Reduced stress method for Class 4 steel section

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Summary

Design of steel cross sections with thin plates has to take in account the effect of local instability that reduce the ultimate resistance.

Eurocode 3 classifies these cross-sections as Class 4 cross-sections and in part 1-5 it shows two procedures to take in account local buckling effects in the ULS resistence evaluation:

- Effective cross section method
- Reduced stress method

Scope of this paper is to show the application of the Reduced stress method to a real case (main roof of High Velocity railway station in Florence, Italy) and some considerations about the relationship with Effective cross section's method.

Keywords: Effective cross section method, Reduced stress method, Eurocode 3, Class 4 steel cross-section.

1. Introduction

Eurocode [1], defines 4 classes of cross-sections according their capacity to develop plastic moment resistance. For class 4 cross-section design resistance R_d is limited by local buckling resistance and it is lower than calculated one adopting full-plastic or elastic distribution stresses.

To determine correctly design resistance R_d of class 4 cross-section Eurocode shows 2 methods [2]:

1) Effective cross section's method;
2) Reduced stress method.

These methods are analyzed and compared with observations on their application field and their correlations. It is possible find that in same cases Reduced stress method are more conservative than effective cross-section one.

Finally it is briefly showed an application of Reduced stress method in a real case: the design of High Velocity Railway Station roof in Florence (Italy) [3].

2. Method description, observations and comparation

Eurocode [1] defines 4 classes of cross-sections according their capacity to develop plastic moment resistance (this capacity is limited by local buckling phenomenon).
According this classification Class 4 cross-sections are those in which local buckling occur before the attainment of yeld stress in one or more parts of cross-section.

The classification of a cross-section depends on:

a) the width to thickness ratio of the parts subjected to compression;
b) the tipology of component plates of cross-section (internal or outstand compression plates);

c) the distribution of direct stresses σ on each plate;
d) the mechanical characteristics of steel.

On the basis of these infomations it be possible classify each part of cross-section. Cross-section class will be the highest class of its compression parts.

It is important to observe that the classification depends only on the direct stresses σ_x. Shear stresses τ and stresses acting parallel to cross-section plane (σ_z) are not considered.

Design resistance R_d of class 4 cross-section is limited by local buckling resistance and it is lower than calculated one adopting full-plastic or elastic distribution stresses.

To determine correctly design resistance R_d of class 4 cross-section Eurocode shows 2 methods [2]:

3) Effective cross section's method;
4) Reduced stress method.

In effective cross section's method the portions of plates that are subject to local buckling is removed from cross-section to obtain a residual cross-section named "effective" cross-section. Design resistance is determined from this effective cross-sections assuming Class 3 for it.

Some observations:

1) As in cross-section classification procedure, effective cross section's method depends on:
   a) the width to thickness ratio of the parts subjected to compression;
   b) the tipology of component plates of cross-section (internal or outstand compression plates);
   c) the distribution of direct stresses σ on each plate;
   d) the mechanical characteristics of steel.
2) The reduction from gross cross-section to effective cross-section depends only to direct stresses σ_x. Shear stresses τ and stresses acting parallel to cross-section plane (σ_z) and their influence are treated separately.
3) Stress distribution necessary to define ψ parameter would have to be based on:
   a) gross cross-section for stress distribution on flange plates;
   b) section with effective flange plates for stress distribution on web plates.
4) The riduction factor does not depend on the real intensity of σ_x stresses but only from its distribution. Eurocode allows to take in account stresses intensity for the classification of cross-section (and not for instability resistance evaluation) (see [1] p. 5.5.2(9)) and for effective cross-section evaluation (see [2] p. 4.4(4)). In this way the procedure becames iterative and the heavier computational effort finds giustification only for elements subjected to low stresses.
5) Effective cross-section derived from symmetrical gross cross-section can be without symmetry so in verifications it is necessary take in account an eccentricity e_N (distance between center of mass of gross and effective cross-sections) of axial force and its derived supplementary bending moment $\Delta M = N\, e_N$.
6) Effective cross section's method can be used only when (see [2] p. 2.3(1)):
   a) cross-section plates are rectangular;
   b) flange plates are parallel;
   c) any unstiffened open holes are little.

Alternative method is named as Reduced stress method (see [2] p.10).

The method:

1) allows to take in account of direct stresses σ_x, shear stresses τ, stresses σ_z acting parallel to cross-section plane;
2) allows to define the acceptability of cross-section stresses distribution from the combined point of view of resistance and instability by means of the acceptability of stresses distribution of single cross-section plates;

3) allows to adopt as reference the stresses distribution derived from gross cross-section without iterative procedure and without additional eccentricity e_N;
4) is the generalization of the previous effective cross-sections method.

2.1 Method analytical description

Resistance verification requires that

$$\left(\frac{F_{Ed}}{F_{Rd}}\right)_{sect} \le 1 \tag{1}$$

and assuming $\left(\frac{F_{Ed}}{F_{Rd}}\right)_{sect} = \max_i \left(\frac{F_{Ed}}{F_{Rd}}\right)_i$ it is necessary to check for each i-th plate of cross-section that

$$\left(\frac{F_{Ed}}{F_{Rd}}\right)_i \le 1 \qquad \forall i \tag{2}$$

Naming with $\alpha_{ult,k}$ the minimum load amplifier for the design loads to reach the characteristic value of resistence of the most critical point of the plate, design resistance can be described as

$$F_{Rd} = \frac{\alpha_{ult,k} F_{Ed}}{\gamma_M} \tag{3}$$

Now it is possible take in account plate buckling adopting a reduction factor ρ which depends on plate slenderness λ.

$$F_{Rd} = \frac{\rho \alpha_{ult,k} F_{Ed}}{\gamma_M} \tag{4}$$

The acceptability criteria (2) can be formulated as

$$\frac{\rho \alpha_{ult,k}}{\gamma_M} \ge 1 \qquad \text{(for each plates of cross-section)} \tag{5}$$

The minimum load amplifier for the design loads to reach the characteristic value of resistence (without buckling effects) $\alpha_{ult,k}$ is evaluated from stresses field by applying VonMises criteria:

$$\frac{1}{\alpha_{ult,k}^2} = \left(\frac{\sigma_{x,Ed}}{f_{yk}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{f_{yk}}\right)^2 - \left(\frac{\sigma_{x,Ed}}{f_{yk}}\right)\left(\frac{\sigma_{z,Ed}}{f_{yk}}\right) + 3\left(\frac{\tau_{Ed}}{f_{yk}}\right)^2 \tag{6}$$

Reduction factor ρ is evaluated following these steps:

- determination of the elastic critical buckling stress for each single stress field:

  $\sigma_{cr,x}$ $\sigma_{cr,z}$ τ_{cr}
- determination of the minimum load amplifier for the design loads to reach the elastic critical load of the plate under the single stress field:

  $\alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed}$ $\alpha_{cr,z} = \sigma_{cr,z} / \sigma_{z,Ed}$ $\alpha_{cr,\tau} = \tau_{cr} / \tau_y$
- determination of load amplifier for the design loads to reach the elastic critical load of the plate under the complete stress field:

$$\frac{1}{\alpha_{cr}} = \frac{1+\psi_x}{4\alpha_{cr,x}} + \frac{1+\psi_z}{4\alpha_{cr,z}} + \left[\left(\frac{1+\psi_x}{4\alpha_{cr,x}} + \frac{1+\psi_z}{4\alpha_{cr,z}}\right)^2 + \frac{1-\psi_x}{2\alpha_{cr,x}^2} + \frac{1-\psi_z}{2\alpha_{cr,z}^2} + \frac{1}{\alpha_{cr,\tau}^2}\right]^{1/2} \tag{7}$$

Where ψ_x e ψ_z coefficients take in account the stresses distribution on the plate (with maximum value $\sigma_{x,Ed}$ e $\sigma_{z,Ed}$ respectively, it is assumed that shear stress τ id uniform).

- determination of plate slenderness λ :

$$\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}} \tag{8}$$

- determination of buckling reduction factors for each stress field and for the complete stress field:

$$\rho_x = \rho_x(\bar{\lambda}_p) \qquad \rho_z = \rho_z(\bar{\lambda}_p) \qquad \chi_w = \chi_w(\bar{\lambda}_p) \tag{9}$$

- determination of buckling reduction factors for the complete stress field:

$$\rho = \min(\rho_x, \rho_z, \chi_w) \tag{10}$$

2.2 Elementary cases

Analyzing elementary cases it can be show that from Reduced stress method it is possible to obtain the Effective cross-section method.

2.2.1 Case 1: Plated subjected to compression direct stresses

Plate (b x t) subjected to compression direct stresses field (σ_x) only:

$\sigma_{xEd} \neq 0$ $\quad (= N_{sd} / A = N_{sd} / (bt))$ $\quad \sigma_{zEd} = \tau_{Ed} = 0$ $\quad \alpha_{ult,k} = f_{yk} / \sigma_{xEd}$

$\alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed}$ $\quad \alpha_{cr,z} = \sigma_{cr,z} / \sigma_{z,Ed} \rightarrow \infty$ $\quad \alpha_{cr,\tau} = \tau_{cr} / \tau_{Ed} \rightarrow \infty$

$\sigma_{cr,x} = k_\sigma(\psi)\, \sigma_E$ elastic critical plate buckling stress

where $\sigma_E = \dfrac{\pi^2 E t^2}{12(1-\upsilon^2)b^2}$ Eulerian elastic critical plate buckling stress

$k_\sigma(\psi)$ = buckling factor (according to stresses distribution)

from (7)

$$\alpha_{cr} = \alpha_{cr,x} = k_\sigma(\psi)\frac{\sigma_E}{\sigma_{x,Ed}} = k_\sigma(\psi)\frac{\sigma_E}{\dfrac{f_{yk}}{\alpha_{ult,k}}} = k_\sigma(\psi)\frac{\sigma_E}{\dfrac{235}{\varepsilon^2 \alpha_{ult,k}}} \qquad \bar{\lambda}_p^2 = \frac{\alpha_{ult,k}}{\alpha_{cr}} = \frac{235}{k_\sigma(\psi)\sigma_E \varepsilon^2}$$

Obtaining the expression of effective cross-section method (see [2] p. 4.4(1))

$$\bar{\lambda}_p = \frac{\dfrac{b}{t}}{28{,}4\varepsilon\sqrt{k_\sigma(\psi)}}$$ that it is used to calculate ρ_x (= ρ)

$$\frac{\rho\alpha_{ult,k}}{\gamma_M} \geq 1 \rightarrow \frac{\rho f_{yk}}{\sigma_{xEd}\gamma_M} \geq 1 \rightarrow \frac{A\rho f_{yk}}{A\sigma_{xEd}\gamma_M} \geq 1 \rightarrow \frac{A\rho f_{yk}}{\gamma_M} \geq A\sigma_{xEd} \rightarrow$$

$$\rightarrow A_{eff} f_{yd} \geq A\sigma_{xEd} \rightarrow N_{Rd} \geq N_{Sd}$$

2.2.2 Case 2: Plated subjected to tension direct stress

Plate (b x t) subjected to tension direct stresses field (σ_x) only:

$\sigma_{xEd} \neq 0$ $\quad (= N_{sd} / A = N_{sd} / (bt))$ $\quad \sigma_{zEd} = \tau_{Ed} = 0$ $\quad \alpha_{ult,k} = f_{yk} / \sigma_{xEd}$

$\alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed} \rightarrow \infty$ (tension plate has no buckling) $\quad \alpha_{cr,z} = \sigma_{cr,z} / \sigma_{z,Ed} \rightarrow \infty$

$\alpha_{cr,\tau} = \tau_{cr} / \tau_{Ed} \rightarrow \infty$

from (7)

$$\alpha_{cr} \rightarrow \infty \qquad \bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}} = 0$$

Thus $\rho = \rho_x = 1$ and then

$$\frac{\rho\alpha_{ult,k}}{\gamma_M} \geq 1 \rightarrow \frac{f_{yk}}{\sigma_{xEd}\gamma_M} \geq 1 \rightarrow \frac{Af_{yk}}{A\sigma_{xEd}\gamma_M} \geq 1 \rightarrow \frac{Af_{yk}}{\gamma_M} \geq A\sigma_{xEd} \rightarrow$$

$$\rightarrow Af_{yd} \geq A\sigma_{xEd} \rightarrow N_{Rd} \geq N_{Sd}$$

2.2.3 Case 3: Plated subjected to shear stresses

Plate (h_w x t) subjected to shear stresses field (τ) only:

$\tau_{Ed} \neq 0$ (= V_{Ed} / A = V_{Ed} / (h_w t)) $\sigma_{xEd} = \sigma_{zEd} = 0$ $\alpha_{ult,k} = \frac{f_{yk}}{\sqrt{3}\tau_{Ed}}$

$\alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed} \rightarrow \infty$ $\alpha_{cr,z} = \sigma_{cr,z} / \sigma_{z,Ed} \rightarrow \infty$ $\alpha_{cr,\tau} = \tau_{cr} / \tau_{Ed}$

$\tau_{cr} = k_\tau\, \sigma_E$ elastic critical plate buckling shear stress

where $\sigma_E = \frac{\pi^2 E t^2}{12(1-\upsilon^2)h_w^2}$ Eulerian elastic critical plate buckling stress

$k_\tau(h_w/t)$ = buckling factor (according to height to thickness ratio)

from (7)

$$\alpha_{cr} = \alpha_{cr,t} = k_\tau \frac{\sigma_E}{\tau_{Ed}} = k_\tau \frac{\sigma_E}{\frac{f_{yk}}{\sqrt{3}}\frac{1}{\alpha_{ult,k}}} = k_\tau \frac{\sigma_E}{\frac{235}{\sqrt{3}\varepsilon^2\alpha_{ult,k}}} \qquad \bar{\lambda}_p^2 = \frac{\alpha_{ult,k}}{\alpha_{cr}} = \frac{235}{\sqrt{3}k_\tau\sigma_E\varepsilon^2}$$

Obtaining the expression of shear design resistance (see [2] (5.5))

$\bar{\lambda}_w = \frac{\frac{h_w}{t}}{37{,}4\varepsilon\sqrt{k_\tau}}$ that it is used to calculate $\chi_w(= \rho)$

$$\frac{\rho\alpha_{ult,k}}{\gamma_M} \geq 1 \rightarrow \frac{\rho f_{yk}}{\sqrt{3}\tau_{Ed}\gamma_M} \geq 1 \rightarrow \frac{A\rho f_{yk}}{\sqrt{3}A\tau_{Ed}\gamma_M} \geq 1 \rightarrow \frac{A\rho f_{yk}}{\sqrt{3}\gamma_M} \geq A\tau_{Ed} \rightarrow$$

$\rightarrow$ $V_{Rd} \geq V_{Sd}$

2.3 Stress reduction method vs. Effective cross section method

Using the two methods, the verification of a single plate subjected to a direct stresses field ($\sigma_x \neq 0$, $\sigma_z = \tau = 0$) leads to the same results. This may be not more true when the methods are applied to a section (= set of more plates).

While Effective cross-section method reduces the geometrical cross-section and then gets the stresses field from the given strains field, Reduced stress method first gets the stresses field from the given strains field and then gets the reduction buckling factor ρ.

As example it is possible to assume a square hollow section made by 4 plates: 2 horizontal plates (b_f x t_f = 500x20mm) and two vertical plates (b_w x t_w = 500x10mm) and subjected to compression axial force. Steel class: S355 (f_{yk} = 355 N/mm2, ε = 0.81).

According the Eurocode 3 cross-section classification method, horizontal plates have class < 4 (b_f/t_f = 500/20 = 25 < 42ε = 34) and vertical plates have classe 4 (b_w/t_w = 500/10 = 50 > 42ε = 34) therefore the cross-section has class 4.

Using Effective cross-section method:

Gross cross-section area: A = 2 x (500 x 10 + 500 x 20) = 30000 mm2
Uniform stresses distribution $\rightarrow$ $\psi = 1 \rightarrow k_\sigma = 4$

Vertical plate slenderness: $\bar{\lambda}_p = \frac{\frac{b_w}{t_w}}{28{,}4\varepsilon\sqrt{k_\sigma(\psi)}} = \frac{\frac{500}{10}}{28{,}4x0{,}81\sqrt{4}} = 1{,}087$

Plate reduction factor ρ: $\rho = \frac{\bar{\lambda}_p - 0{,}055(3+\psi)}{\bar{\lambda}_p^2} = \frac{1{,}087 - 0{,}055(3+1)}{1{,}087^2} = 0{,}734$

Vertical plate effective cross-section area: (ρ bw) tw =
= (0,734 x 500) x 10 = 367 x 10 = 3670mm2

Effective cross-section area A_n = 2 x 3670 + 2 x 500 x 20 = 27340 mm2
Cross-section design resistance axial force (named N_{EFF_Rd} for the used method):
$N_{EFF\_Rd} = f_{yd}\ A_n = f_{yk} / \gamma_{M0}\ A_n$ = 355 / 1,05 x 27340 mm2 = 9243 kN

Using Reduced stress method:
Assuming $N_{Ed} = N_{EFF\_Rd}$ = 9243 kN the design stress is
$\sigma_{Ed} = N_{Ed} / A$ = 9243000 / 30000 = 308 N/mm2 (uniform on all plates)

Following the method procedure:

	Horizontal plate	**Vertical plate**
Dimensions b x t [mm]	500 x 20	500 x 10
Steel f_{yk} [N/mm2]	355	355
γ_M	1,05	1,05
σ_{Ed} [N/mm2]	308	308
$\alpha_{ult,k} = f_{yk} / \sigma_{xEd}$	1,15	1,15
$\sigma_E = \frac{\pi^2 E t^2}{12(1-\upsilon^2)b^2}$ [N/mm2]	304	76
ψ, $k_\sigma(\psi)$	1, 4	1, 4
$\sigma_{cr,x} = k_\sigma(\psi)\ \sigma_E$ [N/mm2]	1216	304
$\alpha_{cr} = \alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed}$	3,95	0,99
$\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$	0,540	1,08
$\rho = \rho_x(\bar{\lambda}_p)$	1,00	0,74
$\Gamma = \frac{\rho\alpha_{ult,k}}{\gamma_M}$	1,10 > 1 → verified	0,81 < 1 → not verified

Cross-section is not verified. In fact, according Reduced stress method cross-section design resistance axial force is only N_{RED_Rd} = 7470 kN (with uniform stress σ_{Ed} = 249 N/mm2). Vertical plates Γ ratio is 1,00 and horizontal plates Γ ratio is only 1,36 (they are not fully employed):

	Horizontal plate	**Vertical plate**
Dimensions b x t [mm]	500 x 20	500 x 10
Steel f_{yk} [N/mm2]	355	355
γ_M	1,05	1,05
σ_{Ed} [N/mm2]	249	249
$\alpha_{ult,k} = f_{yk} / \sigma_{xEd}$	1,43	1,43
$\sigma_E = \frac{\pi^2 E t^2}{12(1-\upsilon^2)b^2}$ [N/mm2]	304	76
ψ, $k_\sigma(\psi)$	1, 4	1, 4
$\sigma_{cr,x} = k_\sigma(\psi)\ \sigma_E$ [N/mm2]	1216	304
$\alpha_{cr} = \alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed}$	4,88	1,22
$\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$	0,541	1,08
$\rho = \rho_x(\bar{\lambda}_p)$	1,00	0,74
$\Gamma = \frac{\rho\alpha_{ult,k}}{\gamma_M}$	1,36 > 1 → verified	1,00 > 1 → verified

To have $N_{RED\_Rd} = N_{EFF\_Rd} = 9243$ kN it is necessary to assume a stresses field with σ_{v_Ed} = cost. = 291 N/mm2 on vertical plates and σ_{H_Ed} = cost. = f_{yd} = 338 N/mm2 on horizontal plates but this stresses distribution has no congruence-acceptability.

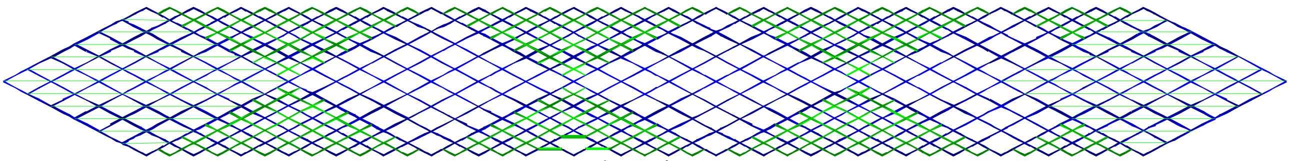
	Horizontal plate	**Vertical plate**
Dimensions b x t [mm]	500 x 20	500 x 10
Steel f_{yk} [N/mm2]	355	355
γ_M	1,05	1,05
σ_{Ed} [N/mm2]	338	249
$\alpha_{ult,k} = f_{yk} / \sigma_{xEd}$	1,05	1,43
$\sigma_E = \frac{\pi^2 E t^2}{12(1-\upsilon^2)b^2}$ [N/mm2]	304	76
ψ, $k_\sigma(\psi)$	1, 4	1, 4
$\sigma_{cr,x} = k_\sigma(\psi)\ \sigma_E$ [N/mm2]	1216	304
$\alpha_{cr} = \alpha_{cr,x} = \sigma_{cr,x} / \sigma_{x,Ed}$	3,60	1,22
$\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$	0,541	1,08
$\rho = \rho_x(\bar{\lambda}_p)$	1,00	0,74
$\Gamma = \frac{\rho \alpha_{ult,k}}{\gamma_M}$	1,00 > 1 → verified	1,00 > 1 → verified

This example shows that, when both methods are applicable, there are cases where Reduced stress method is more conservative than Effective cross-section method.

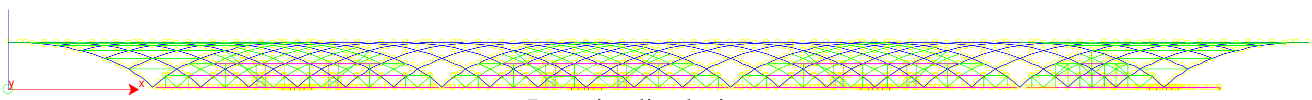
3. A real case: High Velocity Railway Station in Florence (Italy)

Reduced stress method has been adopted for the verification of steel member of the High Velocity Railway Roof in Florence.

The roof structure is thought as a cylindric vault with 350m length and 52m width. At each end the roof goes on with a cantilever "nail" with 50m span. The structure is formed by a romboidal grid of plane arches.Arch vertical planes are inclined respect to roof longitudinal axe.

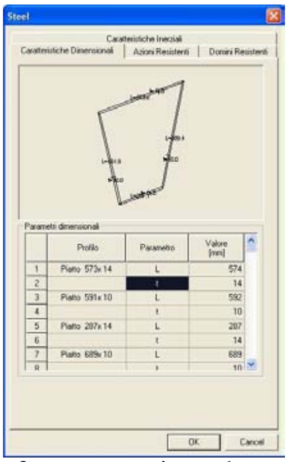


Plan view

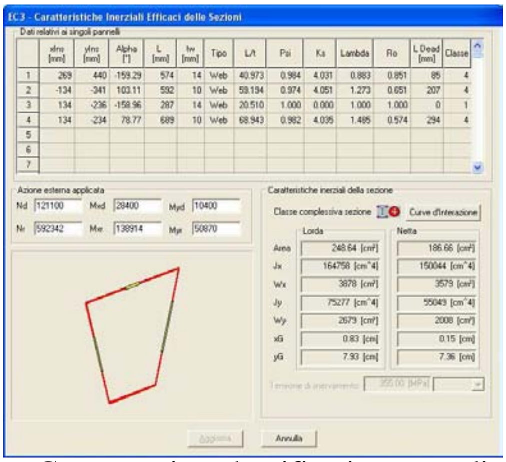


Longitudinal view

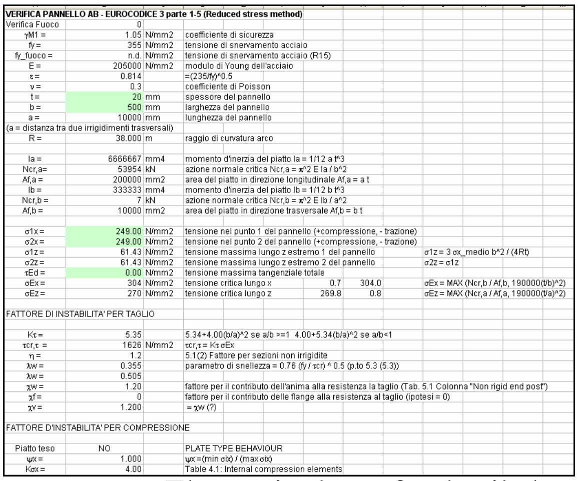
Arches are differentiate by primary and secondary arches. Their cross-sections have trapezoidal hollow shapes with height variable respectively from 900mm and 600mm at mid span to 1600mm and 1200mm at the supports. These box are composed by welding plate with thickness variable from 10mm to 50mm. Except to the joints at the intersection of arches, no internal ribs are planned for these plates. The 3D iperstaticity of the structure causes the presence of all six components of internal action and the use of slender plates moved the Designers to adopt the Reduced stress method for the arch verification ([3]). The constructive phase of design ([4]) has also adopted the method with the implementation of electronic sheets for the detailed analysis of check steps on single elements and of C++ routines for structural software (see following pictures).

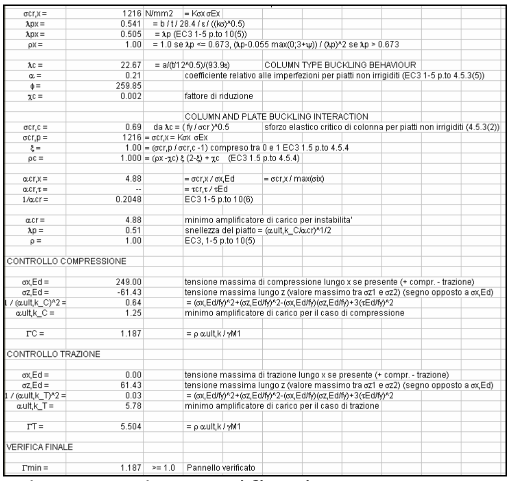


Dimensions of cross-section plates



Cross-section classification according to EN1993





Electronic sheets for detailed step by step plate verification

	$\sigma 1$	$\sigma 2$	τmax taglio	τmax tors	τtot			
	N/mm2	N/mm2	N/mm2	N/mm2	N/mm2	Γ	Verifica	Check
AB	-154.0	-49.0	0.00	0.00	0.00	2.01	>= 1.0	Pannello verificato
BC	-49.0	80.4	0.00	0.00	0.00	4.23	>= 1.0	Pannello verificato
CD	80.4	26.8	0.00	0.00	0.00	3.85	>= 1.0	Pannello verificato
DA	26.8	-154.0	0.00	0.00	0.00	2.19	>= 1.0	Pannello verificato
						2.01	**>= 1.0**	**Sezione verificata**

Cross-section shape and summarizing check results table

4. Conclusions

The methods to evaluate the ULS resistence of class 4 steel cross-section according Eurocode 3 are compared with some observations about their application field and their correlation. When both of them are applicable Reduced stress method may leads to more conservative result than Effective cross-section method. Reduced stress method has found a real application in the design of High Velocity Railway Station roof in Florence (Italy).

5. References

[1] EN1993-1-1, Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings.

[2] prEN1993-1-5, Eurocode 3: Design of steel structures – Part 1-5: Plated structural elements.

[3] RFI, ARUP, FOSTERS and Partners, “Rete Ferroviaria Italiana Spa – Stazione AV di Firenze. Progetto esecutivo – Calcoli strutturali – Sopraelevazione Stazione – Copertura vol.1→5”, May 2005.

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