Patch Loading of Longitudinally Stiffened Webs

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ABSTRACT:

The paper deals with the case of patch loading of steel I shaped girders with two longitudinal stiffeners. The configuration with two longitudinal stiffeners is often an excellent solution for girders higher than 3 meters but has not yet been discussed in EN 1993-1-5 with regard to patch loading resistance. It is proposed a model of resistance to the ultimate limit state based on the works by Lagerqvist and Graciano, and on the more recent works by Clarin and Gozzi, with an approach harmonized with the methods used in Eurocode for the other problems of buckling. The model contains three significant parts: the yield resistance, the elastic critical load used to determine the slenderness parameter and a reduction factor that relates the resistance to the slenderness. The presented work aims to propose a prediction of patch loading resistance, which is able to evaluate the influence of longitudinal stiffeners position.

1 INTRODUCTION

The patch loading or partial edge loading of steel girder webs is a loading condition that occurs when a concentrated force acts perpendicular to a girder's flange. This usually leads to a local buckling of the web near the loaded flange. The patch loading is a loading conditions that occurs during bridges launching when a girder section can be subjected to repeated support reactions provided by the slides (or rollers). Studies conducted by Lagerqvist and those conducted by Graciano, with a few changes, have led to the design criteria contained in Eurocode 3 (EN 1993-1-5) that are valid for girder without or with only one longitudinal stiffener.

In building bridges with steel I girders, the web configuration characterized by the presence of two longitudinal stiffeners is often the best solution for more than three meters high girders (so for spans grater than 50 meters), but it is not treated in EN 1993-1-5. In particular, it is of great interest the possibility of treating the case of I girder doubly stiffened and of evaluating the influence of the stiffeners position on the resistance to patch loading, at the same time. In fact the positioning of stiffeners is influenced by the demand of the maximum efficiency in operating conditions and is therefore essential to seek a solution that takes into account the phases of the launch too.

Chapter 2 details the numerical study on which is based the proposed procedure for calculating the ultimate patch loading resistance of the doubly stiffened girder.

In Chapter 3 describes the proposed procedure for calculating the ultimate patch loading resistance.

Chapter 4 presents some statistical evaluations on the effectiveness of the proposed method.

In chapter 5 lists some observations on the study presented in the paper.

The study presented was conducted by examining longitudinal stiffeners open section. It is also important to extend the study to the case of the section closed with significant rotational inertia.

2 NUMERICAL ANALYSIS

The numerical analysis is performed for a girder with two longitudinal stiffeners. The girder under consideration, shown in figure 1, is 2400mm long, 1200mm high, with flanges measuring 450x20mm. The study is conducted for two different lengths of application of the load: 200mm (called model P200) and 700mm (called model P700). For each of the two cases a set of analysis was conducted with different thicknesses of the web, and with different placements of longitudinal stiffeners along the height of the girder.

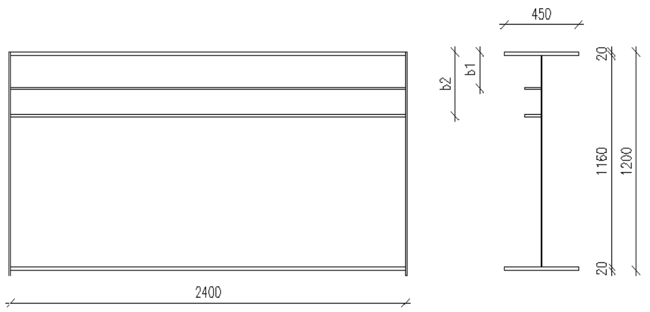

Figure 1. Beam geometry studied

In particular in this paper are shown the following variants of the two geometry P200 and P700:

- the girder without longitudinal stiffeners;
- the girder with a single longitudinal stiffener placed at a distance of 0.20 times the height of the beam (i.e. 240mm) below the upper flange; from literature is known that this is the optimal position of the stiffener in the case of a single element;
- the girder with two longitudinal stiffeners, placed at a distance of 0.28 and 0.20 times the height (i.e. 240mm and 336mm) below the top flange;
- the girder with two longitudinal stiffeners, placed at a distance of 0.28 and 0.16 times the height (i.e. 192mm and 336mm) below the top flange;
- the girder with two longitudinal stiffeners, placed at a distance of 0.20 and 0.32 times the height (i.e. 192mm and 384mm) below the top flange.

The four variants described above are shown with the thickness of 5mm and 6mm for the web.

The choice of the three solutions mentioned above for the positioning of the two longitudinal stiffeners is descended from a preliminary analysis that showed as optimal solution the geometry with stiffeners at the distances of 0.28 and 0.16 times the height, then the second of the three presented.

The finite element analysis was performed with MIDAS FEA (release 2.9.6). This software is dedicated to advanced nonlinear and detail analysis of civil structures.

The model was built using the following element types:

- two-dimensional, four-node elements (shell elements) for flanges, web and stiffeners of the girder
- three-dimensional, eight-node elements (solid elements) for loading plates
- connecting elements (rigid link elements) to connecting rigidly in the vertical direction only, the nodes of the loading plates with the corresponding nodes of the top flange.

With regard to the size and the type of the elements used was made a sensitivity analysis with the aim to evaluate the accuracy of the solution and simultaneously the time required to perform analysis. This preliminary evaluation has shown that there are not significant advantages in changing from 4 nodes to 8 nodes two-dimensional elements and shifting from 8 nodes to 20 nodes for the three-dimensional elements if the maximum size of the same elements is not grater than 50mm.

The numerical study of the two samples is conducted by means of a nonlinear static analysis. Nonlinearity is provided both for the material and for geometry. As known the nonlinear static analysis highlights correctly the sensitivity of the structure to instability phenomena only if the initial geometry is perturbed, or by applying an external force or considering an initial imperfection. In the present work has been chosen the second solution, then a preliminary modal analysis was performed to identify an initial geometric configuration similar to the expected deformation due to the application of the load.

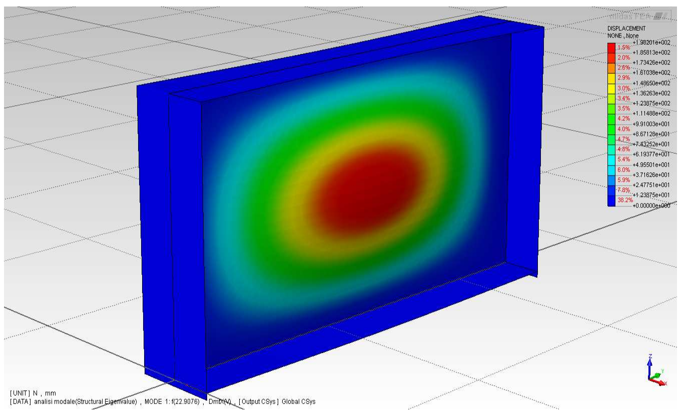

Figure 2. First modal deformed shape

So all analysis presented in this chapter were carried out considering an initial geometry of the web derived from the first modal deformed shape with the maximum amplitude equal to 1/200 the height of the girder (i.e. 4.8mm) at the middle of the vertical section in correspondence of the centerline, according to what stated in EN 1993-1-5, as shown in figure 2 and 3.

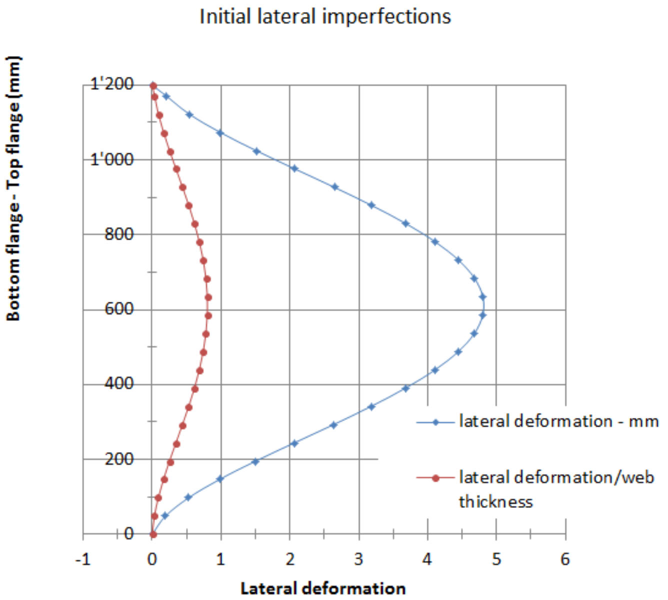

Figure 3. Initial imperfection on the centerline of the web

At the bottom edge of the vertical stiffeners, boundary conditions in the vertical direction were applied as well as in the longitudinal direction on one side of the girder. Moreover, also the midpoints of the bottom edges of the stiffeners were constrained in the transverse direction. The loading plates were constrained from moving in the transverse direction as well.

The mechanical nonlinearity is taken into account in the model by defining a function that describes the hardening behavior of the material (steel) of flanges, web and stiffeners as shown in Figure 4.

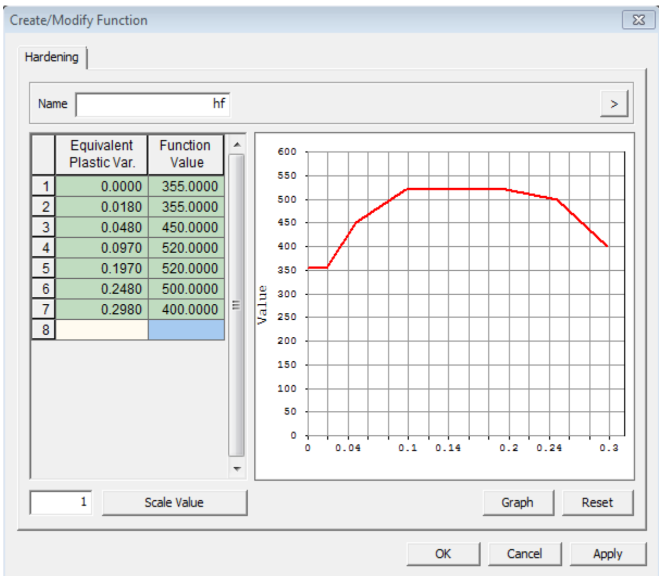

Figure 4. Hardening function for the material nonlinearity

All the numerical study was previously validated by means of a comparison with the laboratory tests conducted by Gozzi (2007) on girders without longitudinal stiffeners. It is observed a good agreement of numerical results with test data on the physical models, this evidence attests to the reliability of numerical modeling.

2.1 *Model P200*

The results of numerical analysis performed on the model called P200, shown in figure 5, are presented.

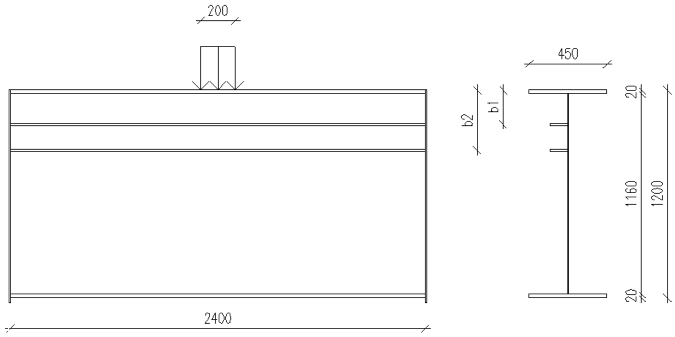

Figure 5. Model P200

In figure 6 is shown the finite element model of P200 geometry.

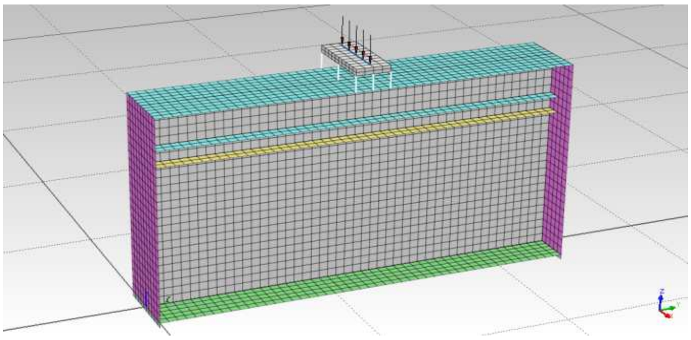

Figure 6. Finite element model P200

Figures from 7 to 9, shows the load-displacement curves of the girder with 5, 6 and 7 mm thick web, with application of the load 200mm length.

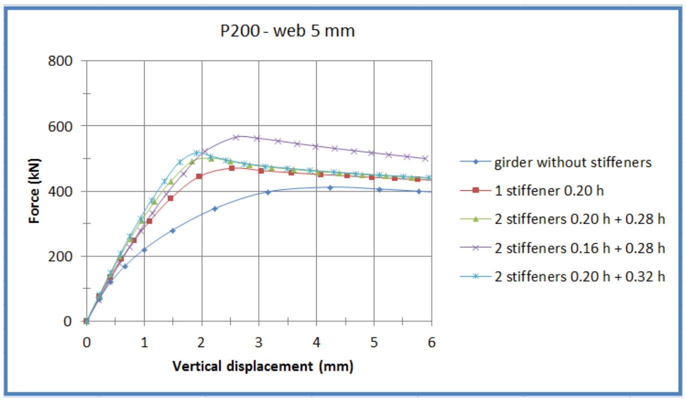

Figure 7. Model P200- web 5mm – Vertical displacement of the midpoint top flange

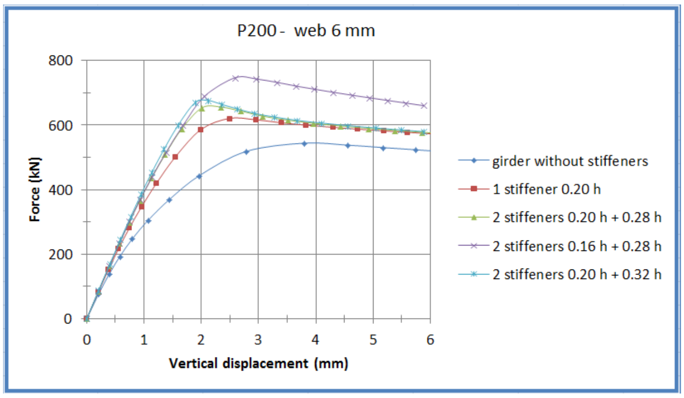

Figure 8. Model P200- web 6mm – Vertical displacement of the midpoint top flange

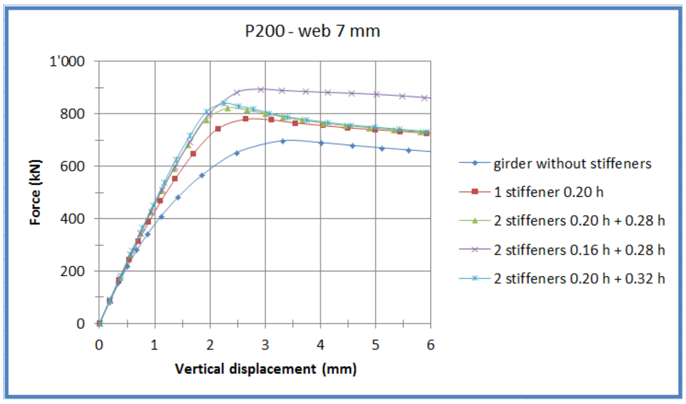

Figure 9. Model P200- web 7mm – Vertical displacement of the midpoint top flange

The overlapped load-displacement curves represent the vertical displacement of the midpoint of the top flange (the same position of the middle of the load application length) in the same variants cited in chapter 2: without longitudinal stiffeners, with 1 longitudinal stiffener at 0.20 times the girder height and with two stiffeners at 0.28+0.20 times the height, 0.16+0.28 times the height and 0.20+0.32 times the height, respectively.

2.2 *Model P700*

The results of numerical analysis performed on the model called P700, shown in figure 10, are presented.

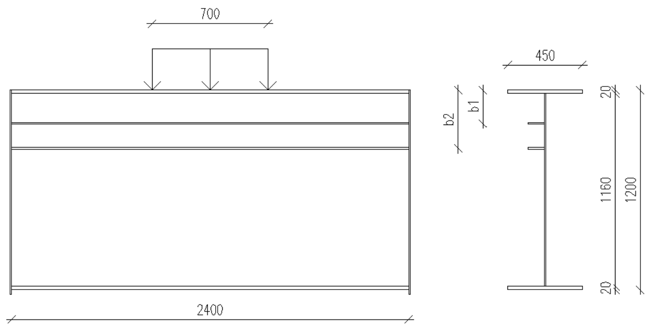

Figure 10. Model P700

In figure 11 is shown the finite element model of P700 geometry.

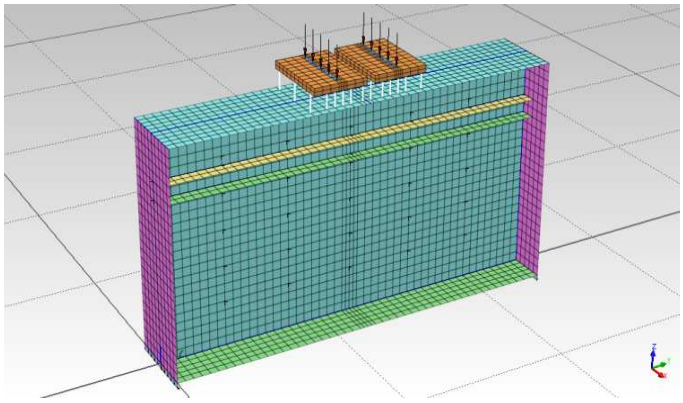

Figure 11. Finite element model P700

Figures from 12 to 14, shows the load-displacement curves of the girder with 5, 6 and 7 mm thick web, with application of the load 700mm length.

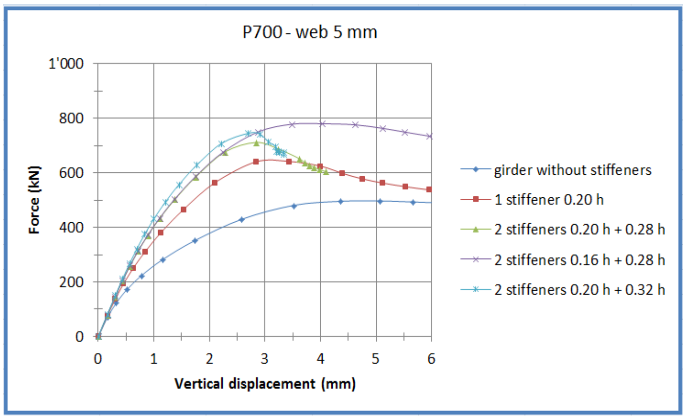

Figure 12. Model P700- web 5mm – Vertical displacement of the midpoint top flange

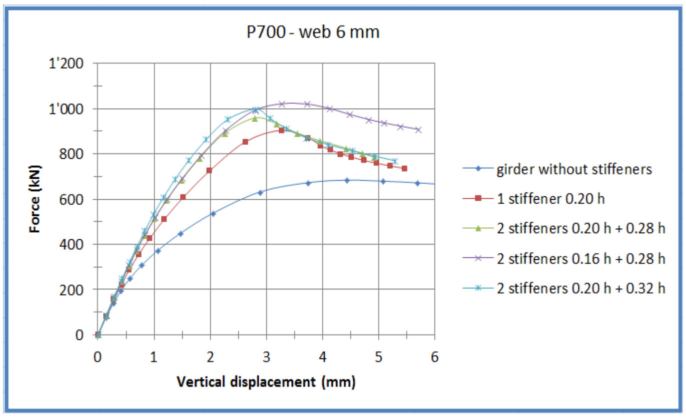

Figure 13. Model P700- web 6mm – Vertical displacement of the midpoint top flange

The overlapped load-displacement curves represent the vertical displacement of the midpoint of the top flange (the same position of the middle of the load application length) in the same variants cited in chapter 2: without longitudinal stiffeners, with 1 longitudinal stiffener at 0.20 times the girder height and with two stiffeners at 0.28+0.20 times the height, 0.16+0.28 times the height and 0.20+0.32 times the height, respectively.

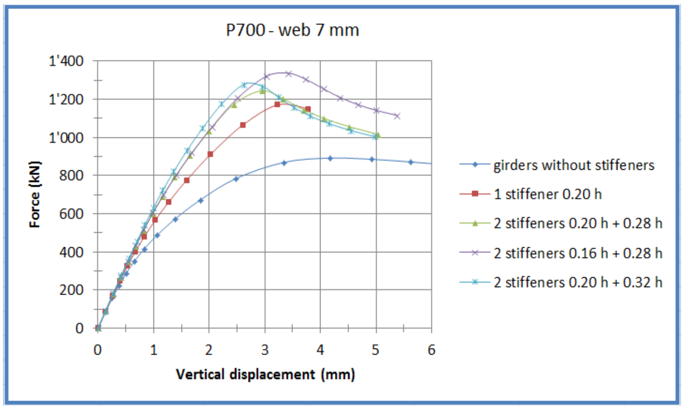

Figure 14. Model P700- web 7mm – Vertical displacement of the midpoint top flange

2.3 *Summary of results*

The table 1 shows the summary of the analysis results in terms of ultimate load for the two geometries P200 and P700.

		P200	P700
Web th (mm)	Long stiff	$F_{u,FE}$ (kN)	$F_{u,FE}$ (kN)
5 mm	-	412	497
	1 a 0.20 h	471	642
	2 a 0.20 h e 0.28 h	502	712
	2 a 0.16 h e 0.28 h	566	780
	2 a 0.20 h e 0.32 h	518	769
6 mm	-	544	684
	1 a 0.20 h	621	904
	2 a 0.20 h e 0.28 h	656	959
	2 a 0.16 h e 0.28 h	747	1022
	2 a 0.20 h e 0.32 h	676	998
7 mm	-	698	891
	1 a 0.20 h	780	1170
	2 a 0.20 h e 0.28 h	823	1244
	2 a 0.16 h e 0.28 h	894	1337
	2 a 0.20 h e 0.32 h	840	1278

Table 1. Results P200 and P700

Results are shown in all configurations studied: without longitudinal stiffeners, with 1 longitudinal stiffener at 0.20 times the girder height and with two stiffeners at 0.28+0.20 times the height, 0.16+0.28 times the height and 0.20+0.32 times the height, respectively.

3 PATCH LOADING RESISTANCE

The basic elements to estimate the patch loading resistance of girders with two longitudinal stiffeners with a procedure harmonized with the standards already established by the European code EN 1993-1-5 for girders without stiffeners or with a single stiffener, are:

- the formulation of the yield strength of the beam;
- evaluation of the elastic critical load to determine the slenderness (according to the method of von Kármán);
- the estimation of the reduction factor relating the yield strength and the slenderness to the resistance

3.1 *Yield strength*

Some codes, such as the European standard EN 1993-1-5, recommend the use of the same equations for the calculation of the yield strength both for unstiffened girders and for stiffened girders. This approach gives an unitary statement to a range of homogeneous problems and is preferable from the point of view of the design engineers.

So for the yield strength of the girder with two longitudinal stiffeners subjected to patch loading will be used the expression (1) which is the same provided for the unstiffened girders by the Eurocode

$$F_y = f_{yw} t_w \left(s_s + 2t_f \left(1 + \sqrt{\frac{f_{yf} b_f}{f_{yw} t_w}} \right) \right) \quad (1)$$

where the part between the brackets corresponds to the effective load length l_y, , expression (2), and is limited to the distance between two vertical stiffeners.

$$L_{eff} = s_s + 2t_f \left(1 + \sqrt{\frac{f_{yf} b_f}{f_{yw} t_w}} \right) \quad (2)$$

3.2 *Elastic critical load*

The most intuitive method, proposed in this paper and also in accordance with the studies of Clarin

(2007), is to use the lowest between the critical loads of each panel.

So in the case of girder with two longitudinal stiffeners will be significant the critical load of the entire panel of the web F_{cr1}, the critical load F_{cr2} of the panel between the top flange and the upper of two stiffeners and the critical load F_{cr3} of the intermediate web panel (i.e. the panel of the web between the upper stiffeners and second stiffener).
Then the elastic critical load will be, expression (3)

$$F_{cr} = min\begin{cases}F_{cr1}\\F_{cr2}\\F_{cr3}\end{cases} \tag{3}$$

The value of critical load of the entire panel of the web is calculated in accordance with the expression given in EN 1993-1-5

$$F_{cr1} = 0.9 \cdot k_{F1} \cdot E \cdot \frac{t_w^3}{h_w} \tag{4}$$

where the buckling coefficient k_{F1} estimate the presence of two longitudinal stiffeners through the terms k_{st1} *and* k_{st2} (expression 5)

$$k_{F1} = 6 + 2 \cdot \left(\frac{h_w}{a}\right)^2 + k_{st1} + k_{st2} \tag{5}$$

The evaluation of the two terms and k_{st1} and k_{st2} that appear in the expression (5) is certainly the fundamental point of the proposed approach to calculating the resistance to patch loading of the girders with two longitudinal stiffeners.

The previous studies, while giving a direction with regard to the placement of the stiffener taken into account (through an upper limit and a lower limit), don't correlate different positions with different values of the ultimate load but prescribe only one value of the resistance regardless of the positioning height of the stiffener (under the condition that the stiffener is positioned between the upper limit and the lower limit).

In the case of two stiffeners is essentially necessary to introduce a procedure to evaluate their effectiveness taking into account the vertical positioning. This option allows a formulation of the resistance closer to the true geometry of the girder taken into consideration.

Through the numerical analysis were then calibrated the two buckling coefficients for the whole panel. In this way they are able to take into account the contribution offered by the presence of stiffeners positioned at the distance d_1 the upper and d_2 the lower respectively from top flange.

In particular for the upper stiffener

if $d_1 < 0.16\ h$

$$k_{st1} = \left(0.675 \cdot \frac{h_w}{a}\right) \cdot \sqrt{\gamma_{st1}} \cdot (6.25 \cdot d_1) \tag{6}$$

if $d_1 \geq 0.16\ h$

$$k_{st1} = \left(0.675 \cdot \frac{h_w}{a}\right) \cdot \sqrt{\gamma_{st1}} \cdot (1.190 - 1.190 \cdot d_1) \tag{7}$$

where *0.16 h* result the optimal position for the upper stiffener.

And for the lower stiffener

if $d_2 < 0.28\ h$

$$k_{st2} = \left(0.675 \cdot \frac{h_w}{a}\right) \cdot \sqrt{\gamma_{st2}} \cdot (3.571 \cdot d_2) \tag{8}$$

if $d_2 \geq 0.28\ h$

$$k_{st2} = \left(0.675 \cdot \frac{h_w}{a}\right) \cdot \sqrt{\gamma_{st2}} \cdot (1.389 - 1.389 \cdot d_1) \tag{9}$$

where *0.28 h* result the optimal position for the lower stiffener.

In the expressions from (6) to (9) appear the flexural rigidity of the stiffeners as stated in the European standard EN 1993-1-5,

$$\gamma_{sti} = 10.9 \cdot \frac{I_{sti}}{h_w \cdot t_w^3} \tag{10}$$

where the moment of inertia is calculated, in agreement with the same European standard, taking into account the web contribution as shown in Figure 15.

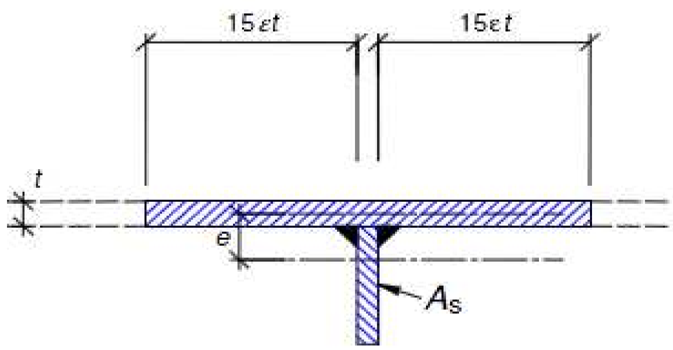

Figura 15 - Effective section of longitudinal stiffener in agreement with EN 1993-1-5

Regarding the upper panel (between the top flange and the upper stiffener, thus directly affected by the load) the elastic critical load is proposed to be calculated according to Davaine, using

$$F_{cr2} = k_{F2} \cdot \frac{\pi^2 \cdot E}{12 \cdot (1-\upsilon^2)} \cdot \frac{t_w^3}{b_1} \quad (11)$$

with a buckling coefficient of

$$k_{F2} = \left(0.8 \cdot \left(\frac{s_s+2\cdot t_f}{a}\right) + 0.6\right) \cdot \left(\frac{a}{b_1}\right)^{\left(0.6 \cdot \frac{s_s+2\cdot t_f}{a} + 0.5\right)} \quad (12)$$

Finally, regarding the intermediate panel (between the two stiffeners) the elastic critical load is calculated with the expression (13), similar to that used for the whole web panel in the case of unstiffened web

$$F_{cr3} = 0.75 \cdot k_{F3} \cdot E \cdot \frac{t_w^3}{b_2} \quad (13)$$

where the buckling coefficient is

$$k_{F3} = 6 + 2 \cdot \left(\frac{b_2}{a}\right)^2 \quad (14)$$

3.3 *Reduction Function*

For the expression of the reduction function we use the formulation of Gozzi (2007) which, although originally developed for unstiffened girder, define resistance values closer to numerical results compared to the expression contained in EN 1993-1 -5.

$$\chi_F = \frac{1}{\varphi_F + \sqrt{\varphi_F^2 - \lambda_F}} \leq 1.2 \quad (15)$$

where

$$\varphi_F = \frac{1}{2} \cdot (1 + \alpha_F \cdot (\lambda_F - \lambda_{F0}) + \lambda_F) \quad (16)$$

and where $\alpha_F = 0.5$, $\lambda_{F0} = 0.6$ according to EN 1993-1-5.

The slenderness parameter λ_F contained in (15) and (16) is calculated using the von Kármán approach according to

$$\lambda_F = \sqrt{\frac{F_y}{F_{cr}}} \quad (17)$$

The design resistance is predicted using

$$F_{Rd} = \chi_F \cdot F_y / \gamma_{M1} \quad (18)$$

with the partial safety factor according to European standard EN 1993.

4 VALIDATION OF THE METHOD

The design procedure proposed to estimate the patch loading resistance of I shaped girders with two longitudinal stiffeners described in chapter 3 has been applied to the cases studied by numerical analysis.

The comparison is shown in table 2, which shows the following parameters (in addition to the name of the girder geometry under consideration):

- the thickness of the web, *web th*, mm;
- the slenderness, λ_F;
- the ratio between distance of upper longitudinal stiffener from the top flange and height of the girder, b_1/h;
- the ratio between distance of lower longitudinal stiffener from the top flange and height of the girder, b_2/h;
- the design resistance calculated with the proposed formulation, F_u, kN;
- the ultimate load calculated with finite element analysis, $F_{u,FE}$, kN;
- the ratio $F_{u,FE} / F_u$.

	web th	λ_f	b_1/h	b_2/h	F_u	$F_{u,FE}$	$F_{u,FE}/F_u$
P200	5mm	2.23	0.20	0.28	334	502	1.503
		1.89	0.16	0.28	393	566	1.440
		2.23	0.20	0.32	334	518	1.551
	6mm	1.81	0.20	0.28	466	656	1.408
		1.63	0.16	0.28	517	747	1.445
		1.81	0.20	0.32	466	676	1.451
	7mm	1.52	0.20	0.28	618	823	1.332
		1.43	0.16	0.28	655	894	1.365
		1.52	0.20	0.32	618	840	1.359
P700	5mm	2.57	0.20	0.28	528	712	1.348
		2.55	0.16	0.28	532	780	1.466
		2.55	0.20	0.32	532	769	1.445
	6mm	2.24	0.20	0.28	706	959	1.358
		2.22	0.16	0.28	710	1022	1.439
		2.22	0.20	0.32	710	998	1.406
	7mm	1.98	0.20	0.28	905	1244	1.375
		1.97	0.16	0.28	911	1337	1.468
		1.97	0.20	0.32	910	1278	1.404

Table 2. Comparison between predicted resistance and numerical results

The ratio $F_{u,FE} / F_u$ is plotted as a function of the slenderness of the girder in Figure 16.

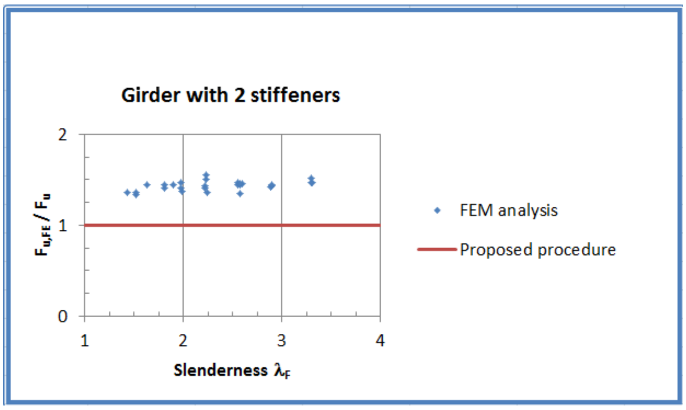

Figure 16 – Ratio $F_{u,FE}/F_u$ as a function of the slenderness λ_F

In table 3 is given a statistical interpretation of the results presented in graphical form in Figure 16, by calculating the mean value, standard deviation, Coefficient of variation, Upper 5-percent fractile and Lower 5-percent fractile.

Mean	1.433
Standard deviation	0.053
Coefficient of variation	0.003
Upper 5% fractile	1.338
Lower 5% fractile	1.539

Table 3 - Statistical evaluation of the proposed design procedure

We underline as the statistical interpretation of the results is in good agreement with the studies presented previously by other authors for both the unstiffened girder and the girder with a single stiffener, even showing a lower dispersion of the results.

5 CONCLUDING REMARKS

The results presented in this paper show a very good agreement between the patch loading resistance calculated with the proposed method and the collapse load determined by means of numerical analysis.

The proposed method is very effective for the prediction of the patch loading resistance of girders with two longitudinal stiffeners, the case for which has been calibrated, but it provides very good results in the prediction of resistance of the unstiffened girders or with a single stiffener (eliminating in the expression of the elastic critical load the contribution of both ribs or one of them, respectively). This evidence demonstrates the robustness of the proposed method, which could be, with a good calibration, a unified method for all cases of patch loading (with one, two, or without stiffeners).

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