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HYBRID STEEL PLATE GIRDERS SUBJECTED TO PATCH LOADING

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Abstract. *The structural case of hybrid girders subjected to patch loading is treated identically than the one for homogenous specimens in EN1993-1-5. The EN1993-1-5 formulation is based upon a theoretical model which consists of a plastic resistance F_y partly reduced by a resistance function χ_F, this latter accounting for instability. The EN1993-1-5 formulation predicts that the ultimate load capacity of steel plate girders subjected to patch loading increases, among others, with the hybrid grade f_{yf}/f_{yw}. In this work, an appraisal of the theoretical and numerical responses of hybrid and homogenous specimens subjected to patch loading is presented. Some peculiarities concerning the treatment of hybrid girders are pinpointed though. It is numerically demonstrated that the moment capacity of the flanges (and thus, f_{yf}/f_{yw}) does not play any role in the resistance of girders predicted in EN1993-1-5. Accordingly, a design proposal which enhances the current formulation is provided.*

1 INTRODUCTION

A girder is deemed as being hybrid when it is fabricated with different steel strengths for the flange and web panels. In hybrid design, the nominal yield strength of one or both flanges is larger than the nominal yield strength of the web. This type of girder is popular as the girder yields a greater flexural capacity at lower cost and weight compared to a homogeneous girder [1]. On the other hand, patch loading phenomena has been widely analyzed since the early sixties. Experimental and theoretical analyses have pinpointed the typical failure mechanisms of girders subjected to patch loading and consequently ultimate load predictions are nowadays available [2]-[4]. Broadly speaking, two magnitudes have been given to describe the resistance of members subjected to this sort of loads. The former defines a plastic resistance F_y of the member whereas the latter, an elastic critical load F_{cr}. The former has been generally obtained by limit analysis whereas the latter, by theoretical formulae properly calibrated with numerical simulations. The factual situations to which these members are subjected lie inside a blurred transition between yielding and instability. It is well known that the root square of the ratio between the plastic resistance F_y and the elastic critical load F_{cr} is commonly referred to as the slenderness parameter. Admittedly, there exists a direct relation between this slenderness and the actual failure mode. This relation has been labeled in the European guidelines for the design of plated structural elements EN1993-1-5 [5] as the resistance function. The patch loading phenomena has been harmonized to this procedure.

Despite the vast amount of research devoted separately to both hybrid girders and the patch loading field, the research work that matches both subjects is rather scant [6]-[8]. In this paper, the resistance of hybrid steel plate girders subjected to patch loading is dealt with simultaneously. Theoretically, it is demonstrated that the EN1993-1-5 formulation predicts the resistance of plate girders subjected to patch loading as a monotonic increasing function with, among other parameters, the flange yield strength f_{yf} (and consequently, with the hybrid grade f_{yf}/f_{yw}). Numerically, a vast study aimed at comparing numerical and theoretical results is presented. In this study, it is found that the results obtained with the

EN1993-1-5 provisions do not reproduce satisfactorily the trends obtained numerically. Alternatively, a design proposal in accordance with the procedure implemented in EN19931-5 and aimed at correcting the aforementioned anomaly is proposed.

2 EN1993-1-5. PLATED STRUCTURAL ELEMENTS

2.1 Hybrid girders

The European design rules EN1993-1-5 overtly consider the hybrid girder usage. These rules recommend a maximum value of $\Phi_h = f_{yf}/f_{yw} < 2,0$. The treatment of hybrid girders is identical to one of homogeneous prototypes except for the following remarks. First, as the resistance to direct stresses of plate girders is calculated by using the effective area of the cross-section, in the particular case of hybrid design, f_{yf} must be used in determining the effective area of the web for plate buckling purposes. Second, for the particular case of hybrid plate girders it is indicated that the potential yielding of the web must be taken into account in direct stresses verifications.

2.2 Patch loading

Regarding the verification to patch loading, the general approach currently included in EN1993-1-5 is based upon a plastic resistance F_y which is partially reduced by means of the resistance function χ_F. The plastic resistance is based upon the mechanical model suggested in [2]. In eq. (1), l_y is the yield-prone effectively loaded length and is calculated from geometrical and mechanical properties of the girders by using equations (2), being "l_y" not greater than the distance between adjacent transverse stiffeners "a". χ_F takes instability into account by means of equations (3) and (4) and can be obtained with eq. (5). The buckling coefficient k_F for longitudinally unstiffened panels is given in (6).

$$F_{Rd} = \frac{\chi_F \cdot F_y}{\gamma_{M1}} = \frac{\chi_F \cdot f_{yw} \cdot l_y \cdot t_w}{\gamma_{M1}} \leq \frac{\chi_F \cdot f_{yw} \cdot a \cdot t_w}{\gamma_{M1}} \tag{1}$$

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

$$\bar{\lambda}_F = \sqrt{\frac{f_{yw} \cdot l_y \cdot t_w}{F_{cr}}} \tag{3}$$

$$F_{cr} = 0,9 \cdot k_F \cdot E \cdot \frac{t_w^3}{h_w} \tag{4}$$

$$\chi_F = \frac{0,5}{\bar{\lambda}_F} \leq 1,0 \tag{5}$$

$$k_F = 6 + 2 \cdot \left(\frac{h_w}{a}\right)^2 \tag{6}$$

In eq. (2), it is observed that l_y is an increasing function with the term m_1 (which includes the hybrid ratio $\Phi_h = f_{yf}/f_{yw}$). As a result, F_{Rd} is an increasing function with Φ_h accordingly.

3 NUMERICAL MODEL

3.1 Description

A numerical model implemented in Abaqus [9] was used systematically as a simulation tool. In this work, fully nonlinear analyses were performed on ideally modeled steel plate girders using quadrilateral shell elements for the web, flanges and stiffeners. These models were based upon the following numerical features. Geometrically, S4 shell elements found in Abaqus libraries were employed for the simulations. Materially, an elastic-perfectly plastic constitutive equation was adopted for all cases. The used nonlinear solution strategy was the arc-length method (based on the modified Riks algorithm). The used iterative procedure was the Newton-Raphson method. Eigenvalue extractions were also performed for the sake of obtaining elastic critical loads as well as the elastic critical shapes typically associated to failure modes.

All numerical simulations were performed by following the current European guidelines EN1993-1-5-Annex C. In a previous work performed by the authors, the validity of these guidelines when developing numerical models on plate girders subjected to patch loading was pointed out [10]. The main conclusions pinpointed in such work are given herein. Firstly, the initial shape of the geometry of the girders can be based upon the *1st* critical eigenmode. Secondly, the largest amplitude w of this critical shape can be scaled to a value equaling 80% of the fabrication tolerances. Eventually, the structural imperfections must be included in the form of residual stress patterns. Further information concerning those topics can be found [6]-[8] and [10].

3.2 Numerical database

Numerical simulations were performed on a single panel centrically loaded with a patch. The panel was locally loaded up to failure. The load was introduced as a pressure on the top flange within the load length s_s. The panels were modeled as simply supported (a beam with support reactions) with additional restrains in all flange corners. Transverse stiffeners were provided in the bearing sections. The numerical database was constructed by varying geometrical and material parameters. Table 1 summarizes the set of variations, which resulted in an amount of 192 specimens. Four different groups form the framework of the sample. Each group consists of a web panel presenting a given value of h_w. Within each group, three different distances between transverse stiffeners "a" were studied. Likewise, two different values of t_w studied for each case leading to varying the web slenderness within each group. The hybrid parameter $\Phi_h=f_{yf}/f_{yw}$ was varied systematically. The web yield strength was held constant whereas the flange yield strength was accordingly increased from $\Phi_h=f_{yf}/f_{yw}$ =235/235=1,0 (homogenous girder) to $\Phi_h=f_{yf}/f_{yw}$ =460/235=1,95.

3.3 Numerical results

Numerical results of 192 plate girders subjected to concentrated loads are available for all the depicted specimens [6]-[7]. Ultimate load capacities $F_{u,num}$ as well as elastic critical buckling loads $F_{cr,num}$ were obtained in all prototypes. In this paper, for the sake of conciseness, these results are presented only graphically in figure 1. This plot represents the resistance function curve defined in EN1993-1-5 (Eq. 6) together with the results obtained numerically. These numerical results are plotted in the form of $F_{u,num}/F_y$ (being $F_{u,num}$ the ultimate load obtained with the numerical model and F_y the theoretically predicted plastic resistance according to Eq. (1).

At first glance, all dots corresponding to numerical results are located above the theoretical EN1993-1-5 resistance function. This finding is structurally sound and on the safety side. By contrast, in previous works performed by the authors [6]-[8], it was found that the structural response of girders subjected to patch loading differ considerably whether the calculated effectively loaded length "l_y" is less than or greater than the distance between transverse stiffeners "a". The former case is typically associated with web folding as the failure mode whereas the latter, to a failure mode involving both web folding and flange yielding. In the developed numerical database, 148 girders belong to the former category (largely spaced transverse stiffeners, l_y<a). This category represents the vast majority of

realistic structural cases of steel plate girders subjected to concentrated loading in, for instance, bridge applications. The conclusions presented in this paper are related to this category only.

Table 1. Numerical database

Numerical database variations	Group 0	Group I	Group II	Group III
Web yield strength f_{yw} (N/mm^2)	235	235	235	235
Flange yield strength f_{yf} (N/mm^2)	235 275 355 460	235 275 355 460	235 275 355 460	235 275 355 460
h_w (mm)	1000	2000	3000	4000
a (mm)	1000 2000 3000	2000 4000 6000	3000 6000 9000	4000 8000 12000
t_w (mm)	8 12	12 20	15 25	15 30
s_s (mm)	250 500	500 1000	750 1500	1000 2000
Flange dimensions (mm^2)	800x60	900 x 80	1000 x 80	1200 x 100
Stiffener thickness (mm)	40	60	60	80
Girders per group	48	48	48	48
Total number of numerical simulations			192	

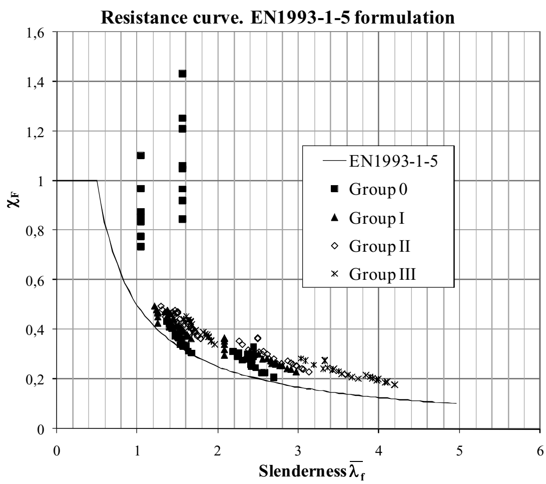

Figure 1. Resistance function and numerical results.

4 ANALYSIS OF THE RESULTS

The structural response of hybrid steel plate girders subjected to patch loading is analyzed on a sample of typical load-displacement plots extracted for 16 girders of the whole numerical database (namely, only girders with geometrical proportions such as l_y<a). All plots are drawn from values of the actual applied load and, in addition, the vertical displacement of a node located at the mid-span cross-section of the top flange. Figure 2 displays four different plots. In each one, four curves corresponding to girders with identical geometry are displayed. Fundamentally, the only varying parameter within each plot is the nominal yield strength of the flange f_{yf} (and consequently, the $\Phi_h=f_{yf}/f_{yw}$ ratio). Each plot corresponds to a sample of girders excerpted from each group (0 to III). Three additional remarks

feature the selected sample. Firstly, all girders present an aspect ratio a/h_w=3,00. Secondly, the web slenderness is different from one group another. Girders belonging to the group 0 are fairly stocky (h_w/t_w=83,33) whereas girders belonging to group III are fairly slender (h_w/t_w=266,66). Thirdly, iIt is worth mentioning that the geometric proportions of the girders (web, flange and stiffeners proportions) are different from one group another. Numerically obtained ultimate loads F_u are indicated for all cases.

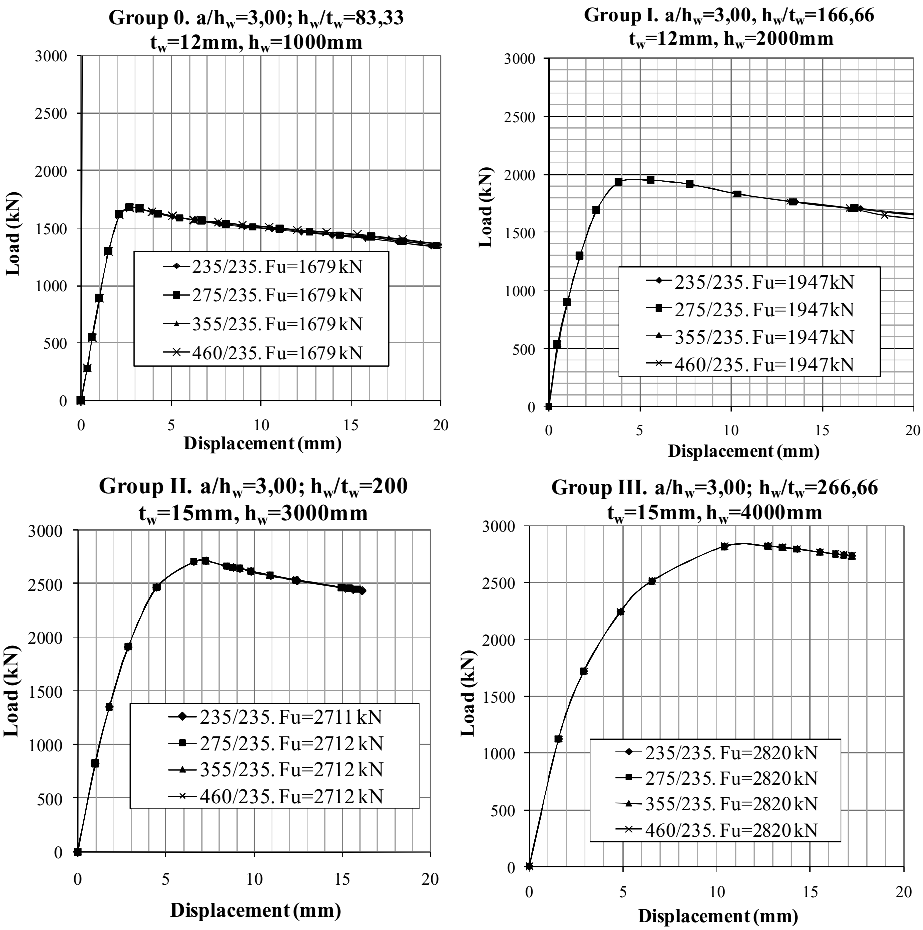

Figure 2. Structural response of girders subjected to concentrated loads.

All girders present a similar load-deflection plot with a monotonically increasing branch as well as a peak load at which the load-bearing capacity is exhausted (F_u). Subsequently, a softening branch is observed in all cases. Surprisingly, the influence of the flange yield strength (and thus, the hybrid ratio $\Phi_h=f_{yf}/f_{yw}$) is negligible. For each series of girders in which Φ_h is varied ranging from Φ_h=1,00 to Φ_h=1,96, the shape of the curves as well as the magnitudes of the ultimate load coincide. This fact is observable for all groups (insistently, solely in girders with $l_y<a$).

Moreover, an appraisal of EN1993-1-5 formulation when obtaining ultimate loads of hybrid specimens subjected to patch loading is presented. For the sake of illustration, F_{Rd} (theoretical) and F_u (numerical) values are standardized to the ultimate load obtained with a geometrically equivalent homogeneous prototype (in all cases, the material yield strength in these homogenous prototypes is $f_{yf}=f_{yw}=235$ N/mm^2). Namely, the plotted ratio is equal to F_{hyb} / F_{hom}. This ratio is plotted against the variation of the flange steel grade $\Phi_h=f_{yf}/f_{yw}$. Figure 3 shows the evolution of this ratio as long as $\Phi_h=f_{yf}/f_{yw}$ is increased for both numerical and EN1993-1-5 results. 32 specimens are included in such appraisal. It is observed that the EN1993-1-5 formulation predicts a considerable increment of ultimate load capacity of the girders as the yield strength of the flange is increased. Different maximum increments are observed for each case (Group 0≈15%; Group III≈10%). The numerical model, however, neither predicts the same results nor the same trend. The ultimate load capacity is maintained constant as the $\Phi_h=f_{yf}/f_{yw}$ ratio is increased. The present EN1993-1-5 formulation leads to a structural anomaly and must be evaluated.

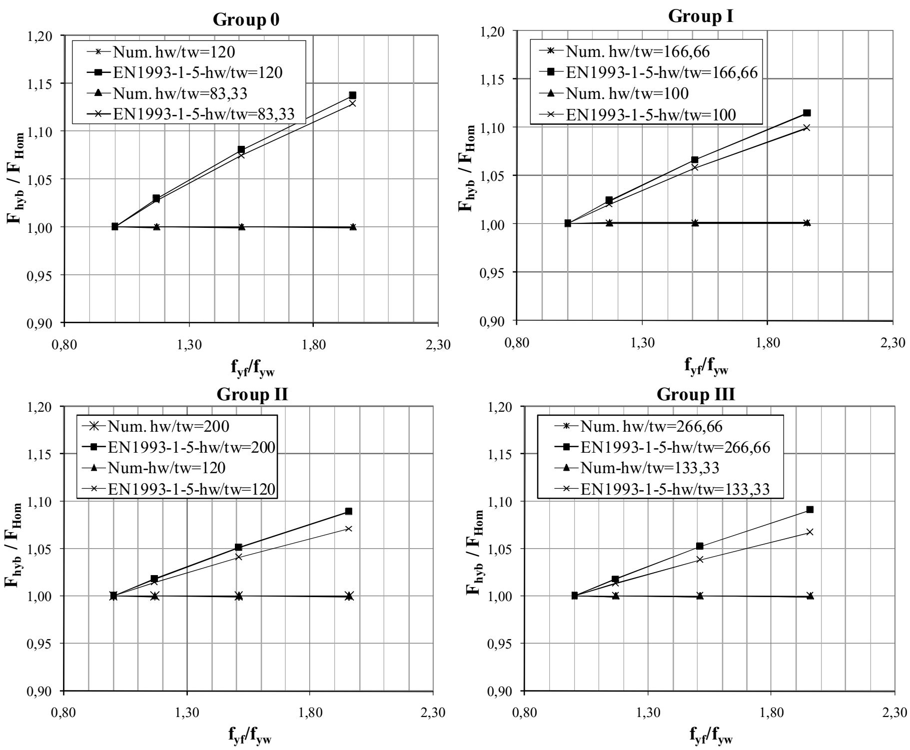

Figure 3. Numerical results vs. EN1993-1-5 predictions.

5 DESIGN PROPOSAL

The numerical studies on hybrid steel plate girders subjected to patch loading hitherto presented have shown that for girders with largely spaced transversal stiffeners (l_y<a), the contribution of the flange yield strength f_{yf} upon the patch loading resistance seems to be negligible. The current formulation of EN1993-1-5 takes this ratio into account in such a way that, the greater the ratio $\Phi_h=f_{yf}/f_{yw}$, the higher the ultimate load capacity of the girders. Presently, the term m_l included in Eq. (2) is a linear function of $\Phi_h=f_{yf}/f_{yw}$. One first attempt for correcting this anomaly is to take the f_{yf}/f_{yw} ratio equal to 1,0 in the current expression for F_{Rd}, according to EN1993-1-5. This attempt leads to reshaping the effectively loaded length l_y into eq. (8), in which m_l is shifted by m_l*. This modification of the formulation has been tested both structurally and statistically in [6]-[8]. The former verification has permitted to draw limits to the formulation (depicted in eq (8)) and the

latter, to evaluate the corresponding enhancement this new formula gives to the safety margin of the formulation.

$$l_y^* = s_s + 2 \cdot t_f \cdot \left(1+\sqrt{m_1^* + m_2}\right) = s_s + 2 \cdot t_f \cdot \left(1+\sqrt{\frac{b_f}{t_w} + 0{,}02\left(\frac{h_w}{t_f}\right)^2}\right) \text{ if } \left(\left(h_w/t_w\right) \Big/ \left(b_f/t_f\right)\right) \geq 12{,}5 \quad (8)$$

In this paper, the ratio $F_{u,num} / F_{Rd}$ is used for evaluation of the formulation (in this assessment, the partial factor is treated as γ_{M1}=1,00). $F_{u,num} / F_{Rd}$ represents the safety margin of the formulation. Figure 4 (a) shows the variable $F_{u,num} / F_{Rd}$ as a function of $\Phi_h = f_{yf}/f_{yw}$. Each value of f_{yf}/f_{yw} includes a number of numerical results (n=37). All populations fit to a normal distribution. It is noticeable that as long as f_{yf}/f_{yw} is increased, the scatter gradually moves down (the arrow in the plot shows such trend). Remarkable statistical information extracted from each sample is presented in Table 2. This information gives hints about the trends observed within the plots. From Table 2, one can point out significant results. First, for each studied value of f_{yf}/f_{yw}, the mean value for n=37 decreases with f_{yf}/f_{yw}. Second, the sample standard deviation S_x and the sample variation V_x remain nearly constant in all cases and third, maxima and minima values of the sample decrease gradually with f_{yf}/f_{yw}. According to the results obtained, one can observe a certain dependency of the statistics upon the f_{yf}/f_{yw} ratio (fundamentally, the mean and the extremes). These statistics, which are essentially estimators of the safety margin, decrease monotonically. This fact may be structurally detrimental and undesirable.

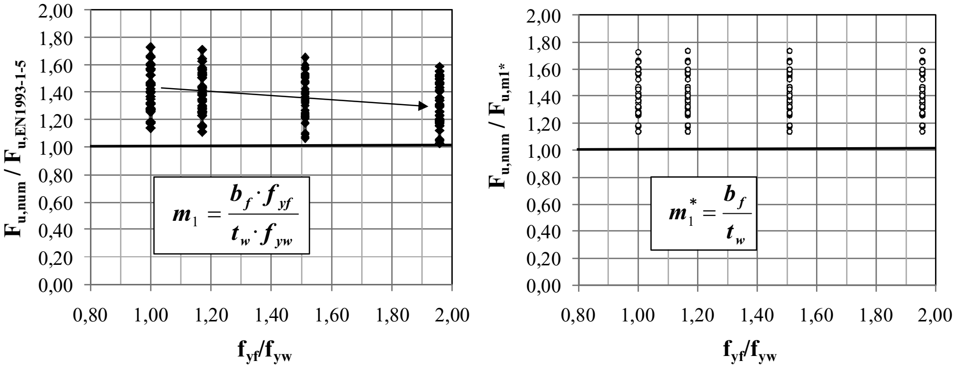

Figure 4. $F_{u,num}/F_{Rd}$ vs f_{yf}/f_{yw}. (a) based upon m_1 (b) based upon m_1*.

Table 2. Statistical values for the safety margin variable $F_{u,num}/F_{Rd}$. Values based upon m_1.

n	f_{yf}/f_{yw}	$\overline{X}$	Sx	Vx	Maximum	Minimum
37	1,00	1,42	0,157	0,111	1,73	1,14
37	1,17	1,39	0,155	0,111	1,70	1,11
37	1,51	1,36	0,156	0,115	1,65	1,07
37	1,96	1,32	0,149	0,113	1,59	1,03

Table 3. Statistical values for the safety margin variable $F_{u,num}/F_{Rd}$. Values based upon m_1*.

n	f_{yf}/f_{yw}	$\overline{X}$	Sx	Vx	Maximum	Minimum
37	1,00	1,42	0,159	0,112	1,73	1,14
37	1,17	1,42	0,158	0,111	1,74	1,14
37	1,51	1,43	0,162	0,113	1,74	1,14
37	1,96	1,43	0,157	0,110	1,74	1,14

Correspondingly, the ratio $F_{u,num}$ / $F_{Rd,m1*}$ is used for evaluation. Figure 4 (b) shows a plot in which the populations (n=37 for each value of Φ_h) are plotted against the f_{yf}/f_{yw} ratio. A substantial change in the trend is observed regarding the influence of f_{yf}/f_{yw}. Table 3 shows similar statistics for the population in which l_y is based upon m_1*. In this case, all statistics are nearly constant for all groups. The mean and the extremes in all cases practically coincide. Accordingly, the aforementioned peculiarities vanish when m_1 is shifted by m_1*. According to the results obtained, the term m_1* corrects quite satisfactorily the potential overestimation encountered within the numerical results.

6 CONCLUSIONS

Numerical results presented in this paper have shown some aspects concerning the effect of the flange yield strength (and thus, the hybrid parameter $\Phi_h=f_{yf}/f_{yw}$) on the resistance of steel plate girders subjected to patch loading. Numerically, it is predicted that for girders with largely spaced transverse stiffeners (l_y<a), there is null influence of this ratio upon the ultimate load capacity of patch loaded girders. 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} is, the higher the ultimate load capacity of the girders. For the sake of correcting this anomaly, a modification on the current EN1993-1-5 formulation that enhances the results quite satisfactorily is proposed. Readably, it is suggested that m_1 be shifted by m_1*. This new formula has been tested both structurally and statistically. The results lead to a satisfactory improvement of the formulation. The results obtained with the upgraded coefficient m_1* are structurally sound and on the safety side.

7 ACKNOWLEDGMENTS

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