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Influence of flange strength on transversally stiffened girders subjected to patch loading

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ABSTRACT

In this paper, a mechanical model aimed at predicting the ultimate load capacity of transversally stiffened steel plate girders subjected to patch loading is revisited. This mechanical model gives accurate results for homogeneous steel plate girders (identical yield strength for web and flanges) but it is found that for the case of hybrid girders (f_{yf}/f_{yw}), certain correction factors must be added for maintaining the same level of accuracy. The provided correction is inferred empirically from a series of experimentally calibrated numerical results and the resulting formulae are expressed in accordance with the EN1993-1-5 procedure.

1. Introduction

Patch loading has been one of the most active fields of fundamental and applied research in steel structures throughout the last sixty years. Patch loading is a structural situation which often occurs in steel I-girders with doubly-symmetric transverse stiffeners separated by a distance “a” (Fig. 1). A concentrated load is applied on one flange (either top or bottom) over a distance s_s and it is generally found during launching of steel bridges. If the transverse stiffeners are largely spaced, the load-carrying mechanism primarily involves the flange stiffness ($b_f \cdot t_f$), the web slenderness (h_w/t_w) and the web strength (f_{yw}). If the transverse stiffeners are closely spaced, the failure mechanism involves the flange, web and stiffener rigidity as well as the flange and web strength (f_{yf} and f_{yw} respectively).

For the former case, the resistance of steel plate girders subjected to patch loading has been thoroughly analyzed in the last decades [1–10]. Theoretical, experimental and numerical analyses have widely shown the structural behavior of such cases. All these investigations have contributed to develop design formulae which accurately predict the ultimate load capacity of such girders. Broadly speaking, it can be stated that the failure mechanism that governs such structural case is web folding (Fig. 2). For slender girders, the web folds considerably and noticeable semicircular yield lines develop in the vicinity of the applied load. For stocky webs, the out-of-plane displacement of the web is less noticeable (though existing) and a considerable membrane yielding of the web appears. The approximate horizontal projection of the semicircular line has been labeled by researchers as the effectively loaded length “l_y”.

For the latter case, which represents the minority of routinely designed I-girders, the failure mechanism involves the web, the flanges and the transverse stiffeners. This particular case has been studied to a lesser extent [11,12].

Monitored monotonic loading processes of the cases depicted in previous research performed by the authors (Fig. 3) show an equilibrium path as follows:

- Firstly, linear relationship between the applied load and resulting displacement.
- At a load labeled as F_1, the web folds and semicircular yield lines form in the web. The horizontal projection of the outer line is “a” and it is eventually anchored in the flange-to-stiffener juncture. The equilibrium path shows a clear loss of rigidity.
- The load can be increased up to F_2. The web is completely exhausted throughout this stage but the flanges are able to carry the load until four hinges are formed and the ultimate load F_2 is achieved. The difference $F_2 - F_1 = \Delta F_f$ is thus the flange contribution to the ultimate load capacity for such cases.

For the former case, EN1993-1-5 [13] provides design formulae that have been thoroughly tested and studied in recent years [14] for both homogeneous ($f_{yf} = f_{yw}$) and hybrid girders ($f_{yf} > f_{yw}$). For the latter case, a design proposal aimed at predicting the value of ΔF_f has been presented only recently for the case of homogeneous prototypes [11,12].

In this paper, the previously presented mechanical model is updated for the particular case of hybrid girders since the flange strength is the primary parameter governing this contribution. The numerical observations presented in Sections 4 and 5 pinpoint that the formulation depicted in [12] should be corrected by additional factors in girders with transverse stiffeners (but longitudinally unstiffened webs).

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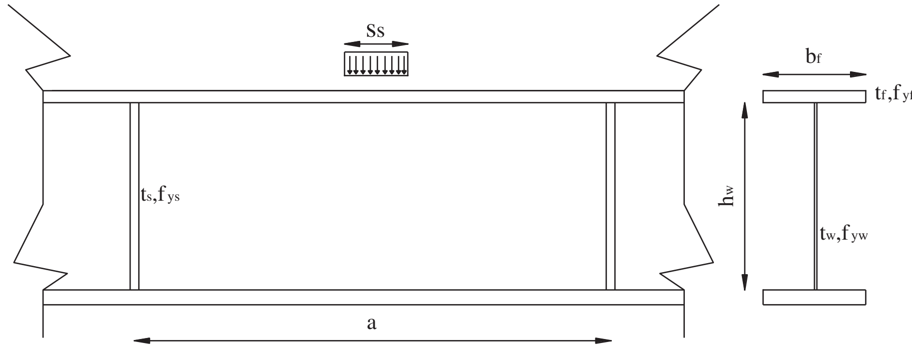

Fig. 1. Geometrical value for steel I-girder subjected to patch loading.

Section 6 includes a proposal for correcting this anomaly and thus, the mechanical model can be used with vaster generality.

2. EN1993-1-5. Resistance to transverse forces

The prediction of ultimate load capacity of girders subjected to concentrated loads is included in EN1993-1-5 in the same form as in other instability-related problems, i.e., the χ–λ approach. This approach defines a plastic resistance F_y (1) obtained by limit analysis. This resistance is partially reduced by a χ_F coefficient (3) which takes instability into account. In Eq. (1), l_y is defined as the yield-prone effectively loaded length (horizontal projection of the semicircular yield line). This length is calculated from geometrical and mechanical properties of the girders (2). In this paper, $\gamma_{M1} = 1.0$ for comparison purposes.

$$F_{R,d} = \frac{\chi_F \cdot F_y}{\gamma_{M1}} = \frac{\chi_F \cdot f_{yw} \cdot l_y \cdot t_w}{\gamma_{M1}} \leq \frac{\chi_F \cdot f_{yw} \cdot a \cdot t_w}{\gamma_{M1}} \quad (1)$$

$$\begin{aligned} l_y &= s_s + 2 \cdot t_f \cdot \left(1 + \sqrt{m_1 + m_2}\right) \\ &= s_s + 2 \cdot t_f \cdot \left(1 + \sqrt{\frac{f_{yf} \cdot b_f}{f_{yw} \cdot t_w} + 0.02 \cdot \left(\frac{h_w}{t_f}\right)^2}\right) \leq a \\ &\text{if } \overline{\lambda}_F < 0.5 \; m_2 = 0 \end{aligned} \quad (2)$$

$$\chi_F = \frac{0.5}{\overline{\lambda}_F} \quad \overline{\lambda}_F = \sqrt{\frac{F_y}{F_{cr}}} \quad F_{cr} = 0.9 \cdot k_f \cdot E \cdot \frac{t_w^3}{h_w} \quad (3)$$

Noticeably, l_y has an upper bound. The calculated effectively loaded length cannot exceed the distance “a” between transverse stiffeners. As a result, l_y must be shifted in Eq. (1) by this distance resulting in a structural anomaly: the shorter the distance between transverse stiffeners, the lower the ultimate load capacity to concentrated forces.

It is therefore inferred from this shift that the ultimate load capacity of the girders with such cases is limited to F_1 (web folding along the distance “a”). The flange contribution is thus, dismissed.

3. Mechanical model for girders with closely spaced transverse stiffeners

For the sake of correcting the aforementioned structural underestimation and of providing more generality to the present formulation included in EN1993-1-5, a mechanism solution for predicting the collapse loads of plate girders subjected to patch loading was proposed in [12]. This solution represents a suitable alternative for the calculation of the ultimate load capacity of girders presenting the particular case of closely stiffened web panels subjected to concentrated loads in which the flange contribution is accounted for.

The proposed model is based upon two terms in Eq. (4). The first term contains the web contribution whereas the second, a newly proposed value of ΔF_f. The former term is based upon the current EN1993-1-5 formulation by using the distance “a” as the effectively loaded length l_y. The latter is obtained by applying the first theorem of plastic collapse on the numerically observed four hinge mechanism model depicted in Fig. 3. The term $F_2 - F_1 = \Delta F_f$ becomes active only whether the effectively loaded length “l_y” is greater than the distance “a” between transverse stiffeners.

$$\begin{aligned} F_{Rd,proposed} &= F^*_{Rd} = F_{Rd(ly=a)} + \Delta F_f = \frac{\chi \cdot F_{y,(l_y=a)} + \Delta F_f}{\gamma_{M1}} \\ &= \frac{\chi \cdot f_{yw} \cdot a \cdot t_w + \Delta F_f}{\gamma_{M1}} \end{aligned} \quad (4)$$

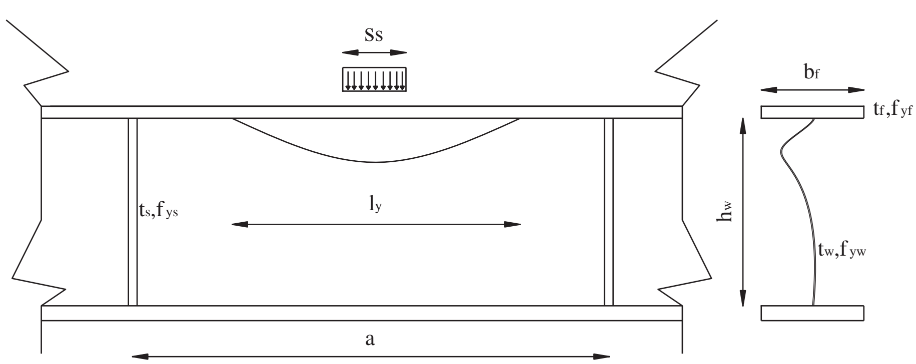

Fig. 2. Failure mode in I-girder with largely spaced transverse stiffeners subjected to patch loading.