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CONSOLIDATION OF STEEL PLATE GIRDERS
APPLICATION OF EUROCODES

BY

ŞTEFAN I. GUŢIU*, CĂTĂLIN MOGA and RALUCA BOLDOR

Technical University of Cluj-Napoca
Faculty of Civil Engineering

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Abstract. In this paper we focus on the design basis concerning the steel plate girder consolidation. This consolidation is achieved by adding a supplementary plate to one flange or plates to both flanges, which results in an increase of the resistance characteristics and of the bending resistance. The design methodology is adapted to the European codes EN 1993: *Design of Steel Structures*. Part 1-1: *General Rules and Rules for Building* and Part 1-5: *Plated Structural Elements.*A design example which will exemplify the theoretical methodology and some concluding remarks are also presented in this paper.

Key words: steel plate girders; strengthening; euro codes; efficiency analysis.

1. Introduction

Physical and dynamic wear and also the modifications in the exploitation conditions of a bridge can lead to the necessity of consolidation and rehabilitation works, especially with the purpose of enhancing the bearing capacity of the structure.

By adding a supplementary element to one flange or elements to both flanges, an increase of the second moment of inertia and, consequently, a reduction of the stresses and deformations under the live loadings are obtained.

*Corresponding author: *e-mail*: stefan.gutiu@cfdp.utcluj.ro

In Fig. 1 some possibilities of increasing the cross-section characteristics are presented.

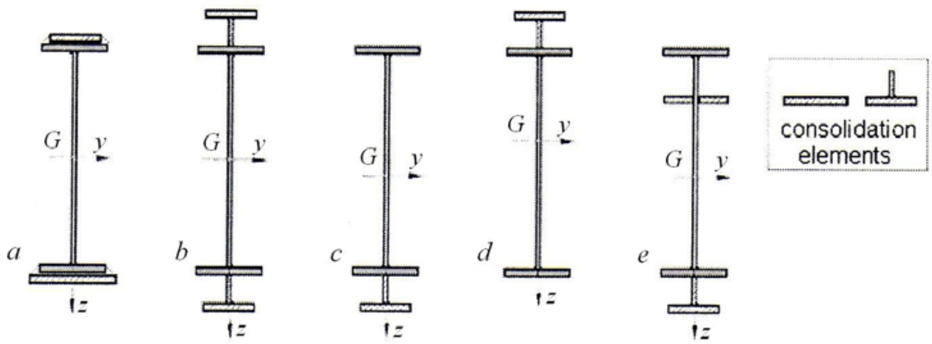


Fig. 1 – Steel plate girders consolidation.

The efficiency of the consolidation is directly dependent on the level of the girder unloading when strengthening operations are performed; the most common case is that when the girder is loaded only with the permanent loads.

2. Design Basis

In Fig. 2 we illustrate the state of bending stresses of a steel plate girder in the case of the strengthening with a T element added to the bottom flange.

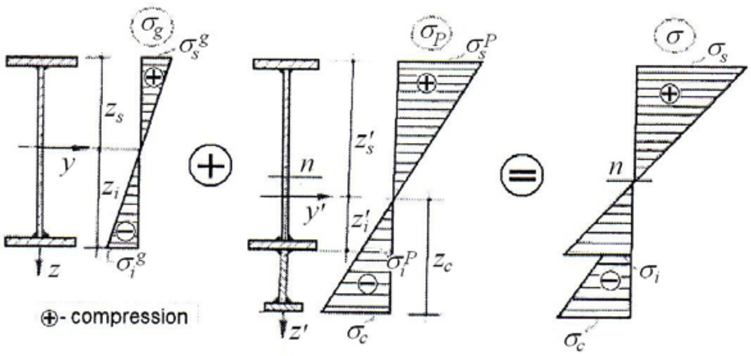


Fig. 2 – State of bending stresses on strengthened girder.

Phase I: *Girder unconsolidated, loaded by permanent actions:*

$$\sigma_s^g = \frac{M_{Eg}}{I_{y,\text{eff}}} z_s , \tag{1 a}$$

$$\sigma_i^g = \frac{M_{Eg}}{I_{y,\text{eff}}} z_i . \tag{1 b}$$

Phase II: *Girder consolidated, loaded by live actions*:
Besides the stresses of phase I, the following stresses are added:

$$\sigma_s^P = \frac{M_{EP}}{I_{y',\text{eff},c}} z_s' , \tag{2 a}$$

$$\sigma_i^P = \frac{M_{EP}}{I_{y',\text{eff},c}} z_i' , \tag{2 b}$$

where $I_{y',\text{eff},c}$ is the moment of inertia of the consolidated cross-section.

The state of the stresses in the cross-section and in the added element, *c*, is

$$\sigma_s = \frac{M_{Eg}}{I_{y,\text{eff}}} z_s + \frac{M_{EP}}{I_{y',\text{eff},c}} z_s' \le \frac{f_y}{\gamma_{M0}} , \tag{3 a}$$

$$\sigma_i = \frac{M_{Eg}}{I_{y,\text{eff}}} z_i + \frac{M_{EP}}{I_{y',\text{eff},c}} z_i' \le \frac{f_y}{\gamma_{M0}} , \tag{3 b}$$

$$\sigma_c = \frac{M_{EP}}{I_{y',\text{eff},c}} z_c \le \frac{f_y}{\gamma_{M0}} . \tag{3 c}$$

Because of the changes in the cross-section of the flanges, the gravity centre will modify so that a re-evaluation of the cross-section class is necessary.

2.1. Elastic Girder Deformation

By the modification of the girder rigidity, favourable effects are also obtained in connection with the elastic girder deflection.

The deflection for a girder with variable cross-section can be calculated with the relation

$$\delta = \frac{5}{48} \cdot \frac{M_{\max} L^2}{E I_m} \cong \frac{5.5}{48} \cdot \frac{M_{\max} L^2}{E I_y} , \tag{4}$$

where $I_m = \frac{\sum I_i \ell_i}{L}$ is the average moment of inertia of the girder.

It results the following deflection values:

a) unconsolidated girder

$$\delta = \frac{5.5}{48} \cdot \frac{\left(M_g + \varphi_3 M_P\right) L^2}{E I_y}, \qquad (5\,a)$$

b) consolidated girder

$$\delta = \frac{5.5}{48E} \left(\frac{M_g}{I_y} + \frac{\varphi_3 M_P}{I_y^c} \right) L^2, \qquad (5\,b)$$

where I_y^c is the moment of inertia of the consolidated cross-section.

3. Worked Example

Next the state of the bending stresses of a consolidated steel plate girder of a bridge superstructure is analysed.

The following design data are known:

A. *Characteristics of the girder:*

a) Elevation (Fig. 3).

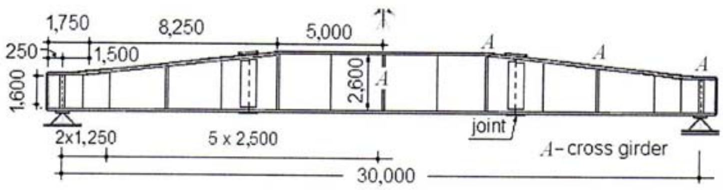
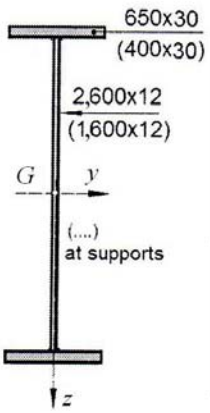


Fig. 3 – Girder elevation.

b) Material, loading, cross-section (Fig. 4).



A_x, [cm²]=	702.00
A_y, [cm²]=	326.20
A_z, [cm²]=	311.30
I_x, [cm⁴]=	1,295.0
I_y, [cm⁴]=	8.502E6
I_z, [cm⁴]=	1.373E5
I_{yz}, [cm⁴]=	0.7
I_ω, [cm⁶]=	2.374E9
W_y,pl, [cm³]=	7.156E4
W_z,pl, [cm³]=	6431.0
W_y,el,t, [cm³]=	6.392E4
W_y,el,b, [cm³]=	6.392E4
W_z,el,t, [cm³]=	4226.0
W_z,el,b, [cm³]=	4226.0

STEEL: S355 ML

CROSS-SECTION:

at middle span:

flanges: $b_f \times t_f$ = 650 × 30 mm

web: $h_w \times t_w$ = 2,600 × 12 mm

at supports:

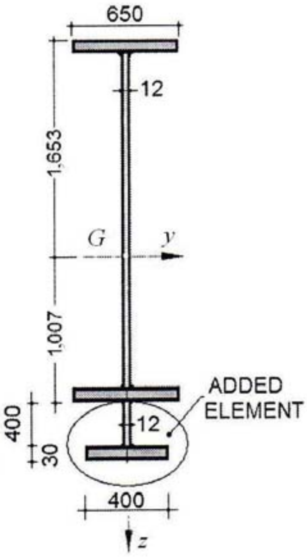
flanges: $b_f \times t_f$ = 400 × 30 mm

web: $h_w \times t_w$ = 1,600 × 12 mm

Fig. 4 – Material, loading, cross-section.

c) Bending moment: M_{Ed} = 21,500 kN·m, divided in: M_{Eg} = 4,400 kN.m; M_{EP} = 17,100 kN.m.

B. *Consolidated cross-section* (Fig. 5).



A_x, [cm^2] =	870.00
A_y, [cm^2] =	390.10
A_z, [cm^2] =	349.40
I_x, [cm^4] =	1,671.0
I_y, [cm^4] =	1.237E7
I_z, [cm^4] =	1.534E5
I_{yz}, [cm^4] =	0
I_ω, [cm^6] =	2.811E9
W_y,pl, [cm^3] =	9.399E4
W_z,pl, [cm^3] =	7,645.0
W_y,el,t, [cm^3] =	7.472E4
W_y,el,b, [cm^3] =	8.618E4
W_z,el,t, [cm^3] =	4,719.0
W_z,el,b, [cm^3] =	4,719.0

Fig. 5 – Consolidated cross-section.

3. Consolidation Solution Analysis

a) ***Unconsolidated girder***

A. *Cross-section class*

Compression flange

$$\frac{c}{t_f} = \frac{(650-12)/2}{30} = 10.6 < 14\varepsilon = 14 \times 0.81 = 11.34\,.$$

$\Rightarrow$ Class 3

Web

$$\frac{c}{t_w} = \frac{2,600}{12} = 216.7 > 124\varepsilon = 124 \times 0.81 = 100.44\,.$$

$\Rightarrow$ Class 4

Cross-section Class = 4.

B. *Effective cross section of web*

The web is an internal partial compressed plate (Fig. 6).

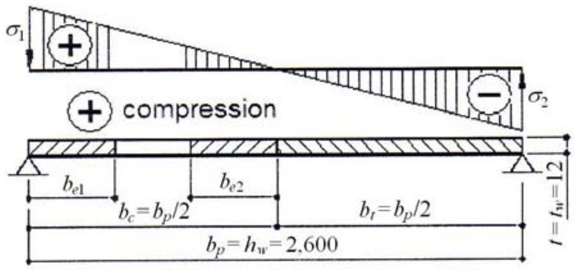


Fig. 6 – Internal partial compressed plate.

For

$$\psi = \frac{\sigma_2}{\sigma_1} < 0,\ b_{\text{eff}} = \rho b_c = \frac{\rho b_p}{1-\psi};\ b_{e1} = 0.4 b_{\text{eff}};\ b_{e2} = 0.6 b_{\text{eff}}\ .$$

In this case $\psi = -1$; $k_\sigma = 23.9$. It results:

$$\bar{\lambda}_p = \frac{b_p / t}{28.4\varepsilon\sqrt{k_\sigma}} = 1.93 > 0.673\ ;\quad \rho = \frac{\bar{\lambda}_p - 0.055\,(3+\psi)}{\bar{\lambda}_p^2} = 0.49 < 1$$

and consequently $b_{\text{eff}} = 0.49 \times 130 \approx 64$ cm; b_{e1}=26 cm; b_{e2}=38 cm.

In Fig. 7 the effective cross-section and the stress distribution are presented.

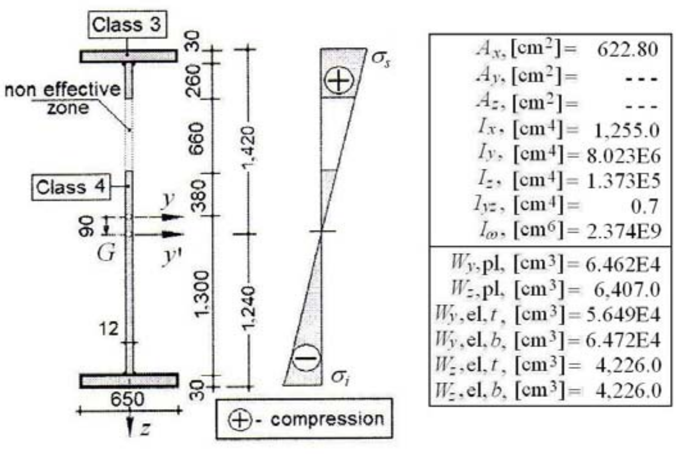


Fig. 7 – The effective cross-section.

The following stresses are obtained:

$$\sigma_s^n = \frac{M_{Ed}}{I_{y,\text{eff}}} z_s = \frac{21{,}500\times10^4}{8{,}023\times10^6}142 = 3{,}805\ \text{daN/cm}^2 > f_y = 3{,}550\ \text{daN/cm}^2\ ;$$

$$\sigma_i^n = \frac{M_{Ed}}{I_{y,\text{eff}}} z_i = \frac{21{,}500\times10^4}{8{,}023\times10^6}124 = 3{,}323\ \text{daN/cm}^2 < f_y = 3{,}550\ \text{daN/cm}^2\ .$$

b) ***Consolidated girder***

The effective cross-section of the web is re-evaluated, according to the stress distribution presented in Fig. 8. The following values are obtained

$$\psi = -0.60\ ,\ k_\sigma = 7.81 - 6.29\psi + 9.78\psi^2 = 15.1\ ,$$

$$\overline{\lambda}_p = \frac{b_p / t}{28.4\varepsilon\sqrt{k_\sigma}} = 2.42 > 0.673\ ,\ \rho = \frac{\overline{\lambda}_p - 0.055\,(3+\psi)}{\overline{\lambda}_p^2} = 0.39 < 1\ .$$

The web effective cross-section is b_{eff} = 0.39 ×1623 = 633 mm; b_{e1} = = 253 mm; b_{e2}=380 mm.

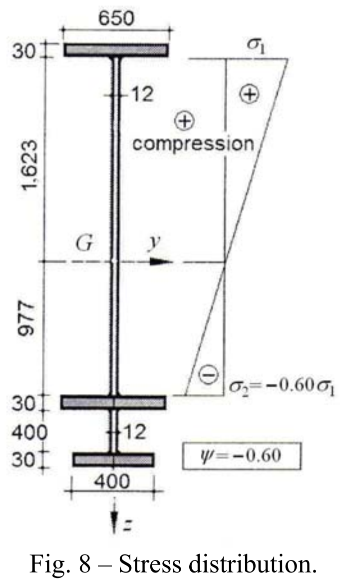
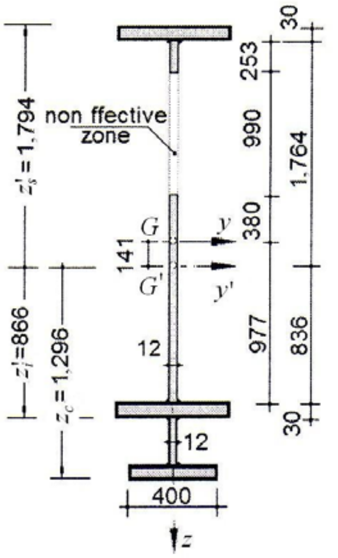


Fig. 8 – Stress distribution.

In Fig. 9 the effective cross-section is presented.



A_x, [cm²]=	751.20
A_y, [cm²]=	- - -
A_z, [cm²]=	- - -
I_x, [cm⁴]=	1,611.0
I_y, [cm⁴]=	1.121E7
I_z, [cm⁴]=	1.533E5
I_{yz}, [cm⁴]=	0
I_ω, [cm⁶]=	2.811E9
W_y,pl, [cm³]=	7.62E4
W_z,pl, [cm³]=	7,610.0
W_y,el,t, [cm³]=	6.25E4
W_y,el,b, [cm³]=	8.649E4
W_z,el,t, [cm³]=	4,718.0
W_z,el,b, [cm³]=	4,718.0

Fig. 9 – The effective cross-section.

2.2. State of Stresses

P h a s e I: *Unconsolidated girder, loaded by permanent actions* (Fig. 10). The following values are obtained:

$$\sigma_s^g = \frac{M_{Eg}}{I_{y,\text{eff}}} z_s = 779 \text{ daN/cm}^2 , \ \sigma_i^g = \frac{M_{Eg}}{I_{y,\text{eff}}} z_i = 680 \text{ daN/cm}^2 .$$

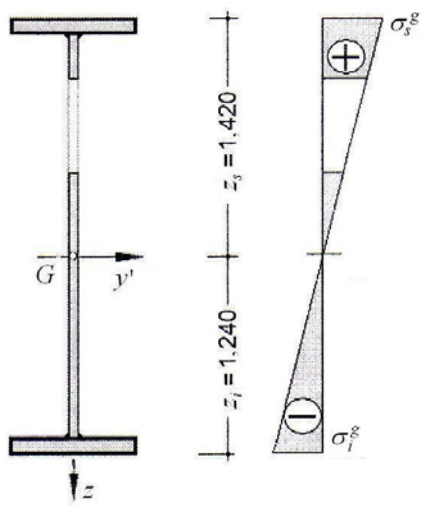


Fig. 10 – Unconsolidated girder.

P h a s e II: Consolidated girder, *loaded by live actions*:

To the stresses of phase I, the following stresses are added (Fig. 11):

$$\sigma_s^P = \frac{M_{EP}}{I_{y',\text{eff},c}} z_s^{'} = 2730 \text{ daN/cm}^2, \ \sigma_i^P = \frac{M_{EP}}{I_{y',\text{eff},c}} z_i^{'} = 1{,}327 \text{ daN/cm}^2 .$$

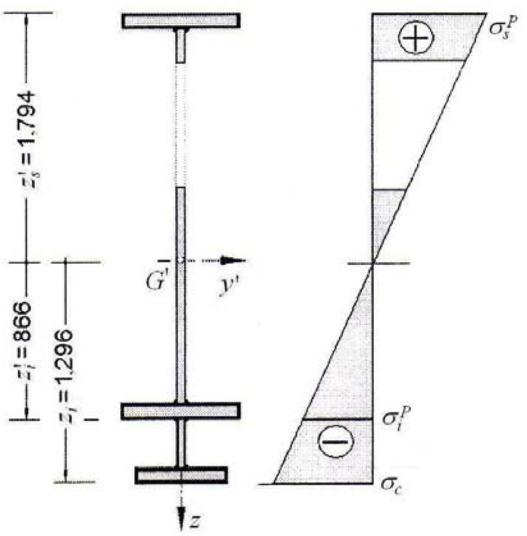


Fig. 11 – Consolidated Girder.

The final state of the stresses in the cross-section and in the added element, *c*, is as follows (see Fig. 12):

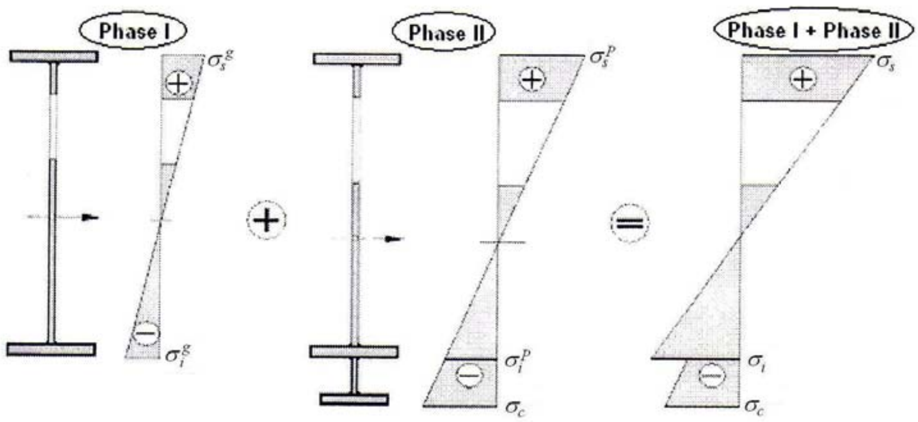


Fig. 12 – Final state of the stresses.

$$\sigma_s = \frac{M_{Eg}}{I_{y,\mathrm{eff}}} z_s + \frac{M_{EP}}{I_{y',\mathrm{eff},c}} z_s^{'} = 779 + 2{,}730 = 3{,}509 \text{ daN/cm}^2 \le \frac{f_y}{\gamma_{M0}} = 3{,}550 \text{ daN/cm}^2,$$

$$\sigma_i = \frac{M_{Eg}}{I_{y,\mathrm{eff}}} z_i + \frac{M_{EP}}{I_{y',\mathrm{eff},c}} z_i^{'} = 680 + 1{,}327 = 2{,}007 \text{ daN/cm}^2,$$

$$\sigma_c = \frac{M_{EP}}{I_{y',\mathrm{eff},c}} z_c = \frac{17{,}100 \times 10^4}{1{,}121 \times 10^7} 129.6 = 1{,}977 \text{ daN/cm}^2 \le \frac{f_y}{\gamma_{M0}}.$$

4. Conclusions

By adding a supplementary element to the bottom flange, the following reductions of the bending stresses are obtained:

a) top flange

$$\Delta\sigma_s = \frac{\sigma_s^n - \sigma_s}{\sigma_s^n} \cdot 100 = \frac{3{,}805 - 3{,}509}{3{,}805} \cdot 100 = 7.8\ \%;$$

b) bottom flange

$$\Delta\sigma_i = \frac{\sigma_i^n - \sigma_i}{\sigma_i^n} \cdot 100 = \frac{3{,}323 - 2{,}007}{3{,}323} \cdot 100 = 40\ \%.$$

Obviously, the appropriate consolidation solution for each particular case of steel plate girder has to be analysed. Adding a longitudinal stiffener besides the elements added to one or to both flanges can also be favourable.

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* * * *Proiectarea structurilor de oţel.* Partea 1-5: *Elemente din plăci plane solicitate în planul lor*. Eurocod 3, SR EN 1993-1-5/2006.

APLICAREA EURONORMELOR LA CALCULUL CONSOLIDĂRII GRINZILOR METALICE CU INIMĂ PLINĂ

(Rezumat)

Se prezintă baza de calcul privind consolidarea grinzilor metalice cu inimă plină prin adăugarea unor elemente sudate la una sau la ambele tălpi ale grinzii, prin care se majorează caracteristicile de rezistenţă şi implicit se poate mări capacitatea portantă la încovoiere a grinzii. Metodologia de calcul este adaptată la norma europeană privind calculul elementelor din oțel, normativul EUROCODE 3. Part 1. *Design of Steel Structures.* EN 1993: 2003, respectiv standardele române corespunzătoare: SR EN 1993-1-1/2006. Eurocod 3: *Proiectarea structurilor de oțel.* Partea 1-1: *Reguli generale şi reguli pentru clădiri* şi SR EN 1993-1-5/2006. Eurocod 3: *Proiectarea structurilor de oțel.* Partea 1-5: *Elemente din plăci plane solicitate în planul lor*. Metodologia de calcul este exemplificată în cadrul unui exemplu numeric, care facilitează înțelegerea bazei teoretice de calcul.