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Efficiency Analysis of some Steel Plate Girders Consolidation Methods

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Abstract

Steel plate girders with webs of high slenderness ratio are frequently used in steel structures. Generally the hypothesis that some parts of the constitutive plates of the girder are temporary in a buckled shape is accepted, taking into account the post-buckling behaviour of the thin plates and the resistance reserve of such members. This paper presents the efficiency analysis of some steel plate girders consolidation methods, regarding the bending resistance increase and the supplementary steel used for strengthening.

Rezumat

Grinzile cu inimi având zvelteţea ridicată (Clasa 4) intră frecvent în alcătuirea tablierelor de poduri metalice şi a construcţiilor metalice în general, fiind acceptată situaţia ca anumite părţi ale secţiunii elementului să se afle temporar într-o formă de echilibru deformată (voalare locală), având în vedere rezerva de rezistenţă postcritică. ***Î****n lucrare se analizează eficienţa unor metode de consolidare a grinzilor cu inimi zvelte, din punct de vedere al creşterii capacităţii portante în raport cu consumul de oţel folosit pentru elementele de adaos, respectiv în raport cu reducerea eforturilor unitare normale din încovoiere în secţiunea grinzii.*

Keywords: Steel plate girder, high slenderness, consolidation methods, Eurocodes

1. Introduction

Structural efficient, steel plate girders with slender webs are frequently used in steel structures, generally being accepted the situation when some constitutive plates of the cross section are temporary in a buckled shape, without a negative influence on the element safety.
This hypothesis is justified by the fact that after local buckling the slender plates have a significant resistance reserve owned to post-critical behaviour.
The steel plate girders can be considered as being slender when their webs are in Class 4 of the cross-section, respectively when the following conditions are fulfilled:

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$$s = \frac{c}{t_w} \geq \begin{cases} 124 \cdot \varepsilon & \text{– Figure 1.b} \\ 42 \cdot \varepsilon / (0,67 + 0,33\psi) & \text{– when } \psi > -1 \\ 62 \cdot \varepsilon (1-\psi)\sqrt{(-\psi)} & \text{– when } \psi \leq -1 \end{cases} \tag{1}$$

where: $\varepsilon = \sqrt{235/f_y}$; ψ - as shown in Figure 1.c.

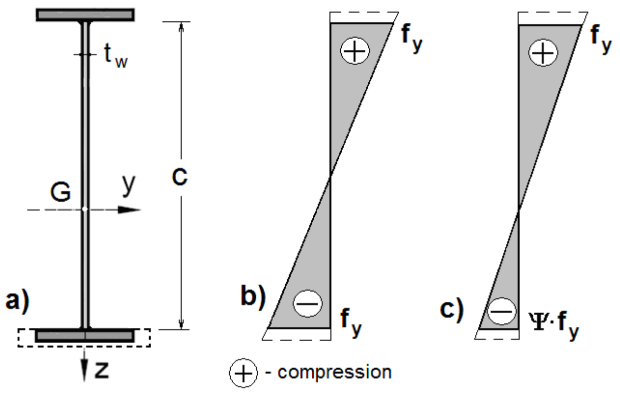


Figure 1

Physical and dynamic wear and also the traffic condition chancing in the bridge case can lead to the necessity of the consolidation and rehabilitation works especially with the scope of the structure bearing capacity increase.
By adding strengthening elements at one or at the both flanges or a longitudinal stiffener in the compression zone will result the increase of the girder moment of inertia and consequently the diminishing of the stresses and deformations under the effect of the live loading.
In Figure 2 some solutions of the girders consolidation are presented.

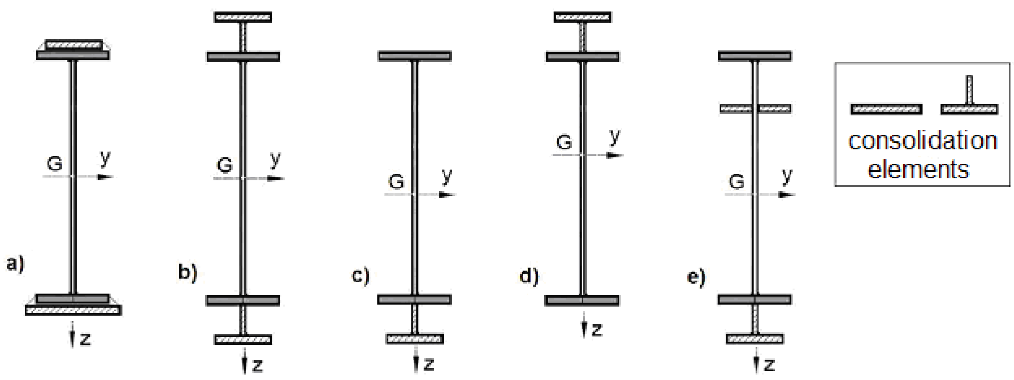


Figure 2: Steel plate girders consolidation

2. Comparative analysis of some strengthening methods

The efficiency of some consolidation methods of the slender steel plate girders (Class 4) is presented.
The following cases are analysed:

- Case 1: Girder not strengthened;
- Case 2: Girder strengthened with a plate to tension flange;
- Case 3: Girder strengthened with a plate to compression flange;

- Case 4: Girder strengthened with plates on both flanges;
- Case 5: Girder strengthened with a longitudinal stiffener;
- Case 6: Girder strengthened with a plate to tension flange plus a longitudinal stiffener.

The analysed girder made by steel S355M has the cross-section presented in Figure 3 and is loaded with the following bending moments:

$M_{Ed} = 13\,800\ kN \cdot m$ - total bending moment, which consist of:

$M_{Eg} = 3\,200\ kN \cdot m$ - bending moment produced by the permanent loading;

$M_{EP} = 10\,600\ kN \cdot m$ - bending moment produced by the live loading.

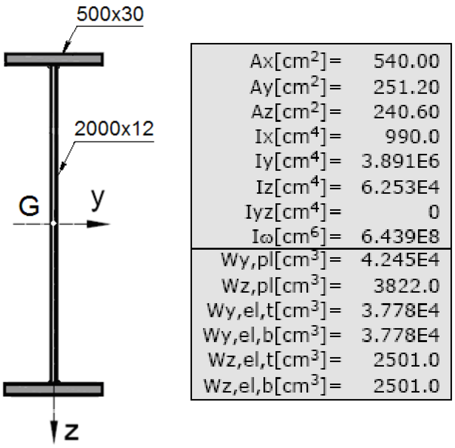


Figure 3: Initial transversal cross-section

Case 1: Girder not strengthened

Cross-section class

Compression flange: $\frac{c}{t_f} = \frac{(500-12)/2}{30} = 8.13 < 14 \cdot \varepsilon = 14 \cdot 0.81 = 11.34 \quad \Rightarrow$ Class 3

Web : $\frac{c}{t_w} = \frac{2000}{12} = 166.67 > 124 \cdot \varepsilon = 124 \cdot 0.81 = 100.44 \quad \Rightarrow$ Class 4

Cross-section Class =max. [web class; compression flange class] = 4

Effective web section

The girder web is an internal non-uniform compression element, Figure 4.

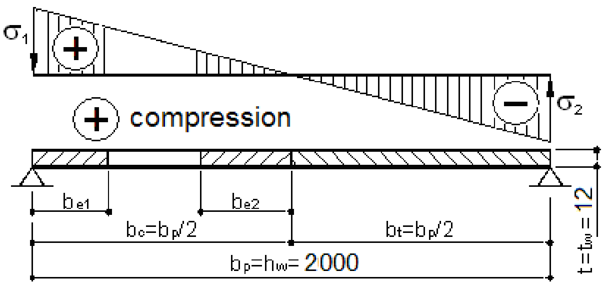


Figure 4

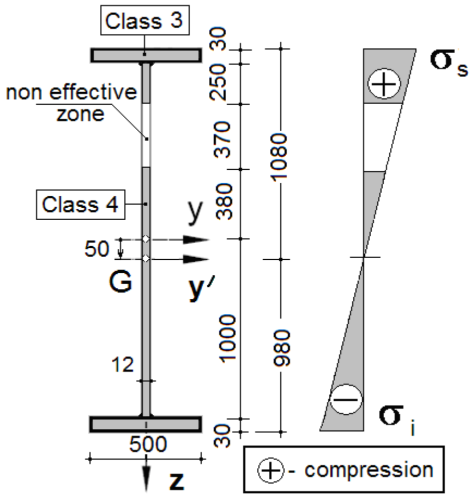
For: $\psi = \frac{\sigma_2}{\sigma_1} < 0$, we have $b_{eff} = \rho \cdot b_c = \rho \cdot b_p / (1-\psi)$; b_{e1}=0.4· b_{eff}; b_{e2}=0.6· b_{eff}

In this case: $\psi = -1$; k_σ =23.9.

It results: $\bar{\lambda}_p = \dfrac{b_p / t}{28{,}4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = 1.48 > 0.673$; $\rho = \dfrac{\bar{\lambda}_p - 0{,}055\,(3 + \Psi)}{\bar{\lambda}_p^2} = 0.63 < 1$

It is obtained: b_{eff}=0.63 x◦100 = 63 cm; b_{e1}=25 cm; b_{e2}=38 cm.

The effective web section is presented in Figure 5.



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Az[cm²]=	---
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Iz[cm⁴]=	6.252E4
Iyz[cm⁴]=	0
Iω[cm⁶]=	6.439E8
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iz[cm]=	11.2
Wy,pl[cm³]=	3.953E4
Wz,pl[cm³]=	3809.0
Wy,el,t[cm³]=	3.453E4
Wy,el,b[cm³]=	3.81E4
Wz,el,t[cm³]=	2501.0
Wz,el,b[cm³]=	2501.0

Figure 5

The following stresses are obtained:

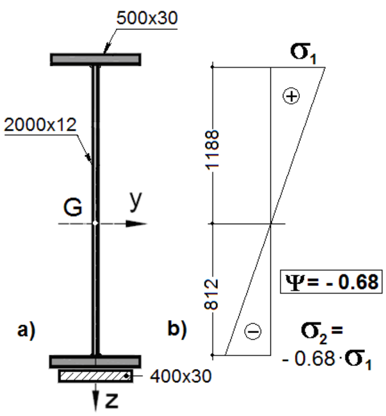
$$\sigma_s^n = \frac{M_{Ed}}{I_{y,eff}} z_s = \frac{13\,800 \cdot 10^4}{3.731 \cdot 10^6} 108 = 3995 \text{ daN/cm}^2 > f_y = 3550 \text{ daN/cm}^2$$

$$\sigma_i^n = \frac{M_{Ed}}{I_{y,eff}} z_i = \frac{13\,800 \cdot 10^4}{3.731 \cdot 10^6} 98 = 3625 \text{ daN/cm}^2 > f_y = 3550 \text{ daN/cm}^2$$

Consequently the girder does not satisfy the resistance conditions.

Case 2: Girder strengthened with a plate to tension flange

A strengthening plate of 400x30 mm section is added to the tension flange, Figure 6.a.



Ax[cm²]=	660.00
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Az[cm²]=	244.30
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Iy[cm⁴]=	4.963E6
Iz[cm⁴]=	7.853E4
Iyz[cm⁴]=	0
Iω[cm⁶]=	7.89E8
Wy,pl[cm³]=	5.198E4
Wz,pl[cm³]=	5022.0
Wy,el,t[cm³]=	4.068E4
Wy,el,b[cm³]=	5.705E4
Wz,el,t[cm³]=	3141.0
Wz,el,b[cm³]=	3141.0

Figure 6

The web effective section is re-evaluated and it is obtained:

$$0 > \psi = -0.68 > -1;\ k_\sigma = 7.81 - 6.29 \cdot \Psi + 9.78 \cdot \Psi^2 = 16.6$$

$$\bar{\lambda}_p = \frac{b_p / t}{28{,}4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = \frac{2000/12}{28.4 \cdot 0.81\sqrt{16.6}} = 1.78 > 0.673$$

$$\rho = \frac{\bar{\lambda}_p - 0{,}055\,(3+\Psi)}{\bar{\lambda}_p^2} = \frac{1.78 - 0.055\,(3-0.68)}{1.78^2} = 0.52 < 1$$

$b_{eff} = 0.52 \times 1188 = 618$ mm; $b_{e1} = 247$ mm; $b_{e2} = 371$ mm.

In Figure 7 the girder effective cross-section is presented.

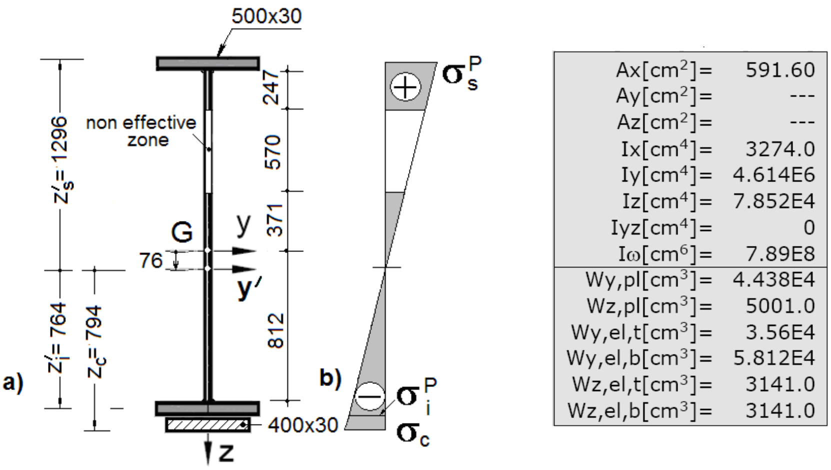


Figure 7

In Figure 8 the final state of stresses on the girder cross-section is presented.

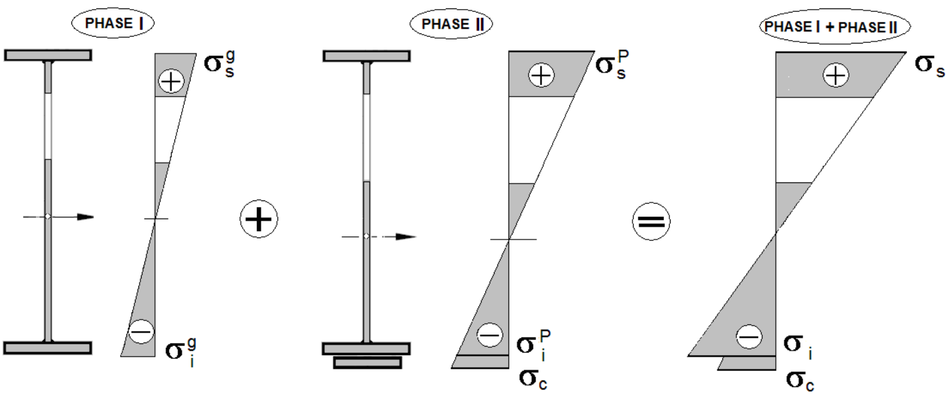


Figure 8

$$\sigma_s = \frac{M_{Eg}}{I_{y,eff}} z_s + \frac{M_{EP}}{I_{y',eff,c}} z_s' = \frac{3200 \cdot 10^4}{3.731 \cdot 10^6} 108 + \frac{10600 \cdot 10^4}{4.614 \cdot 10^6} 129.6 = 3903\ \text{daN/cm}^2 > \frac{f_y}{\gamma_{M0}}$$

$$\sigma_i = \frac{M_{Eg}}{I_{y,eff}} z_i + \frac{M_{EP}}{I_{y',eff,c}} z_i' = \frac{3200 \cdot 10^4}{3.731 \cdot 10^6} 98 + \frac{10600 \cdot 10^4}{4.614 \cdot 10^6} 76.4 = 2596\ \text{daN/cm}^2$$

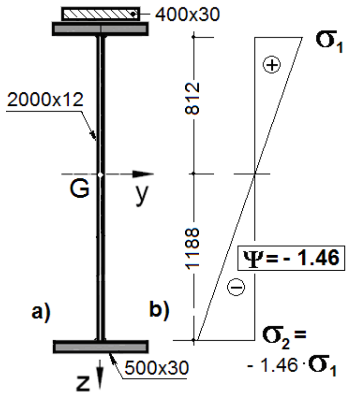
$$\sigma_c = \frac{M_{EP}}{I_{y',eff,c}} z_c = \frac{10600 \cdot 10^4}{4.614 \cdot 10^6} 79.4 = 1824\ \text{daN/cm}^2 \le \frac{f_y}{\gamma_{M0}}$$

By adding a plate to the tension flange of the girder the following reduction of the stresses is obtained:

- top flange: $\Delta\sigma_s = \frac{\sigma_s^n - \sigma_s}{\sigma_s^n} \cdot 100 = \frac{3995 - 3903}{3995} \cdot 100 = 2.3\,\%$
- bottom flange: $\Delta\sigma_i = \frac{\sigma_i^n - \sigma_i}{\sigma_i^n} \cdot 100 = \frac{3625 - 2596}{3625} \cdot 100 = 28.4\,\%$

Case 3: Girder strengthened with a plate to compression flange

A strengthening plate of 400x30 mm section is added to the compression flange, Figure 9.a.



Ax[cm²]=	660.00
Ay[cm²]=	353.90
Az[cm²]=	244.30
Ix[cm⁴]=	3311.0
Iy[cm⁴]=	4.963E6
Iz[cm⁴]=	7.853E4
Iyz[cm⁴]=	-0.1
Iω[cm⁶]=	7.89E8
Wy,pl[cm³]=	5.198E4
Wz,pl[cm³]=	5022.0
Wy,el,t[cm³]=	5.705E4
Wy,el,b[cm³]=	4.068E4
Wz,el,t[cm³]=	3141.0
Wz,el,b[cm³]=	3141.0

Figure 9

The web effective section is re-evaluated and it is obtained:

$$-1 > \psi = -1.46 > -3\,;\; k_\sigma = 5.98\,(1-\Psi)^2 = 36.19$$

$$\bar{\lambda}_p = \frac{b_p / t}{28{,}4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = \frac{2000/12}{28.4 \cdot 0.81\,\sqrt{36.19}} = 1.20 > 0.673$$

$$\rho = \frac{\bar{\lambda}_p - 0{,}055\,(3+\Psi)}{\bar{\lambda}_p^2} = \frac{1.20 - 0.055\,(3 - 1.46)}{1.20^2} = 0.77 < 1$$

b_{eff}=0.77 x◌812 = 625 mm; b_{e1}=250 mm; b_{e2}=375 cm.

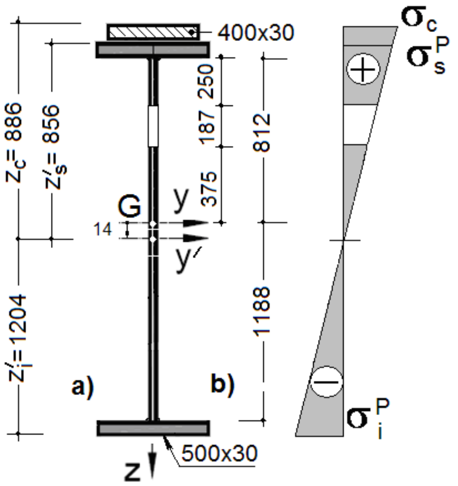
In Figure 10 the girder effective cross-section is presented.

The final state of stresses is as follows:

$$\sigma_s = \frac{M_{Eg}}{I_{y,eff}} z_s + \frac{M_{EP}}{I_{y',eff,c}} z_s^{'} = \frac{3200 \cdot 10^4}{3.731 \cdot 10^6} 108 + \frac{10600 \cdot 10^4}{4.912 \cdot 10^6} 85.6 = 2774\ \mathrm{daN/cm^2}$$

$$\sigma_i = \frac{M_{Eg}}{I_{y,eff}} z_i + \frac{M_{EP}}{I_{y',eff,c}} z_i^{'} = \frac{3200 \cdot 10^4}{3.731 \cdot 10^6} 98 + \frac{10600 \cdot 10^4}{4.912 \cdot 10^6} 120.4 = 3439\ \mathrm{daN/cm^2}$$

$$\sigma_c = \frac{M_{EP}}{I_{y',eff,c}} z_c = \frac{10600 \cdot 10^4}{4.912 \cdot 10^6} 88.6 = 1912\ \mathrm{daN/cm^2}$$



Ax[cm²]=	637.60
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Az[cm²]=	---
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Iy[cm⁴]=	4.912E6
Iz[cm⁴]=	7.853E4
Iyz[cm⁴]=	0
Iω[cm⁶]=	7.89E8
Wy,pl[cm³]=	5.153E4
Wz,pl[cm³]=	5015.0
Wy,el,t[cm³]=	5.541E4
Wy,el,b[cm³]=	4.081E4
Wz,el,t[cm³]=	3141.0
Wz,el,b[cm³]=	3141.0

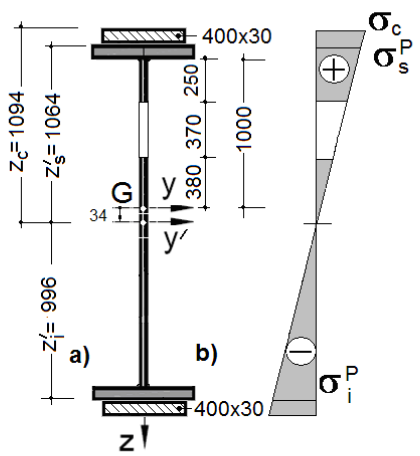
Figure 10

By adding a plate to the compression flange of the girder the following reduction of the stresses is obtained:

- top flange: $\Delta\sigma_s = \dfrac{\sigma_s^n - \sigma_s}{\sigma_s^n}\cdot 100 = \dfrac{3995-2774}{3995}\cdot 100 = 30.6\,\%$
- bottom flange: $\Delta\sigma_i = \dfrac{\sigma_i^n - \sigma_i}{\sigma_i^n}\cdot 100 = \dfrac{3625-3439}{3625}\cdot 100 \approx 5\,\%$

Case 4: Girder strengthened with plates on both flanges

In Figure 11 the effective girder cross-section and its characteristics are presented.



Ax[cm²]=	735.60
Ay[cm²]=	---
Az[cm²]=	---
Ix[cm⁴]=	5604.0
Iy[cm⁴]=	6.357E6
Iz[cm⁴]=	9.452E4
Iyz[cm⁴]=	0
Iω[cm⁶]=	1.009E9
Wy,pl[cm³]=	6.462E4
Wz,pl[cm³]=	6209.0
Wy,el,t[cm³]=	5.81E4
Wy,el,b[cm³]=	6.196E4
Wz,el,t[cm³]=	3781.0
Wz,el,b[cm³]=	3781.0

Figure 11

The final state of stresses is as follows:

$$\sigma_s = \frac{M_{Eg}}{I_{y,eff}} z_s + \frac{M_{EP}}{I_{y',eff,c}} z_s^{'} = \frac{3200\cdot 10^4}{3.731\cdot 10^6}108 + \frac{10600\cdot 10^4}{6.357\cdot 10^6}106.4 = 2700\ \text{daN}/\text{cm}^2$$

$$\sigma_i = \frac{M_{Eg}}{I_{y,eff}} z_i + \frac{M_{EP}}{I_{y',eff,c}} z_i^{'} = \frac{3200\cdot 10^4}{3.731\cdot 10^6}98 + \frac{10600\cdot 10^4}{6.357\cdot 10^6}99.6 = 2501\ \text{daN}/\text{cm}^2$$

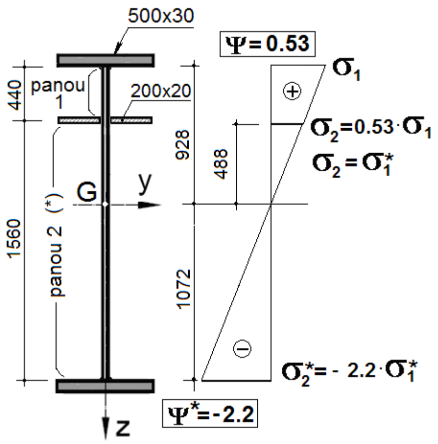
$$\sigma_c = \frac{M_{EP}}{I_{y',eff,c}} z_c = \frac{10600 \cdot 10^4}{6.357 \cdot 10^6} 109.4 = 1824 \text{ daN/cm}^2$$

By adding plates to the both flanges of the girder the following reduction of the stresses is obtained:

- top flange: $\Delta\sigma_s = \frac{\sigma_s^n - \sigma_s}{\sigma_s^n} \cdot 100 = \frac{3995 - 2700}{3995} \cdot 100 = 32.4\,\%$
- bottom flange: $\Delta\sigma_i = \frac{\sigma_i^n - \sigma_i}{\sigma_i^n} \cdot 100 = \frac{3625 - 2501}{3625} \cdot 100 = 31\,\%$

Case 5: Girder strengthened with a longitudinal stiffener

In this case the girder is strengthened by a longitudinal stiffener located in the compression zone of the web and consists of two plates 200x20 mm, Figure 12, made by Steel S235. The stiffener is considered to be rigid enough to create a nodal line for the two web subpanel created.



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Az[cm²]=	239.20
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Iz[cm⁴]=	7.418E4
Iyz[cm⁴]=	0
Iω[cm⁶]=	6.747E8
Wy,pl[cm³]=	4.559E4
Wz,pl[cm³]=	4670.0
Wy,el,t[cm³]=	4.291E4
Wy,el,b[cm³]=	3.728E4
Wz,el,t[cm³]=	2967.0
Wz,el,b[cm³]=	2967.0

Figure 12

Cross-section class

Longitudinal stiffener

$$\frac{c}{t} = \frac{200}{20} = 10 = 10 \cdot \varepsilon \quad \Rightarrow \text{Class 2}$$

Upper subpanel, Figure 13

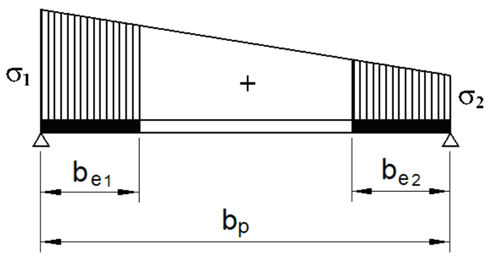


Figure13

$$\frac{c}{t} = \frac{430}{12} = 35.8 < 42 \cdot \varepsilon / (0.67 + 0.33 \cdot \Psi) = 42 \cdot 0.81 / (0.67 + 0.33 \cdot 0.53) = 40.26 \quad \Rightarrow \text{Class 3}$$

Inferior subpanel, Figure 14

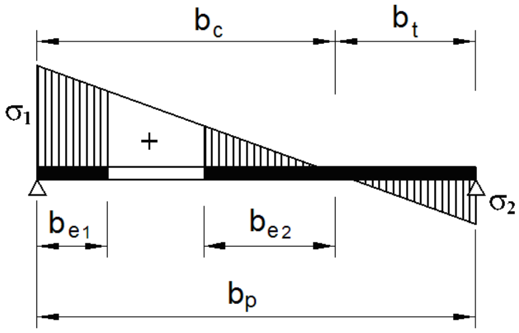


Figure 14

$$\frac{c}{t} = \frac{1550}{12} = 129\,;\ \Psi = \Psi^* = -2.20 < -1$$

$$62 \cdot \varepsilon\,(1 - \Psi)\sqrt{-\Psi} = 62 \cdot 0.81\,(1 + 2.20)\sqrt{2.20} = 238.36$$

$41.5 \cdot \varepsilon / \alpha = 41.5 \cdot 0.81 / 0.31 = 108.4$, where: $\alpha = 488/1560 = 0.31 < 0.5$

$$41.5 \cdot \varepsilon / \alpha = 108.4 < \frac{c}{t} = 129 < 62 \cdot \varepsilon\,(1 - \Psi)\sqrt{-\Psi} = 238.36 \Rightarrow \text{Class 3}$$

It results that the entire web section is effective; the state of stresses is as follows:

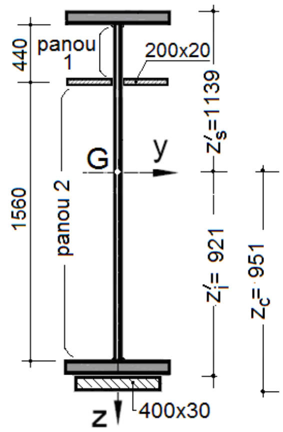
$$\sigma_s = \frac{M_{Eg}}{I_{y,eff}} z_s + \frac{M_{EP}}{I_{y',eff,c}} z_s^{'} = 3398\ \text{daN/cm}^2,\quad \sigma_i = \frac{M_{Eg}}{I_{y,eff}} z_i + \frac{M_{EP}}{I_{y',eff,c}} z_i^{'} = 3683\text{daN/cm}^2 > f_y / \gamma_{M0}$$

By adding a longitudinal stiffener in the compression zone of the web the following reduction of the stresses is obtained:

- top flange: $\Delta\sigma_s = \dfrac{\sigma_s^n - \sigma_s}{\sigma_s^n} \cdot 100 = \dfrac{3995 - 3398}{3995} \cdot 100 = 15\,\%$
- bottom flange: $\Delta\sigma_i = \dfrac{\sigma_i^n - \sigma_i}{\sigma_i^n} \cdot 100 = \dfrac{3625 - 3683}{3625} \cdot 100 \approx 2\,\%$

Case 6: Girder strengthened with a plate to tension flange plus a longitudinal stiffener

In this case the girder is strengthened with a plate 400x30 mm to bottom flange plus a longitudinal stiffener located in the compression web zone, Figure 15.



Ax[cm²]=	740.00
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Iy[cm⁴]=	5.365E6
Iz[cm⁴]=	9.021E4
Iyz[cm⁴]=	9930.0
Iω[cm⁶]=	8.505E8
Wy,pl[cm³]=	5.914E4
Wz,pl[cm³]=	5873.0
Wy,el,t[cm³]=	4.708E4
Wy,el,b[cm³]=	5.638E4
Wz,el,t[cm³]=	3617.0
Wz,el,b[cm³]=	3595.0

Figure 15

The entire cross-section is effective; the state of stresses is as follows:

$$\sigma_s = \frac{M_{Eg}}{I_{y,eff}} z_s + \frac{M_{EP}}{I_{y',eff,c}} z_s^{'} = \frac{3200 \cdot 10^4}{3.731 \cdot 10^6} 108 + \frac{10600 \cdot 10^4}{5.365 \cdot 10^6} 113.9 = 3177 \text{ daN/cm}^2$$

$$\sigma_i = \frac{M_{Eg}}{I_{y,eff}} z_i + \frac{M_{EP}}{I_{y',eff,c}} z_i^{'} = \frac{3200 \cdot 10^4}{3.731 \cdot 10^6} 98 + \frac{10600 \cdot 10^4}{5.365 \cdot 10^6} 92.1 = 2660 \text{ daN/cm}^2$$

$$\sigma_c = \frac{M_{EP}}{I_{y',eff,c}} z_c = \frac{10600 \cdot 10^4}{5.365 \cdot 10^6} 95.1 = 1879 \text{ daN/cm}^2$$

The following reduction of the stresses is obtained:

- top flange: $\Delta\sigma_s = \frac{\sigma_s^n - \sigma_s}{\sigma_s^n} \cdot 100 = \frac{3995 - 3177}{3995} \cdot 100 = 20.5\,\%$
- bottom flange: $\Delta\sigma_i = \frac{\sigma_i^n - \sigma_i}{\sigma_i^n} \cdot 100 = \frac{3625 - 2660}{3625} \cdot 100 = 26.6\,\%$

3. Results analysis and comments

In Table 1 the analysis results regarding the strengthening methods are presented, where the following parameters are used:

- A_c - strengthening element area;
- $\Delta A = \frac{A_c}{A} 100$ - supplementary steel used [%] ;
- $R = \frac{f_y - MAX(\sigma_s ; \sigma_i)}{f_y} 100$ - bending resistance reserve [%].

The following observations can be formulated:
- the strengthening by a plate on bottom flange is not efficient because the non-effective section of the web increases;
- a longitudinal stiffener can be efficient because it can diminish the web class;
- the solution in which both strengthening plates and longitudinal stiffener are used is the most efficient.

Table 1

Case	Scheme	A_c [cm^2]	ΔA [%]	σ_s / σ_i	$\Delta\sigma_s$ [%] / $\Delta\sigma_i$ [%]	Comments
1		0	0	3995	0	$\sigma_s > f_y / \gamma_{M0}$
				3625	0	$\sigma_i > f_y / \gamma_{M0}$
2		120	22.2	3903	2.30	$\sigma_s > f_y / \gamma_{M0}$
				2596	28.4	Strengthening insufficient
3		120	22.2	2774	30.6	R=3.1%
				3439	5.0	
4		240	44.4	2700	32.4	R=23.9%
				2501	31.0	
5		80	14.8	3398	15	Strengthening insufficient
				3683	2.0	$\sigma_i > f_y / \gamma_{M0}$
6		200	37	3177	20.5	R=10.5%
				2660	26.6	

4. References

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