Resistance of hybrid steel plate girders subjected to patch loading

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ABSTRACT: Hybrid girders have proven to be an economical alternative to homogeneous girders since they provide a greater flexural capacity. One of the potential applications of hybrid steel plate girders is their usage in bridge construction. One of the potential constructive methods of these bridges is the push launch method, in which patch loads may condition the design. The aim of this paper is to present advanced conclusions of a research work dealing simultaneously with these two fields; the hybrid typology when subjected to the particular case of patch loading. The most remarkable results of the research work are pointed out. On the one hand, it is shown that the influence of the f_{yf}/f_{yw} ratio (namely, the hybrid grade) is negligible for girders with largely spaced transverse stiffeners. On the other hand, it is shown that this influence can be significant if the transverse stiffeners are closely spaced. Suggestions for considering these findings on design codes are provided at the end paper.

1 INTRODUCTION

Hybrid design of plate girders has proven economically sound when used in continuous bridges. This design is based in girders which are fabricated with different steel strengths for the flange and web panels. Extensive experimental, theoretical and numerical research on hybrid design can be found in the literature. Flexural capacity, shear resistance, instability and fatigue resistance of hybrid prototypes have been widely investigated in the last decades (Veljkovic & Johansson 2004). As a consequence, a great number of bridges have been designed using a hybrid girder structural solution. A vast amount of these bridges have been erected by using the incremental launching method. This construction process implies that the reactions of the piers become moving concentrated loads acting in short lengths of the webs assembling the plate girders. During launching, the reactions of the piers are expected to be considerably large. A concentrated force acting perpendicular to the flange of a steel girder is commonly referred to as patch loading. This type of loading usually induces a local failure of the web plate in the vicinity of the loaded flange. If the web panel is stocky, the failure mode is primarily dominated by yielding whereas whether the panel is slender, the failure mode might be dominated by instability. Patch loading phenomena has been widely analysed since the early sixties (Lagerqvist & Johansson 1996). Several failure mechanisms and critical buckling loads have been proposed throughout the last decades for the case of stiffened and unstiffened panels.

2 REVIEW OF THE EARLIER WORK

Despite the vast amount of research devoted to hybrid girders and patch loading, the research work that matches both subjects is rather scant. Schillings (1967) presented the first and only found publication related to hybrid steel girders dealing explicitly with concentrated loading. The main objective of this work was to assess the influence of the potential web yielding caused by bending in the susceptibility to the phenomena associated with concentrated loading. In order to assess this susceptibility, Schillings performed two tests on the same hybrid specimen. First, a transverse compressive load was applied on the compression flange and second, the transverse load was applied on the tension flange. The tests showed that concentrated loads can be applied in either tension or compression flanges even when the longitudinal stress in the web is close to its yield strength. Moreover, when studying the behavior of slender girders subjected to patch loading, Granath (1997) pointed out interesting conclusions about the influence of the moment capacity of the flanges on the bearing capacity of plate girders subjected to concentrated loads. In this work, though not focused on hybrid girders, the author demonstrated that increasing the yield stress of the web increases considerably the ultimate load capacity of the girders to patch loading while increasing the yield stress of the flange does not. According to the results obtained, there is no yielding of the flange at the low level of deformation occurring at the peak load.

Furthermore, looking attentively the frame of experimental research works on plate girders subjected to patch loading, it is observed that around 400 tests on transversally stiffened girders subjected to patch loading are available in the literature. From these tests, it is also observed that a non negligible amount of girders present a ratio $\Phi_h = f_{yf}/f_{yw} \geq 1{,}25$, i.e, some of the tested girders were hybrid. Presumably, for the vast majority of cases, it seems an accidental fact. It is worth bearing in mind that when using different plates for flange and web panels, it is likely to measure different yield strengths for both plates. Table 1 shows the pool of transversally stiffened hybrid steel plate girders subjected to patch loading found in the literature. A total amount of 72 girders tested by several authors can be included within this category. References and detailed information related to all these tests can be found is given by Lagerqvist & Johansson (1996).

Table 1. Transversally stiffened hybrid steel plate girders.

Researcher	Year	Number of tests	f_{yf}/f_{yw}	a/h_w	h_w/t_w	S_s/h_w	S_s/a
Bamm et al.	1983	3	1,40-1,49	3,30	69,75	0,06-0,13	0,02-0,04
Granholm	1960	7	1,25	13,80	126-263	0,00-0,20	0,00-0,06
Schillings	1967	2	2,50	7,00-13,00	36	0,27	0,019-0,037
Bossert et al	1967	6	1,27-1,29	0,80-1,60	294	0,80-1,60	1,00
Bergfelt	1979	14	1,31-2,65	0,60-3,40	227-241	0,00-0,14	0,00-0,25
Bergfelt	1983	18	1,25-1,38	1,38-8,00	150-400	0,05-0,40	0,013-0,13
Roberts et al.	1981-1988	22	1,25-1,59	0,80-2,40	81-500	0,06-0,20	0,07-0,08

3 EN1993-1-5. PLATED STRUCTURAL ELEMENTS

3.1 *Hybrid girders*

The European design rules EN1993-1-5 (2006) overtly consider the hybrid girder alternative. These rules take the potential yielding of the web into account by limiting the stresses in the web to f_{yw}. The flange strength f_{yf} can be independently increased on all verifications. A maximum value of $f_{yf}=\Phi_h \cdot f_{yw}$. ($\Phi_h = 2{,}0$) is recommended. The treatment of hybrid girders is identical to one of homogeneous prototypes except for the following remarks. Firstly, 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. Secondly, 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.

3.2 *Patch loading*

In EN1993-1-5, section 6, Resistance to transverse forces, the general approach is based upon a plastic resistance F_y which is partially reduced by means of the resistance function χ_F (1). The plastic resistance is based upon the mechanical model suggested by Lagerqvist & Johansson (1996). In (1), l_y is the yield-prone effectively loaded length. This length is calculated from geometrical and mechanical properties of the girders by using equations (2) and (3). Noticeably, the length l_y cannot exceed the distance between transverse stiffeners a. χ_F takes into account instability by means of equations (4) and (5) and can be obtained with eq. (6). The buckling coefficient k_F varies whether the web panels are unstiffened (7), longitudinally stiffened (8) or alternatively, the concentrated load is introduced as end- or opposite- patch loading, which represent a different static configuration and is not treated herein.

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

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

$$m_1 = \frac{f_{yf} \cdot b_f}{f_{yw} \cdot t_w} \; ; \; m_2 = 0{,}02 \cdot \left(\frac{h_w}{t_f}\right)^2 \quad \text{if } \overline{\lambda_F} \ge 0{,}5 \quad \text{otherwise } m_2 = 0 \tag{3}$$

$$\overline{\lambda_F} = \sqrt{\frac{f_{yw} \cdot l_y \cdot t_w}{F_{cr}}} \tag{4}$$

$$F_{cr} = 0{,}9 \cdot k_F \cdot E \cdot \frac{t_w^3}{h_w} \tag{5}$$

$$\chi_F = \frac{0{,}5}{\overline{\lambda_F}} \le 1{,}0 \tag{6}$$

$$k_F = 6 + 2 \cdot \left(\frac{h_w}{a}\right)^2 \tag{7}$$

$$k_F = 6 + 2 \cdot \left(\frac{h_w}{a}\right)^2 + \left(5{,}44 \frac{b_1}{a} - 0{,}21\right)\sqrt{\gamma_s} \tag{8}$$

In (2) and (3), it is observed that l_y is a monotonic increasing function with $\Phi_h=f_{yf}/f_{yw}$. As a result, F_{Rd} happens to be an increasing function with Φ_h as well. This fact might seem structurally sound but, it is considerably contradictory to the conclusions stated by Granath (1997), since allegedly, the ultimate load capacity of the girders subjected to patch loading is not influenced by the yield stress f_{yf}. The following sections are aimed at clarifying this topic.

4 NUMERICAL STUDY

A numerical database of simulations upon hybrid specimens subjected to patch loading was developed. The results obtained are primarily aimed at completing the existing lack of data in this particular field and eventually, clarify the aforementioned anomalies. In the current work, the hybrid parameter $\Phi_h=f_{yf}/f_{yw}$ plays a primary role. A numerical model implemented in ABAQUS (2005) was used systematically as a simulation tool. Nonlinear analyses were performed on steel plate girders using quad-dominant S4 shell elements for web, flanges and stiffeners. Both geometric and material nonlinear effects were considered. An elastic-perfectly plastic constitutive equation was adopted for all cases. The used nonlinear solution strategy was the arc-length based modified Riks algorithm. 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. Detailed information can be found in Chacon et al. (2009). In order to develop adequate numerical simulations on transversally stiffened plate girders subjected to patch loading, it was concluded that the following initial conditions of the models lead to numerical results that are structurally sound.

- The shape of the initial geometry of the girders can be based upon the 1st critical eigenmode.

- The largest amplitude *w* of this critical shape can be scaled to a value equaling 80% of the fabrication tolerances (as suggested by EN1993-1-5-Annex C).
- The structural imperfections should be included in the form of residual stress patterns. The omission of this initial condition in the numerical modeling may lead to slightly overestimated results of the ultimate load capacity of the girders.

The simulations were performed on a single panel centrically loaded in a concentrated fashion. The panel was loaded up to failure by incremental nonlinear analyses. The load was introduced as a pressure on the top flange within the load length s_s. The panels were modeled as simply supported with additional restrains in all flange corners. These points were not allowed to move laterally. Transverse stiffeners were provided in the bearing sections. The numerical database was constructed by varying the most influencing geometrical and mechanical parameters of the girders. The variation was chosen from realistic proportions typically found in European steel bridges. Four different groups formed the framework of the sample. Each group consisted 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 were studied for each case. The hybrid parameter Φ_h systematically varied within the numerical database. The web yield strength was held constant whereas the flange yield strength was systematically increased from $\Phi_h=f_{yf}/f_{yw}=235/235=1{,}0$ (homogenous girder) to $\Phi_h=f_{yf}/f_{yw}=460/235=1{,}95$. Table 2 summarizes the set of variations, which resulted in an amount of 192 specimens.

Table 2. Girder properties of the numerical simulations.

Numerical database variations	Group			
	0	I	II	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			

5 RESULTS

Values of ultimate and critical loads are available for each simulation. The numerical results obtained have shown two different structural responses in hybrid steel plate girders subjected to patch loading. The girders presenting a sufficiently large distance between transversal stiffeners (first category) and the girders with a sufficiently short distance (second category). The distance between transversal stiffeners is labeled short when the calculated effectively loaded length ly (2) is greater than the distance between transverse stiffeners a. Fig. 1 displays the proportions of each category among the sample of simulated girders. Load-deflection plots have been systematically used for the sake of featuring the structural response of the girders. Detailed information of the results can be found in Chacon (2009).

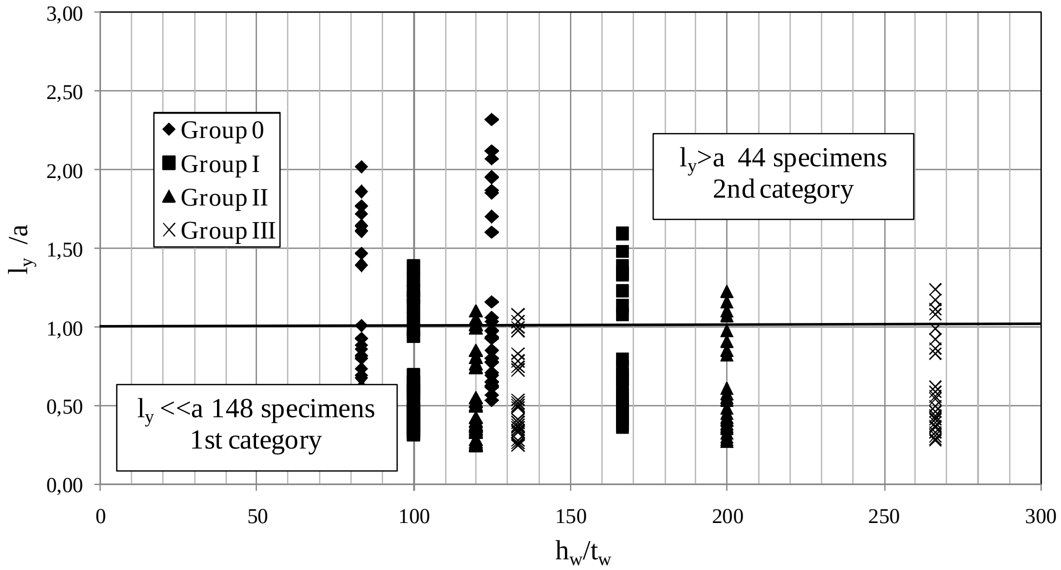

Figure 1. Proportion of categories for the numerical study.

Firstly, the structural response is studied from a sample of typical load-displacement plots extracted for one group in which a/h_w=3,00 and thus, l_y<<a. Fig. 2 (a) displays four load-deflection curves corresponding to one prototype from group 0 in which $\Phi_h = f_{yf}/f_{yw}$ is systematically varied. For these, and all similar cases, the influence of $\Phi_h = f_{yf}/f_{yw}$ is null up to the maximum load. For each series of girders (l_y<<a) in which Φ_h is varied 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. Seemingly, for plate girders subjected to patch loading, the flange yield strength girders do not contribute to the patch loading resistance.

Secondly, load-displacement plots are studied in girders from group 0 in which a/h_w=1,0 and incidentally, l_y>a (Fig. 2 (b)). Looking attentively the load-deflection plots, it is noticeable that a first loss of rigidity occurs for all girders. From this point onwards, the load is significantly increased up to the peak load F_u, where the girder capacity is exhausted. This latter bearing capacity is highly influenced by the $\Phi_h = f_{yf}/f_{yw}$ ratio.

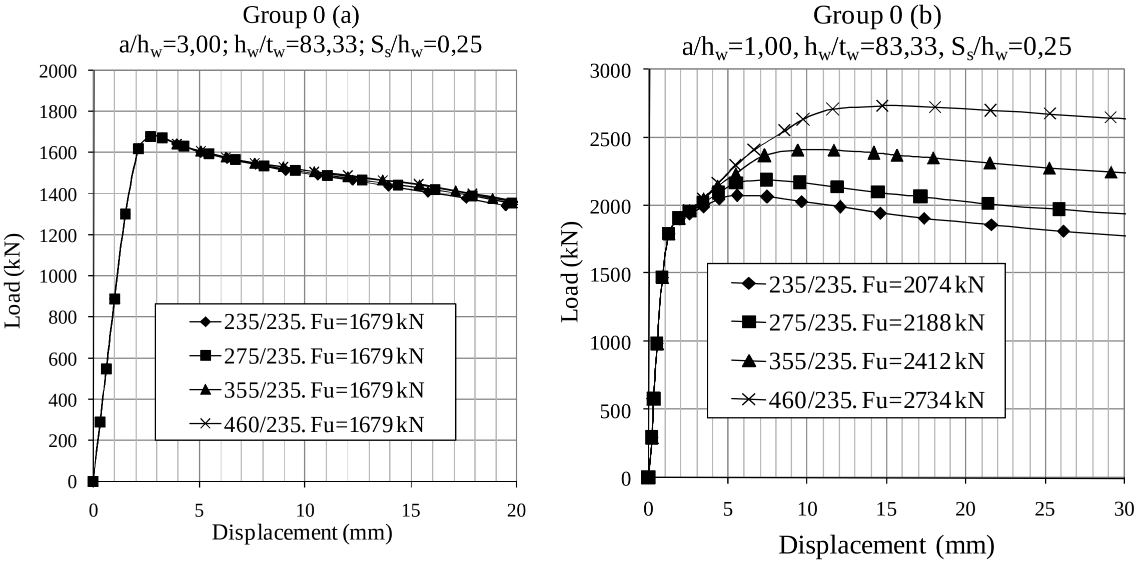

Figure 2. Sample of load-displacement plots extracted for two groups.

On the other hand, the results obtained are compared to those derived from the EN1993-1-5 formulation. For this purpose, the values of numerical and theoretical ultimate loads are standardized to the ultimate load obtained with an equivalent homogeneous prototype, i.e, $F_{u,hybrid}$ / $F_{u,homogeneous}$. This ratio is plotted against $\Phi_h = f_{yf}/f_{yw}$ and thus, the variation of F_u vs. Φ_h can be studied. Fig. 3

shows the results obtained for a sample of girders extracted from groups 0 and I. The extracted sample includes several values of h_w/t_w. The results obtained are quite unexpected and are studied separately for girders presenting largely or closely spaced transverse stiffeners.

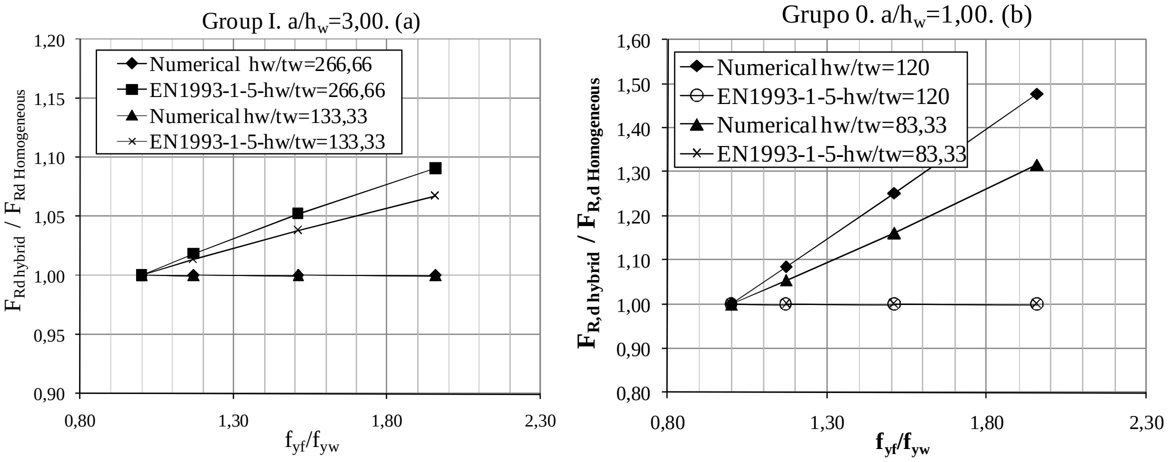

Figure 3. Sample of load-displacement plots extracted for two groups.

For the former category (Fig 3(a)), the EN1993-1-5 formulation predicts a considerable increment of ultimate load capacity of the girders whether the yield strength of the flange is increased (approximately 10%). The numerical model, however, does not predict the same results nor the same trend. The ultimate load capacity is maintained as the f_{yf}/f_{yf} ratio is increased. There seems to be null contribution of the yield strength of the flange for certain cases of girders presenting largely spaced transverse stiffeners. It is worth bearing in mind that presently, the calculated effectively loaded length l_y (3) is a monotonic increasing function with f_{yf}/f_{yf}. The present formulation included in EN1993-1-5 leads to this anomaly and must be evaluated.

For the latter category (Fig 3(b)), the results show rather opposite trends. In this particular case, as long as the f_{yf}/f_{yw} ratio is increased, the ultimate load capacity predicted by the numerical model increases. The maximum increment happens to be approximately 20%. The EN1993-1-5 prediction remains, however, practically constant. In this case, whether the calculated effectively loaded length l_y (3) is found to be greater than the distance between transverse stiffeners a, the design load F_{Rd} must be altered (2). In this new equation, the ultimate load capacity is obtained regardless of the flange and stiffeners properties.

The first analysis is performed upon results obtained from 148 prototypes of the numerical database (l_y<<a, first category). These specimens are divided in four groups of 37 girders (each one corresponding to a value of f_{yf}/f_{yw}). The ratio $F_{u,num}$ / F_{Rd} = X is used for evaluation purposes. Fig 4 shows the variable X as a function of f_{yf}/f_{yw}. It is noticeable that as long as f_{yf}/f_{yw} is increased, the scatter is gradually moved vertically (the arrow in the plot shows such trend).

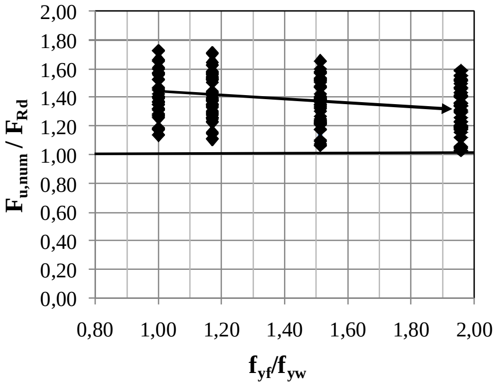

Figure 4. Sample of load-displacement plots extracted for two groups.

Remarkable statistical information extracted from each sample is presented in table 3. This information gives hints about the trends observed within the plots. $\overline{X}$ (the sample mean), S_x, (the sample standard deviation) and V_x (the sample variation) are employed as statistics. In addition, maxima and minima are indicated for each sample. From table 3, one can point out significant results. First, the mean value $\overline{X}$ 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 with f_{yf}/f_{yw}. This fact may be structurally detrimental and undesirable.

Table 3. Statistical values extracted from the population of 148 prototypes.

n	f_{yf}/f_{yw}	$\overline{X}$	Sx	Vx	Max	Min
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

The second analysis is performed from 44 prototypes of the numerical database (ly>a, second category). It is observed that this study requires an in-depth appraisal of the influence of the transverse stiffeners and the top flange. As a matter of fact, two features are inferred from the load-deflection plots studied for these cases. First, a considerable loss of linearity of the plot is noticeable. At this point, web folding occurs (plastic deformation is observable) but the flanges do not present any, this bifurcation point seems independent from the f_{yf}/f_{yw} ratio. Fig 5 (a) shows a typical example of the numerical simulation. Second, at the peak load (capacity exhausted) the web has considerably yielded and plastic hinges are formed in the flange-to-stiffeners juncture (Fig. 5(b)). From the numerical observations, it is concluded that a new resistance mechanism (different from any of the four-hinges mechanisms depicted from other researchers) occurs in this case with the aid of the top flange and the transverse stiffeners.

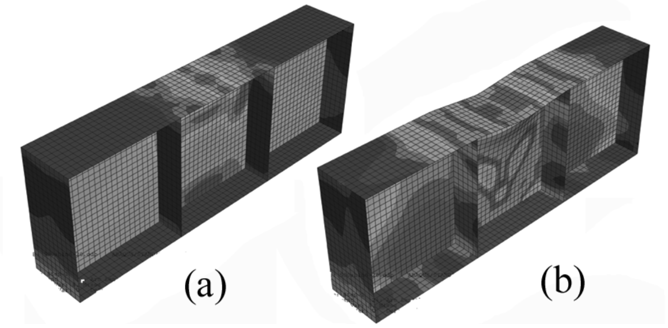

Figure 5. Sample of load-displacement plots extracted for two groups.

A new resistance mechanism which accounts for the presence of the transverse stiffener and the top flange for the particular case of girders in which l_y>a has been presented (Chacon et al. 2008, Chacon 2009). This attempt is aimed at solving the aforementioned inconsistency of the EN1993-1-5 formulation. As a result, the hybrid ratio f_{yf}/f_{yw} can be included in the new formulation and the influence of the top flange can be suitably taken into account.

6 CONCLUSIONS

In this paper, experimental and numerical results on hybrid specimens subjected to patch loading are presented. These results erect the frame of a vaster study on the behavior of hybrid steel plate girders subjected to patch loading. Comparisons between experimental, numerical and theoretical results have pinpointed several inconsistencies of the EN1993-1-5 formulation.

First advances show remarkable results concerning the hybrid parameter $\Phi_h = f_{yf}/f_{yw}$. Numerically, it is predicted that for girders with $l_y << a$, 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. The results show a rather opposite trend when the aspect ratio $l_y > a$. The numerical model predicts a post-buckling capacity which is highly influenced by both the flanges and the transversal stiffening of the panel. Several load-displacement and load-stress plots show how the evolution of the response varies as long as the f_{yf}/f_{yw} ratio is increased. Certainly, there is a strong dependency between this ratio and the ultimate load capacity of the girders. It has been shown though, that the current formulation of EN1993-1-5 underestimates the numerically observed post-peak capacity of the girders. It has been observed that this fact comes mainly as a result of the restriction concerning the maximum allowed value of the effectively loaded length l_y. These conclusions suggest two potential modifications on the current EN1993-1-5 formulation that enhance the results quite satisfactorily.

Firstly, a thorough evaluation of the m_1 coefficient, which accounts for the hybrid parameter $\Phi_h = f_{yf}/f_{yw}$ is suggested. This evaluation must include both structural and statistical procedures. Secondly, a new mechanical model for the particular case of girders with closely spaced transverse stiffeners should be studied. The latter should account for the presence of both the transverse ribs and the top flange. Accordingly, the resistance of hybrid steel plate girders subjected to patch loading can be defined in a more adequate fashion.

7 ACKNOWLEDGEMENTS

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