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# DESIGN OF CLASS 4 CROSS SECTION IN AXIAL COMPRESSION ACCORDING TO EUROCODE 3

SUMMARY

In this paper theoretic basis of design of class 4 cross section in axial compression according to EN1993-1-5 is given. Design procedure is given as an flow chart and ilustrated with an worked example. Plate buckling is treated localy and globaly through the concept of effective cross sections. Interaction between plate-like and column-like behaviour of panels is carried out thought buckling reduction factors and final effective area of cross section.

*Key words: steel, axial compression, Eurocodes, buckling*

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# PRORAČUN AKSIJALNO NAPREGNUTOG ŠTAPA POPREČNOG PRESEKA KLASE 4 PREMA EVROKODU 3

REZIME

U ovom radu date su teorijske osnove za proračun centrično pritisnutih elemenata poprečnog preseka klase 4, u svemu prema Evrokodu 3 (EN 1993-1-5). Postupak proračuna dat je u vidu algoritma i ilustrovan jednim numeričkim primerom. Standard uzima u obzir efekte izbočavanja primenom koncepta efektivnih poprečnih preseka. Interakcijom efekata izvijanja i izbočavanja kako pojedinih delova preseka tako i delova preseka koje čine ploča i ukrućenja dobijaju se koeficijenti redukcije površine koji na kraju daju konačnu efektivnu površinu preseka.

*Ključne reči: čelik, aksijalni pritisak, Evrokodovi, izbočavanje*

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## SCOPE

Plate buckling is often present in large scale structures such as steel bridges or trussing elements of large span trusses. European standards for steel structures, Eurocode 3, deal this phenomenon by concept of effective cross sections. According to EN 1991-1-5 elements with slenderness' such that cross section is classified as class 4 must be considered as reduced due to direct stresses plate buckling effects – effective cross sections. Main rules are given in part 4, and details concerning different cases of unstiffened and stiffened plates are given in annexes A.1 and A.2. Shear induced buckling, and in-plane load effects, together with interaction between various effects, are also given in this document of European standards, but those will not be considered in this paper.

## BASIS OF DESIGN

Procedure of design is based on interaction between plate-like and column-like behaviour of plates buckling. Cross section of element is decomposed to panels (flange region, web region…) and subpanels (plate parts between stiffeners). In case of stiffened cross section it is first necessary to calculate local effects of plate-like buckling of each subpanel. Effective areas (widths) are obtained by reduction factor $\boldsymbol{\rho}$ which is function of relative slenderness of considered subpanel. Expressions for reduction factor depend on whether the subpanel is internal or outstand part of cross section. It also depends on relation between normal stresses $\psi$ due to considered loading state (compression, bending...) in opposite points of subpanel. This relation is equal to 1,0 in case of axial compression. Relative slenderness of subpanel is determined either by function of plate slenderness $\boldsymbol{b/t}$ and buckling factor $\boldsymbol{k}_{\sigma}$, or in general by relation between yield stress and elastic critical plate buckling stress.

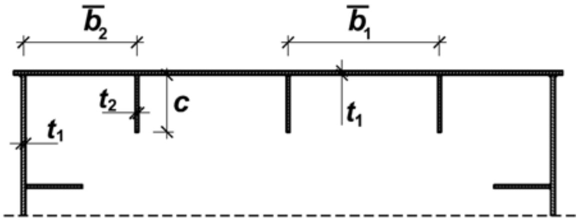


*Fig. 1.* Gross cross section

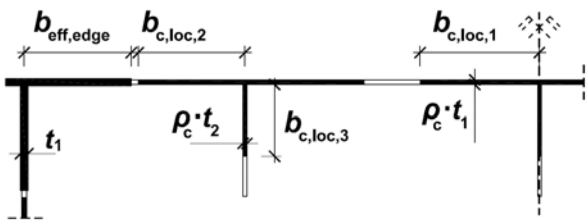


*Fig. 2.* Effective cross section

Presence of longitudinal stiffeners in a panel of cross section may lead to out of plane global buckling (column-like behaviour) of areas composed of stiffener and adjacent parts of plate.

Second part of design presents the interaction between plate-like and column-like behaviour of stiffened plate in means of global buckling of panel (flange or web) composed of effective subpanels, according to expression:

$$\rho_c = (\rho - \kappa_c)\xi(2-\xi) + \kappa_c$$

Factor $\boldsymbol{\xi}$ stands for weight interpolation factor which depends on elastic critical plate buckling stress $\boldsymbol{\sigma}_{cr,p}$ and elastic critical column buckling stress $\boldsymbol{\sigma}_{cr,c}$. Critical stresses should be determined for stiffened plate in global sense taking into account contribution of stiffeners. Reduction factor $\boldsymbol{\rho}$ for stiffened plate has to be calculated on basis of relative slenderness determined with elastic critical plate buckling stress for stiffened plate $\boldsymbol{\sigma}_{cr,p}$. Column-like behaviour of stiffened plate is govern by factor $\kappa_c$ , as for axial compression member composed of stiffener and adjacent parts of plate according to EN1993-1-1.

It is assumed that in only inner part of panel (stiffened zone) is reduced due to global buckling effects. Edge zones, near to adjacent panels (web or flange), does only need to be reduced for local buckling effects. Finally effective area of a panel is determined by the expression:

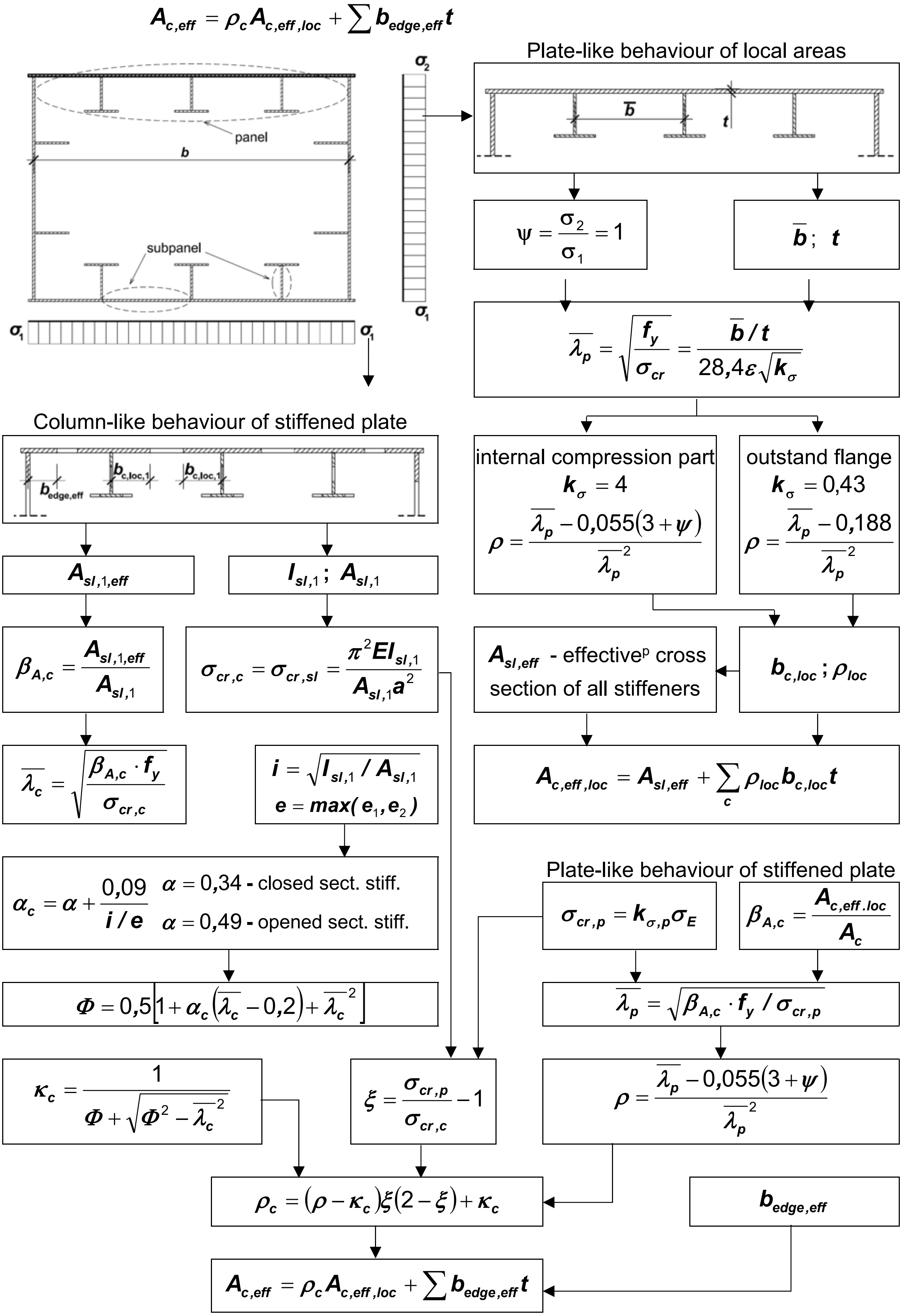


*Fig. 3.* Flow chart for effective area of stiffened element in compression

**WORKED EXAMPLE**

Procedure of design according to EN1993-1-5 of complex class 4 cross section is shown with an example of stiffened box element subjected to axial compression, shown in Figure 4.

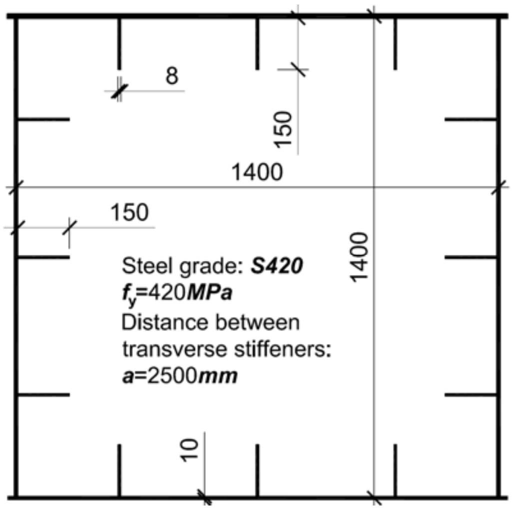


*Fig. 4.* Gross cross section

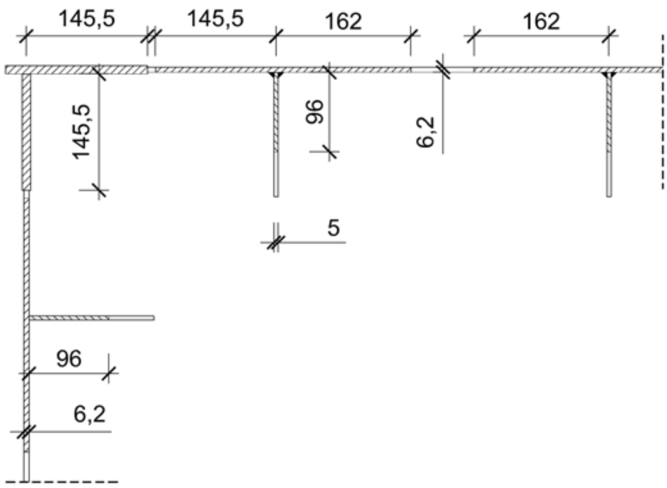


*Fig. 5.* Effective cross section

**Effective widths of subpanels**

Subpanels between longitudinal stiffeners (internal compression part)

$$\overline{\boldsymbol{b}} = \boldsymbol{b} = 400\boldsymbol{mm};\quad \boldsymbol{t} = 10\boldsymbol{mm};\quad \psi = \frac{\sigma_2}{\sigma_1} = 1 \rightarrow \boldsymbol{k}_\sigma = 4;\ \varepsilon = 0{,}75$$

$$\overline{\lambda_p} = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\overline{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}} = \frac{400/10}{28{,}4 \cdot 0{,}748 \cdot 2} = 0{,}941 > 0{,}673$$

$$\rho = \frac{\overline{\lambda_p} - 0{,}055(3+\psi)}{\overline{\lambda_p}^2} = \frac{0{,}94 - 0{,}055(3+1)}{0{,}94^2} = 0{,}81 \le 1{,}0$$

$$b_{e1} = b_{e2} = 0{,}5 b_{eff} = 0{,}5\rho\overline{b} = 0{,}5 \cdot 0{,}81 \cdot 400 = 162\boldsymbol{mm}$$

Subpanel between adjacent panel and first longitudinal stiffener (internal compression part)

$$\overline{\boldsymbol{b}} = \boldsymbol{b} = 300\boldsymbol{mm};\quad \boldsymbol{t} = 10\boldsymbol{mm};\quad \psi = \frac{\sigma_2}{\sigma_1} = 1 \rightarrow \boldsymbol{k}_\sigma = 4$$

$$\overline{\lambda_p} = \frac{300/10}{28{,}4 \cdot 0{,}748 \cdot 2} = 0{,}706 > 0{,}673;\ \rho = \frac{0{,}71 - 0{,}055(3+1)}{0{,}71^2} = 0{,}97 \le 1{,}0$$

$$b_{e1} = b_{e2} = 0{,}5 b_{eff} = 0{,}5\rho\overline{b} = 0{,}5 \cdot 0{,}97 \cdot 300 = 145{,}5\boldsymbol{mm}$$

Longitudinal stiffeners (outsand flange)

$$\boldsymbol{c} = \boldsymbol{h}_{ukr} = 150\boldsymbol{mm};\quad \boldsymbol{t} = 8\boldsymbol{mm};\quad \psi = \frac{\sigma_2}{\sigma_1} = 1 \rightarrow \boldsymbol{k}_\sigma = 0{,}43$$

$$\overline{\lambda_p} = \frac{150/8}{28{,}4 \cdot 0{,}748 \cdot \sqrt{0{,}43}} = 1{,}35 > 0{,}748;\ \rho = \frac{\overline{\lambda_p} - 0{,}188}{\overline{\lambda_p}^2} = 0{,}64$$

$$b_{eff} = \rho c = 0{,}64 \cdot 150 = 96\boldsymbol{mm}$$

**Plate-like behaviour of stiffened panel (web or flange)**

$$A_{sl,eff} = 3 \cdot 96 \cdot 8 = 2304 mm^2 = 23{,}04 cm^2$$

$$\sum_c \rho_{loc} b_{c,loc} t = 0{,}81 \cdot 2 \cdot 400 \cdot 10 + 0{,}97 \cdot 2 \cdot 150 \cdot 10 = 9390 mm^2 = 93{,}90 cm^2$$

$$A_{c,eff,loc} = 23{,}04 + 93{,}90 = 116{,}94 cm^2$$

Elastic critical plate buckling stress according to A.1(2) (EN 1993-1-5)

***b***=1400***mm***; ***t***=10***mm***; ***a***=2500***mm*** – distance between transverse stiffeners

$$\sigma_E = \frac{\pi^2 E t^2}{12(1-\nu^2)b^2} = 190000\left(\frac{t}{b}\right)^2 = 190000\left(\frac{10}{1400}\right)^2 = 9{,}69 MPa$$

$$\alpha = \frac{a}{b} = \frac{2500}{1400} = 1{,}79 \geq 0{,}5;\ I_p = \frac{bt^3}{12(1-\nu^2)} = \frac{bt^3}{10{,}92} = \frac{140 \cdot 1^3}{10{,}92} = 12{,}82 cm^4$$

$$I_{sl} = 2519{,}39 cm^4;\ \gamma = \frac{I_{sl}}{I_p} = \frac{2519{,}39}{12{,}82} = 196{,}52;\quad \psi = \frac{\sigma_2}{\sigma_1} = 1{,}0 \geq 0{,}5$$

$$\sum A_{sl} = 3 \cdot 15 \cdot 0{,}8 = 36 cm^2;\ A_p = 140 \cdot 1 = 140 cm^2$$

$$\delta = \frac{\sum A_{sl}}{A_p} = \frac{36}{140} = 0{,}26;\quad \alpha = 1{,}79 \leq \sqrt[4]{\gamma} = \sqrt[4]{196{,}52} = 3{,}74$$

$$k_{\sigma,p} = \frac{4(1+\sqrt{\gamma})}{(\psi+1)(1+\delta)} = \frac{4(1+\sqrt{196{,}52})}{(1+1)(1+0{,}26)} = 23{,}84$$

$$\sigma_{cr,p} = k_{\sigma,p}\sigma_E = 23{,}84 \cdot 9{,}69 = 231{,}01 MPa$$

Elastic critical column buckling stress according to 4.5.3(2) i (3) (EN 1993-1-5)

$$I_{sl,1} = 819{,}10 cm^4 \qquad A_{sl,1} = 15 \cdot 0{,}8 + 40 \cdot 1{,}0 = 52 cm^2$$

$$\sigma_{cr,c} = \sigma_{cr,sl} = \frac{\pi^2 E I_{sl,1}}{A_{sl,1} a^2} = \frac{\pi^2 \cdot 210000 \cdot 819{,}10}{52 \cdot 250^2} = 522{,}36 MPa$$

Column-like behaviour buckling factor $\kappa_c$ according to 6.3.1.2 EN 1993-1-1

$$A_{sl,1,eff} = 32{,}4 \cdot 1{,}0 + 9{,}6 \cdot 0{,}8 = 40{,}08 cm^2;$$

$$A_{sl,1} = 15 \cdot 0{,}8 + 40 \cdot 1{,}0 = 52 cm^2$$

$$\beta_{A,c} = \frac{A_{sl,1,eff}}{A_{sl,1}} = \frac{40{,}08}{52{,}00} = 0{,}771;\ \overline{\lambda_c} = \sqrt{\frac{\beta_{A,c} f_y}{\sigma_{cr,c}}} = \sqrt{\frac{0{,}771 \cdot 420}{522{,}36}} = 0{,}79$$

$$e_1 = 6{,}98 cm;\quad e_2 = 1{,}02 cm;\quad e = \max(e_1, e_2) = 6{,}98 cm$$

$$i = \sqrt{\frac{I_{sl,1}}{A_{sl,1}}} = \sqrt{\frac{819{,}10}{52}} = 3{,}97 cm;\quad \frac{i}{e} = \frac{3{,}97}{6{,}98} = 0{,}57$$

$$\alpha_c = \alpha + \frac{0{,}09}{i/e} = 0{,}49 + \frac{0{,}09}{0{,}57} = 0{,}65$$

$$\Phi = 0{,}5\left[1 + \alpha_c(\overline{\lambda_c} - 0{,}2) + \overline{\lambda_c}^2\right] = 0{,}5\left[1 + 0{,}65 \cdot (0{,}79 - 0{,}20) + 0{,}79^2\right] = 1{,}004$$

$$\kappa_c = \frac{1}{\Phi + \sqrt{\Phi^2 - \overline{\lambda_c}^2}} = \frac{1}{1{,}00 + \sqrt{1{,}00^2 - 0{,}79^2}} = 0{,}62$$

Plate-like behaviour reduction factor $\rho$ for stiffened panel

$$\beta_{A,c} = \frac{A_{c,eff,loc}}{A_c} = \frac{116,94}{146} = 0,801; \quad A_c = 110 \cdot 1 + 3 \cdot 15 \cdot 0,8 = 146 cm^2$$

$$\overline{\lambda_p} = \sqrt{\frac{\beta_{A,c} f_y}{\sigma_{cr,p}}} = \sqrt{\frac{0,801 \cdot 420}{231,01}} = 1,21 \geq 0,673$$

$$\rho = \frac{\overline{\lambda_p} - 0,055(3+\psi)}{\overline{\lambda_p}^2} = \frac{1,21 - 0,055(3+1)}{1,21^2} = 0,68 \leq 1,0$$

Interaction between plate-like and column-like behaviour of stiffened panel

$$\xi = \frac{\sigma_{cr,p}}{\sigma_{cr,c}} - 1 = \frac{231,01}{522,36} - 1 = -0,56 \notin [0,1] \text{ leads to: } \xi = 0$$

$$\rho_c = (\rho - \kappa_c)\xi(2-\xi) + \kappa_c = (0,68 - 0,62) \cdot 0 \cdot (2-0) + 0,62 = 0,62$$

Effective cross section area of web or flange with stiffeners:

$$b_{edge,eff} = 145,5 mm; \quad t = 10 mm$$

$$A_{c,eff} = \rho_c A_{c,eff,loc} + \sum b_{edge,eff} t = 0,62 \cdot 116,94 + 2 \cdot 14,55 \cdot 1 = 101,60 cm^2$$

Finally for entire cross section of element we have:

$$A_{c,eff} = 4 \cdot 101,60 = 406,4 cm^2 \text{ - efective cross section}$$

$$A = 4 \cdot 140 \cdot 1,0 + 4 \cdot 3 \cdot 15 \cdot 0,8 = 704 cm^2 \text{ - gross cross section}$$

$$N_{c,Rd} = \frac{A_{c,eff} \cdot f_y}{\gamma_{M0}} = \frac{406,4 \cdot 42,0}{1,0} = 17069 kN; \quad \beta = \frac{A_{c,eff}}{A} = \frac{406,4}{704} = 0,577$$

## CONCLUSIONS

Design rules for class 4 elements in axial compression given in Eurocode 3 Part 1-5 are quite concise, leaving no doubts for users. Final cross section resistance of element should be calculated by rules given in Eurocode 3 Part 1-1 (buckling resistance). In case of girders (elements subjected to bending) same procedure should be applied taking into account only panels that are subjected to compression, with stress relations not equal to 1,0 in web panels. Apart from procedure shown in this paper, EN1993-1-5, also gives alternative methods for dealing the phenomenon of plate buckling, such as reduced stress method and application of finite element method in analysis.

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