounts for the flange–web geometry.

## 3. Influence of $f_{yf}/f_{yw}$ on the resistance of plate girders to patch loading

This section deals with the influence of the hybrid ratio $f_{yf}/f_{yw}$ on the resistance of steel girders subjected to patch loading for prototypes with relatively high slenderness of the web when compared to the slenderness of the flanges. This relative proportion is quantified by using the slenderness ratio. The slenderness ratio between flanges and web is defined within this work as the ratio between the web slenderness ($h_w/t_w$) and the flange slenderness ($b_f/t_f$). This magnitude indicates how stiff the flange plate is with respect to the web plate. High values of the slenderness ratio ($(h_w/t_w)/(b_f/t_f) \geq 10$) indicate that the proportion of flange area is considerably greater than the proportion of the web cross-sectional area. Conversely, low values of this ratio ($(h_w/t_w)/(b_f/t_f) \leq 5$) indicate that the web plate presents a considerable amount of web cross-sectional area when compared to the flange. The usual design of plate girders is quite related to the former case.

Fig. 1 displays two histograms showing a count of the data points falling in various ranges of $(h_w/t_w)/(b_f/t_f)$ for the numerical and experimental databases depicted in [4]. Noticeably, the vast majority of the experimentally and numerically tested girders present girders with slenderness ratio $(h_w/t_w)/(b_f/t_f) \geq 10$, i.e., all girders present high slenderness ratios.

The analysis presented herein is based upon the numerical database depicted in [4]. Accordingly, this analysis is valid for