

Univerza v Ljubljani

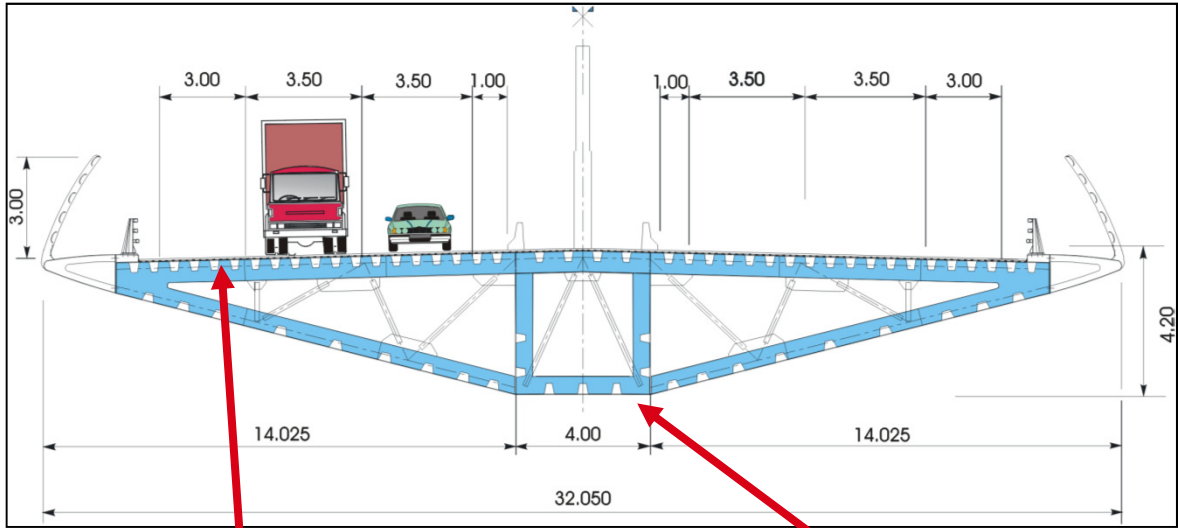
Fakulteta za gradbeništvo in geodezijo

Katedra za metalne konstrukcije

Izbočenje neojačenih in ojačenih pločevin

študijsko gradivo – Jeklene konstrukcije 2. stopnja – Konstrukcijska
smer

Darko Beg



Millau viaduct

Deck - fabrication



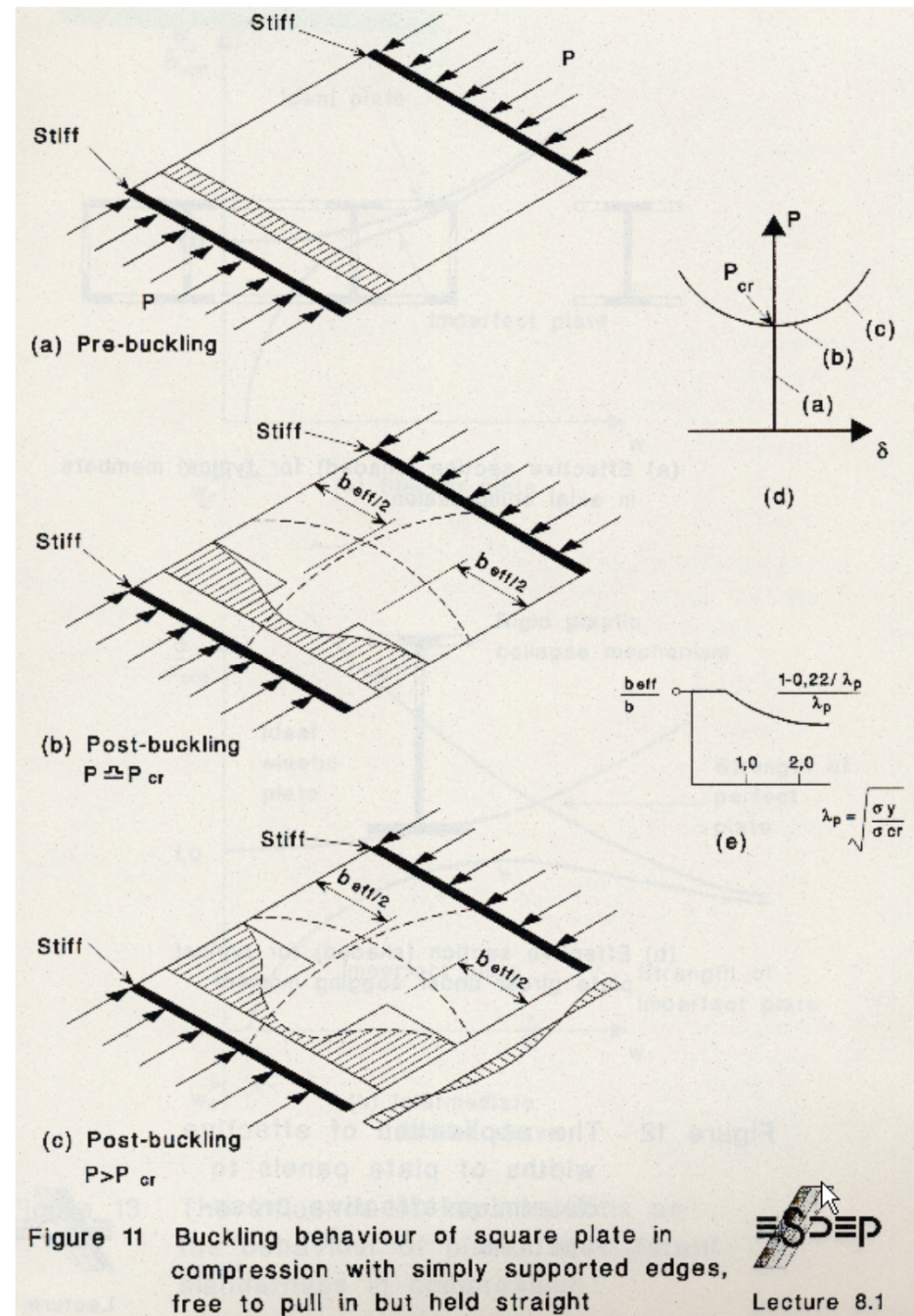
Deck = 36.000 t.



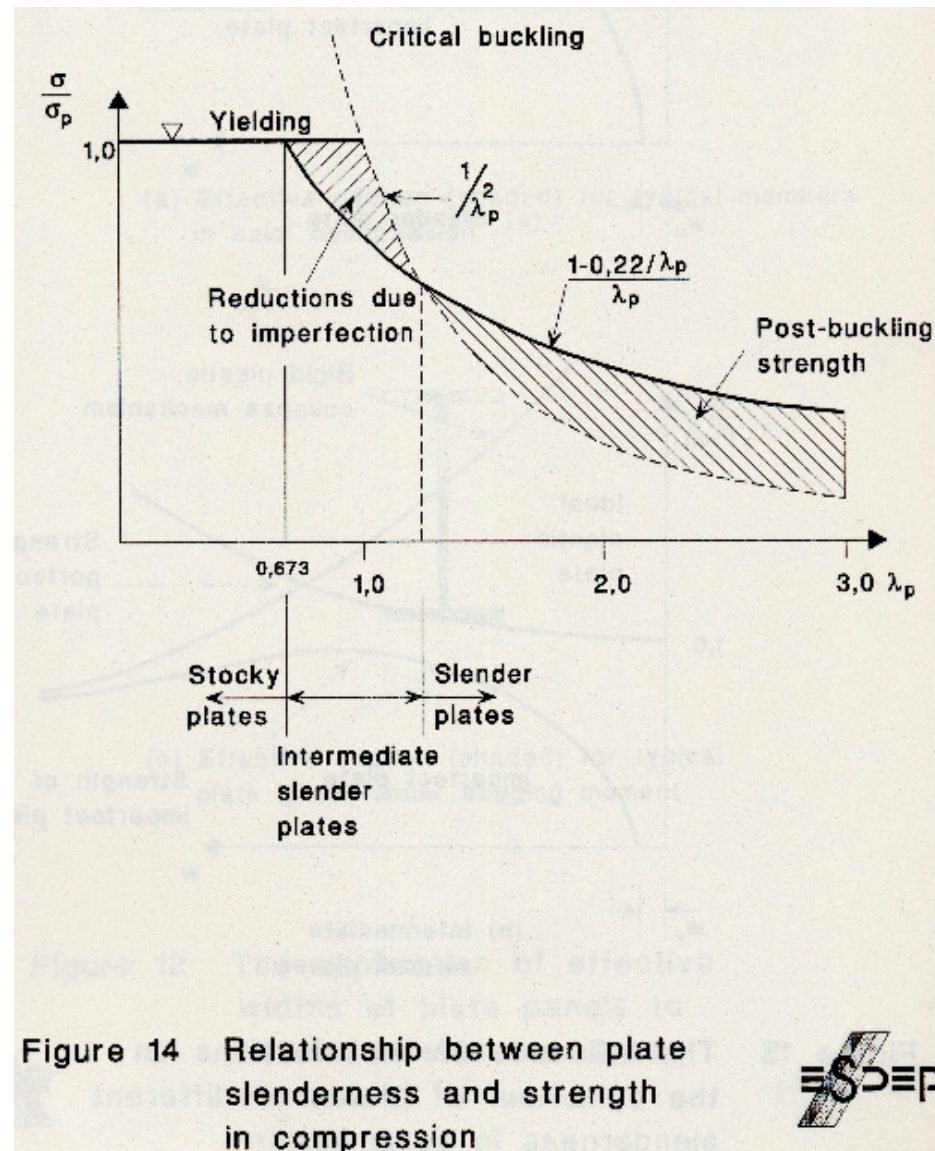
Vitki prerezi

- Metoda sodelujoče širine (lokalno izbočenje)

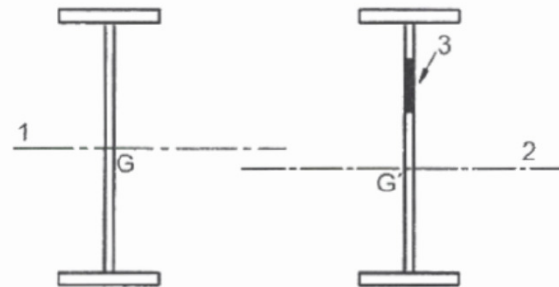
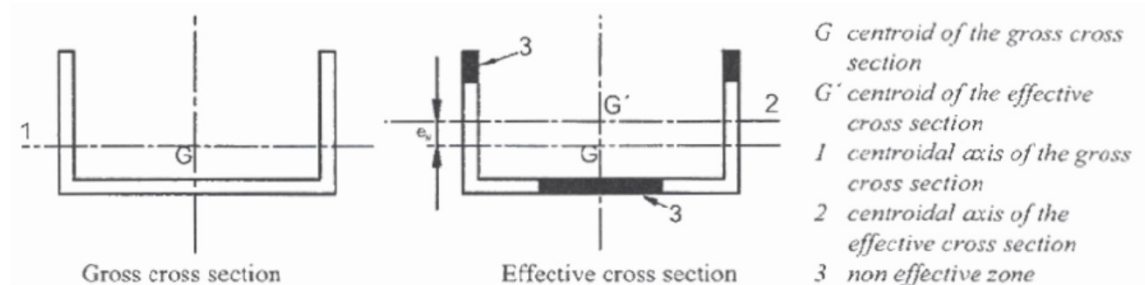
- $b_{\text{eff}} = \rho b$
- $\rho = \rho(\lambda)$



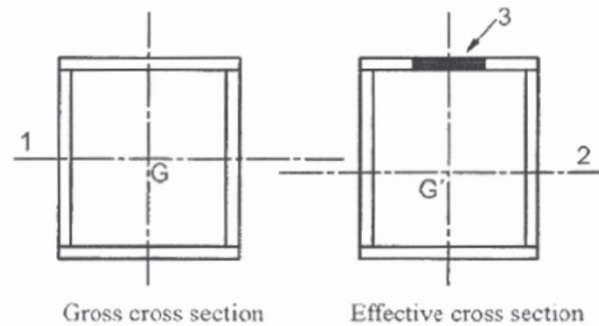
Lokalno izbočenje



Lokalno izbočenje



$$\frac{N}{A_{eff}} + \frac{M + Ne_N}{W_{eff}} \leq \frac{f_y}{\gamma_{M0}}$$



- G* centroid of the gross cross section
G' centroid of the effective cross section
 1 centroidal axis of the gross cross section
 2 centroidal axis of the effective cross section
 3 non effective zone

Figure 4.2: Class 4 cross-sections - bending moment

Kontrola stabilnosti ojačenih ali neojačenih pločevin po SIST EN 1993-1-5

- Metoda sodelujoče širine
- Metoda reduciranih napetosti?
- Stojine iz profilirane pločevine
- Napotki za MKE analizo (z lupinastimi elementi)

Možni načini porušitve pri polnostenskih nosilcih

Problemi:

- izbočenje v strigu
- bočna zvrnitev
- izbočenje v tlaku
- vertikalni uklon pasnic
- vnos koncentriranih sil F
- interakcija M-V
- interakcija M-F
- kontrola ojačitev
- strižna podajnost

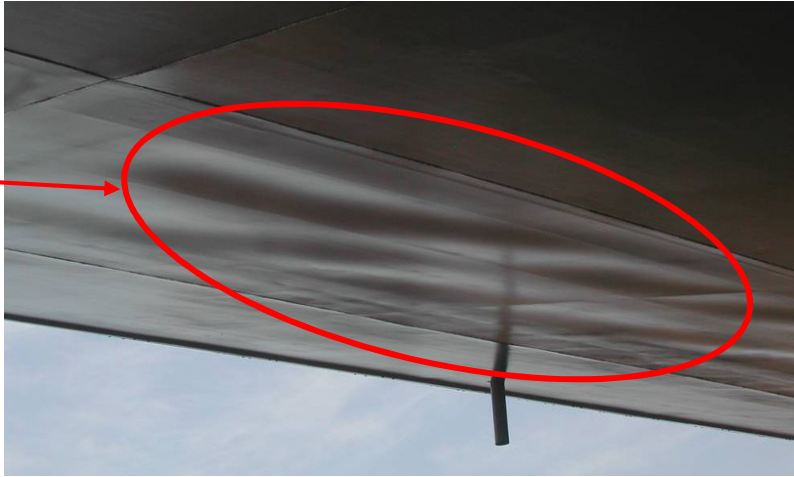
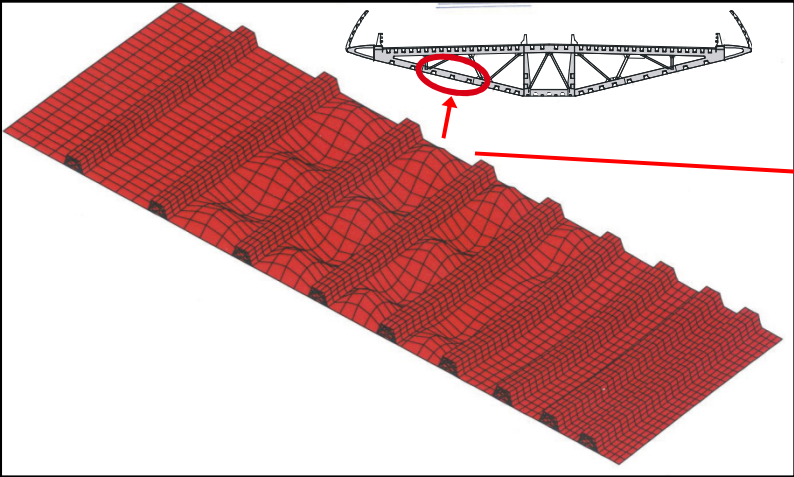
Način nestabilnosti	Ilustracija
Izbočenje stojine v strigu	
Bočna zvrnitev	
Lokalno izbočenje pasnice v tlaku	
Lokalno izbočenje stojine v tlaku	
Vertikalni uklon pasnic	
Lokalno izbočenje stojine (patch loading)	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <p>Enakomerna</p> </div> <div style="text-align: center;"> <p>Koncentrirana</p> </div> <div style="text-align: center;"> <p>Upogib</p> </div> </div>

Millau viaduct

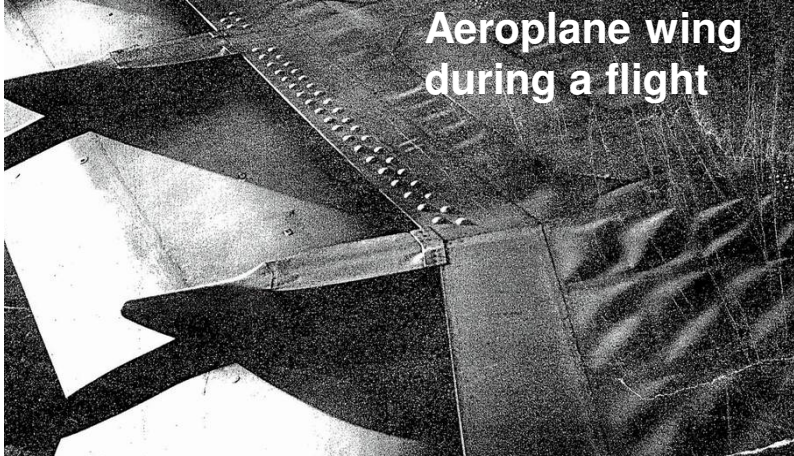
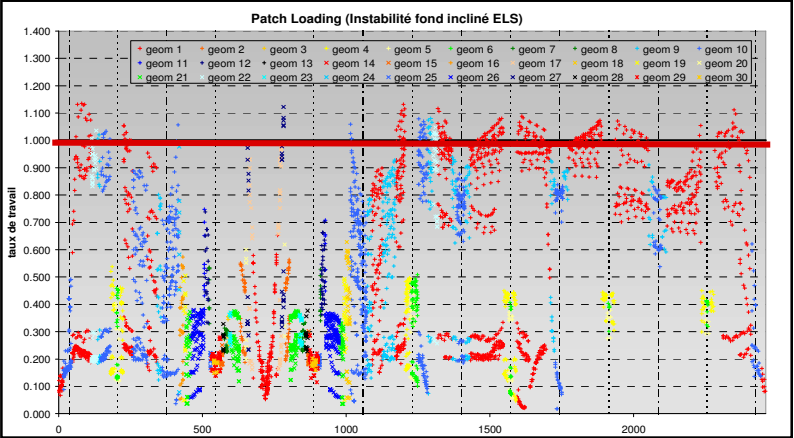
Launching
Deck design

INSTABILITY

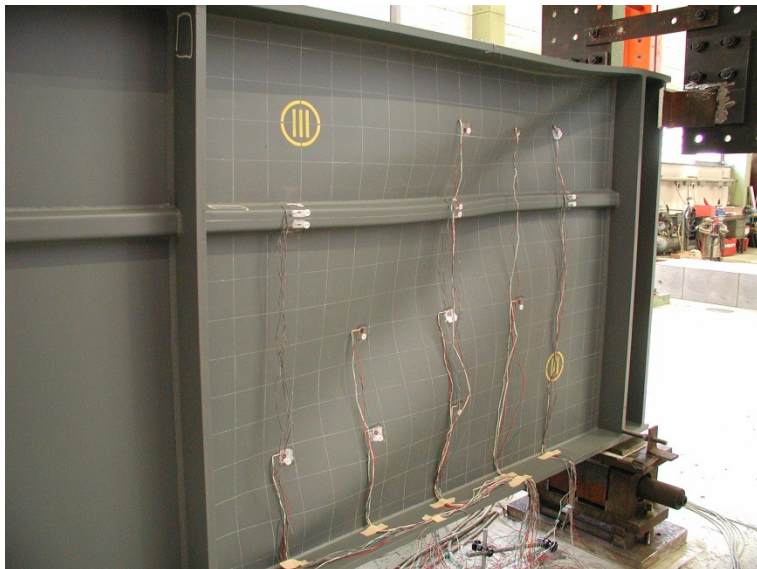
PLATE BUCKLING: during launching = SLS



Inclined lower flange of box girder



GLOBALNO IZBOČENJE PANELA

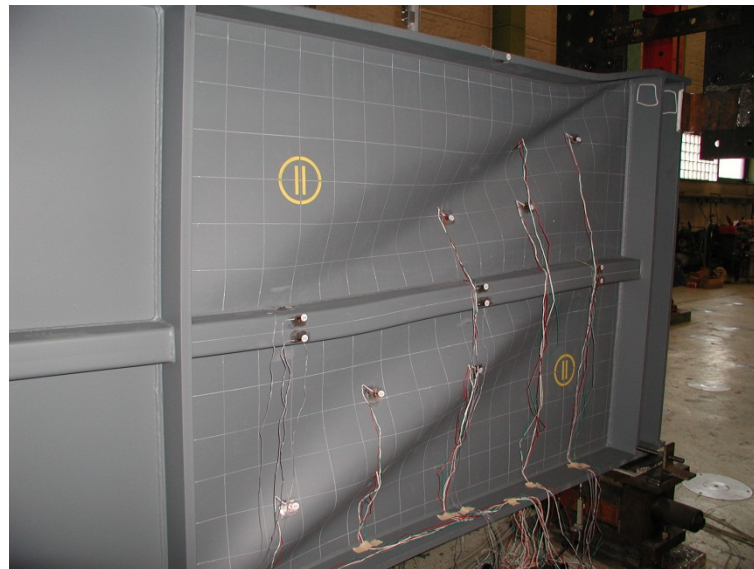


Končna obtežba, $F=1245$ kN, $w=34,8$ mm

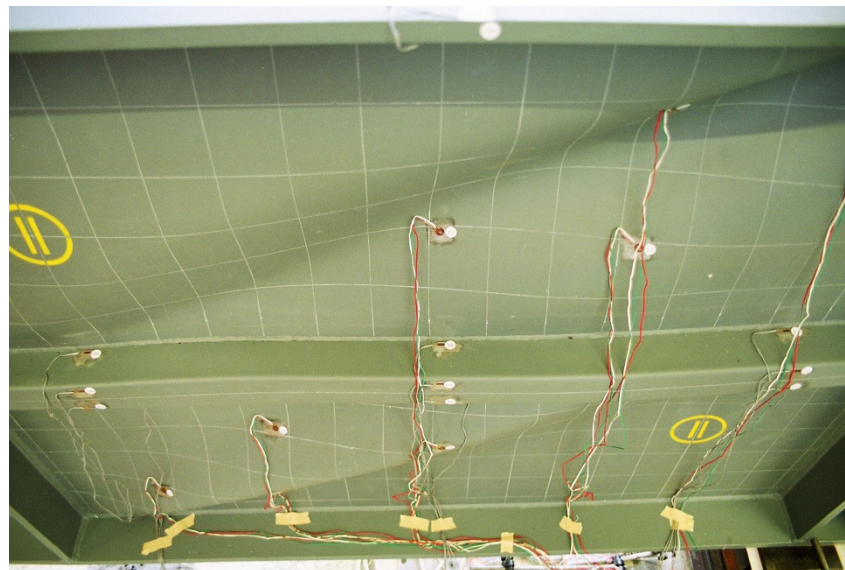


Razbremenjeno stanje

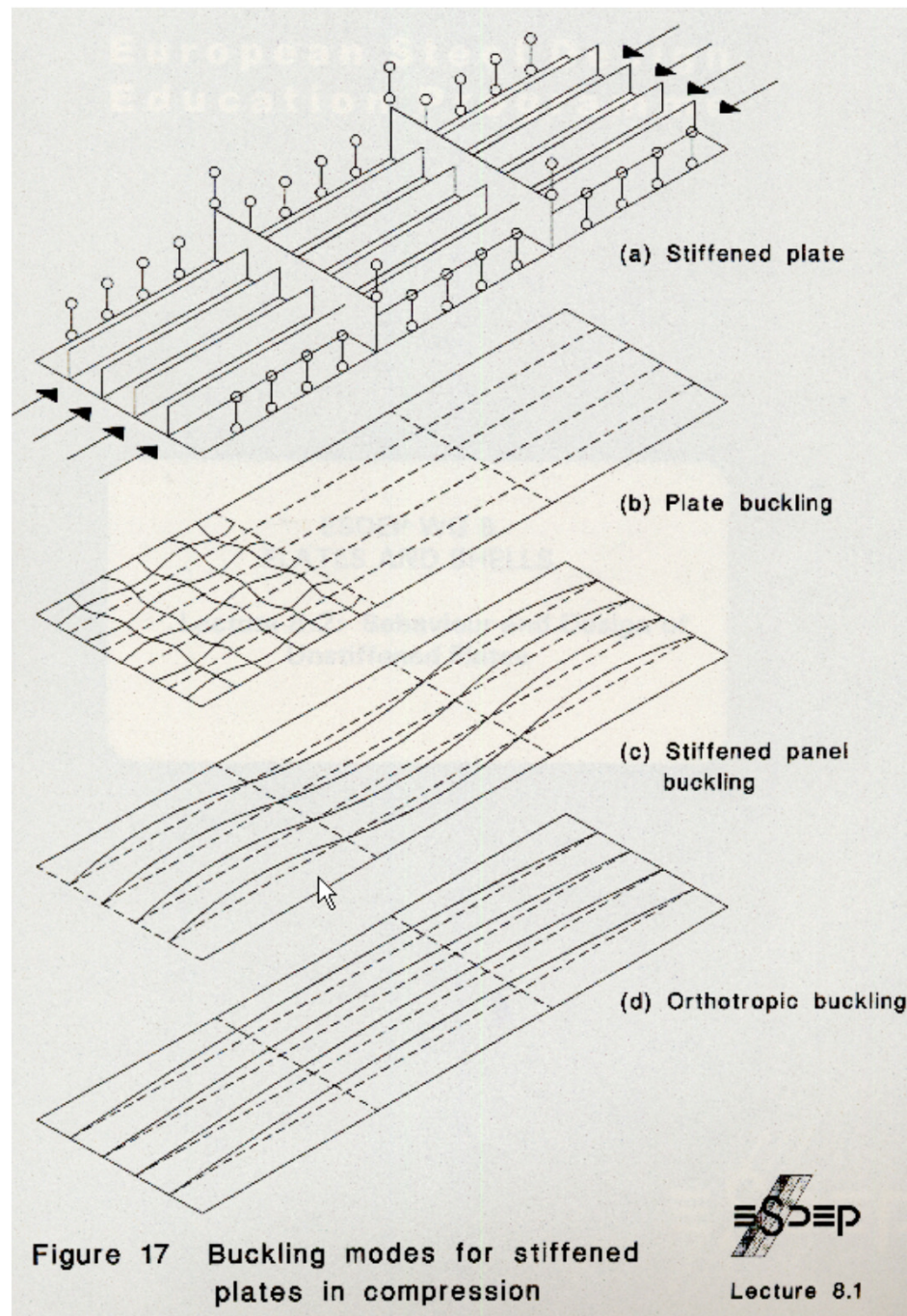
LOKALNO IZBOČENJE PANELA

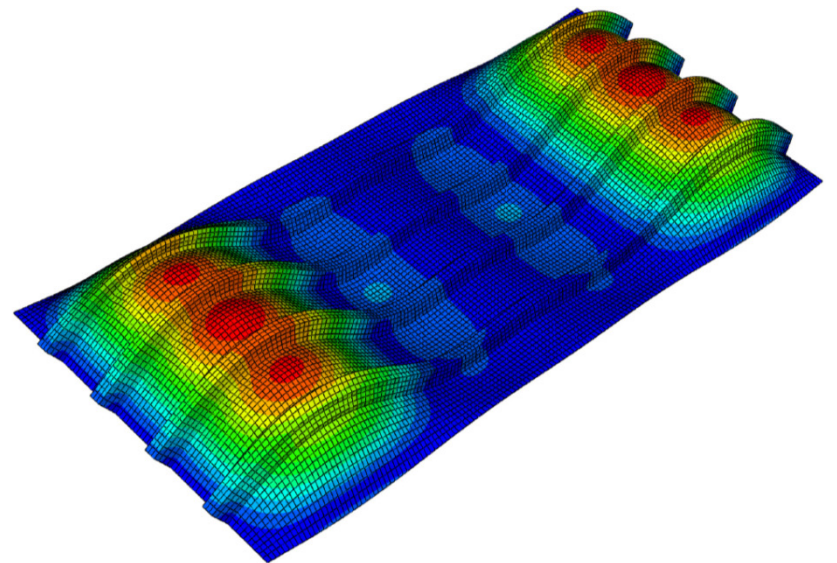
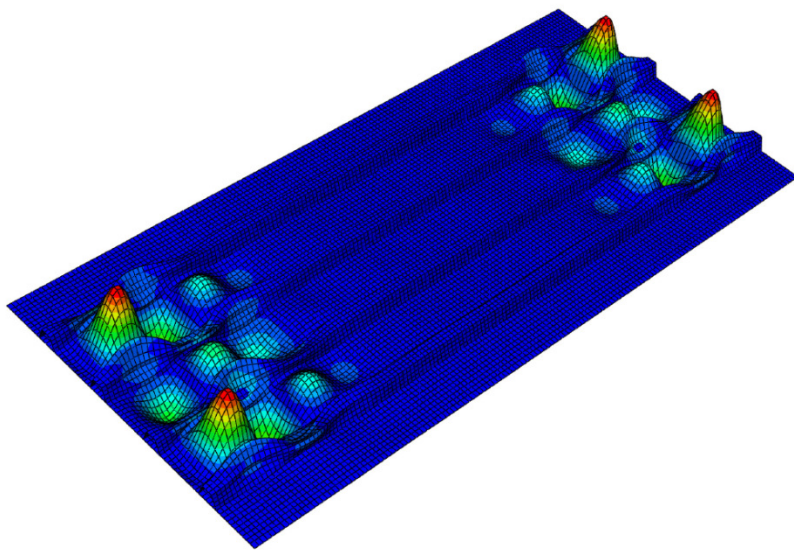
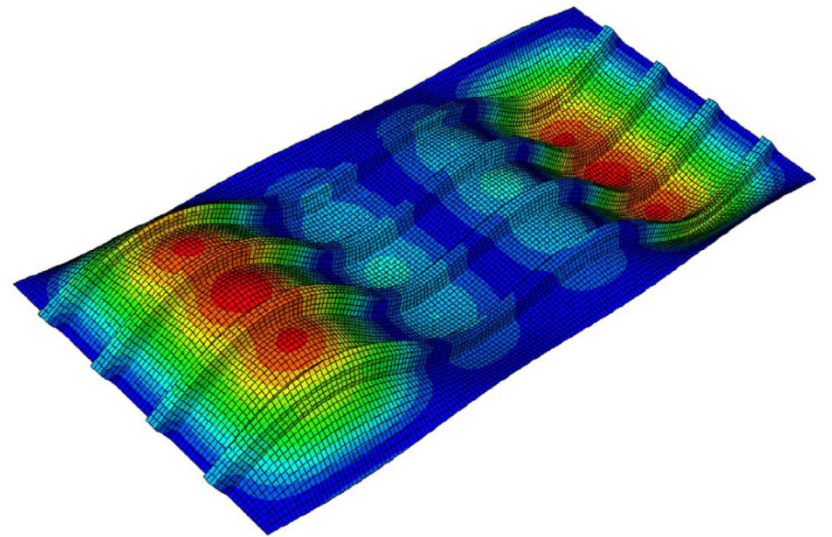
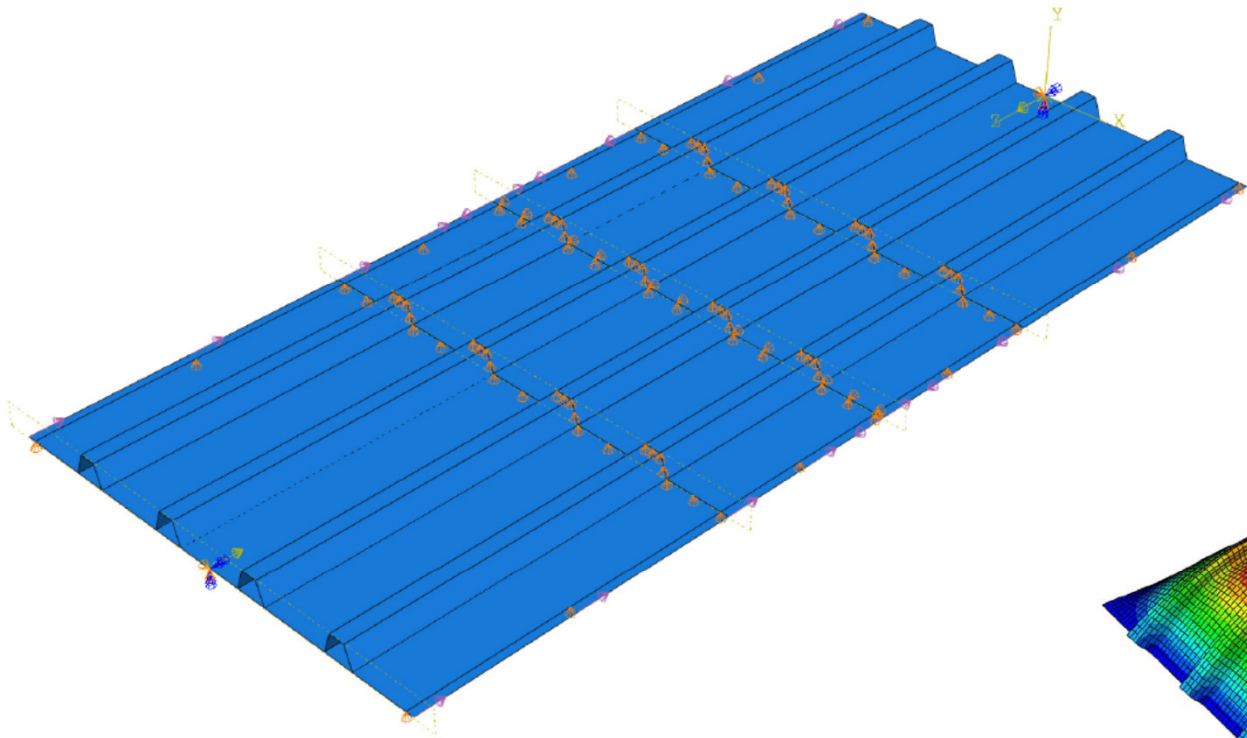


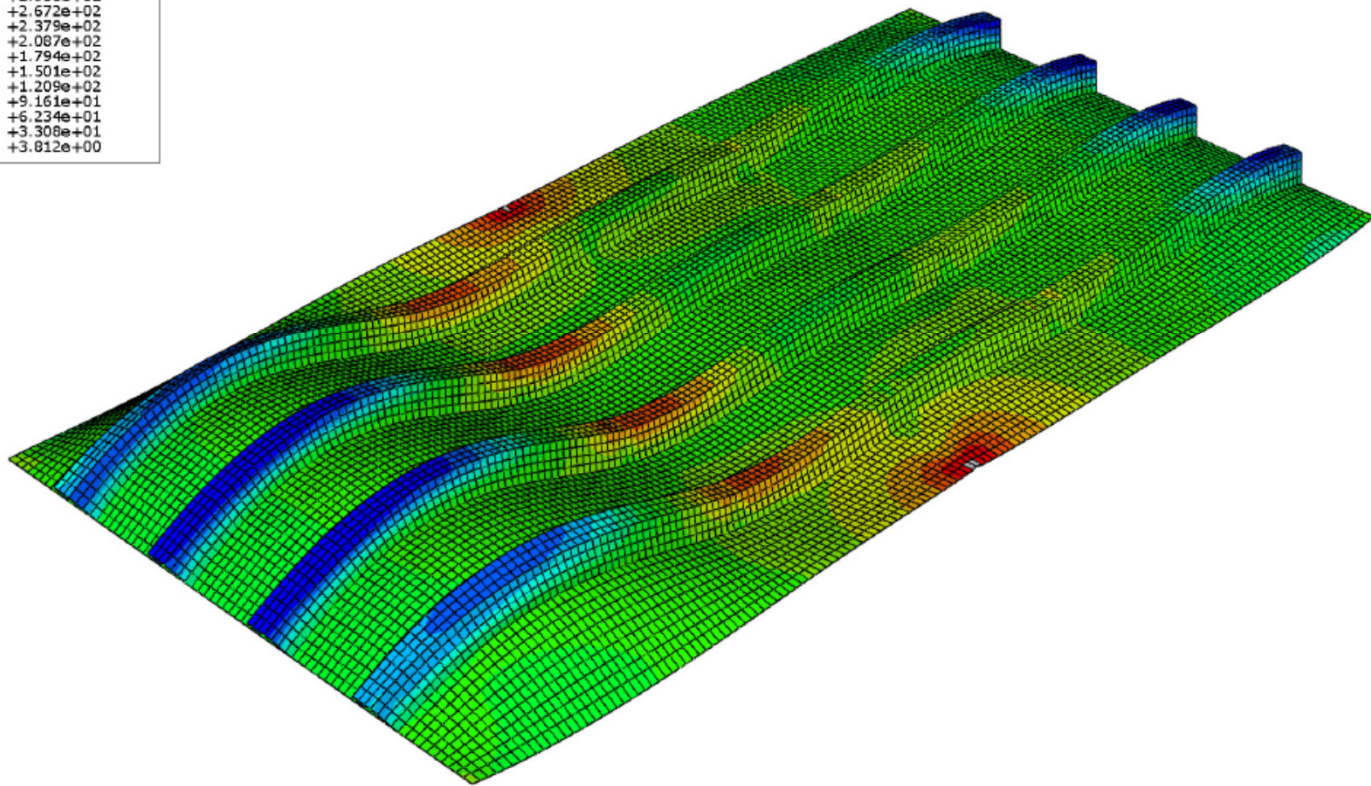
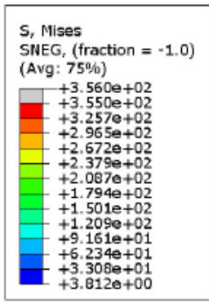
Končna obtežba, $F=1248$ kN, $w=66,9$ mm



Razbremenjeno stanje





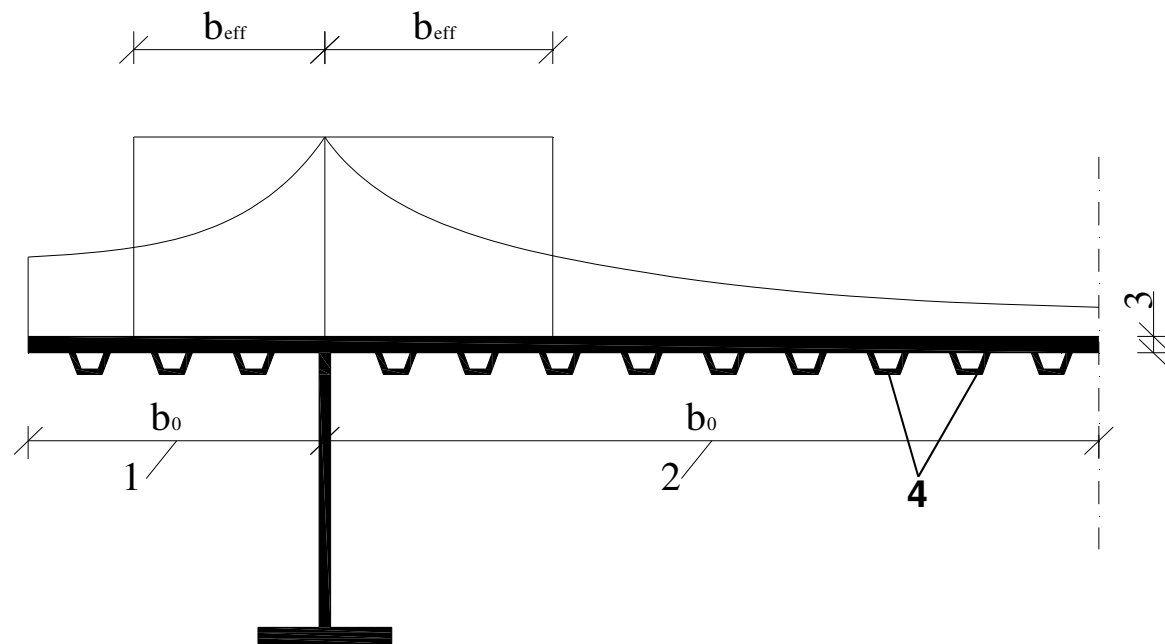


STRIŽNA PODAJNOST ELEMENTOV

$b_0 \leq L_e / 50 \rightarrow$ Strižne podajnosti ne obravnavamo

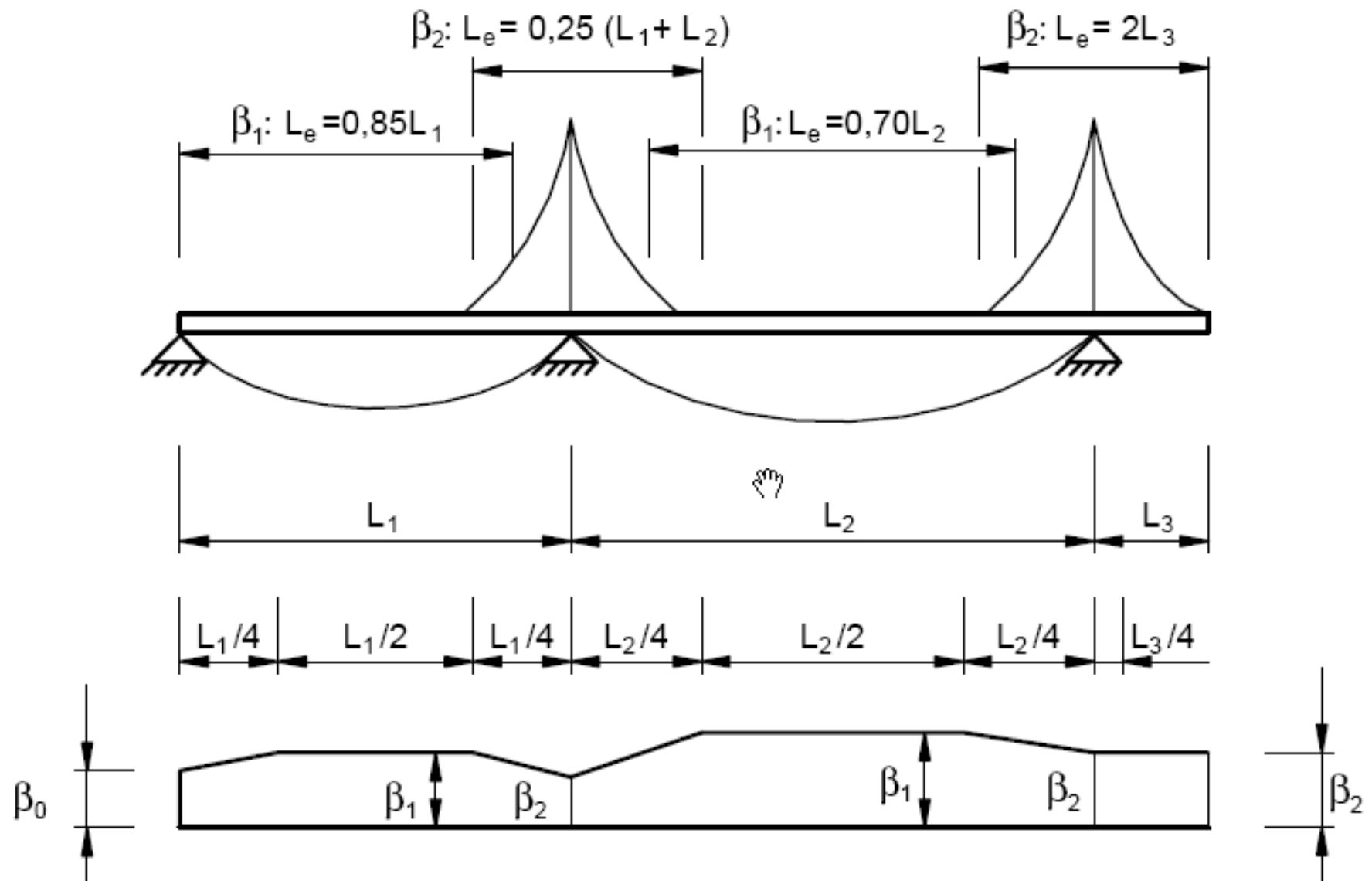
b_0 _____ širina previsnega dela pasnice oz. $1/2$ pasnice

L_e _____ razdalje med ničelnima točkama momenta



- 1 zunanja pasnica
- 2 notranja pasnica
- 3 debelina pločevine
- 4 ojačitve

STRIŽNA PODAJNOST ELEMENTOV



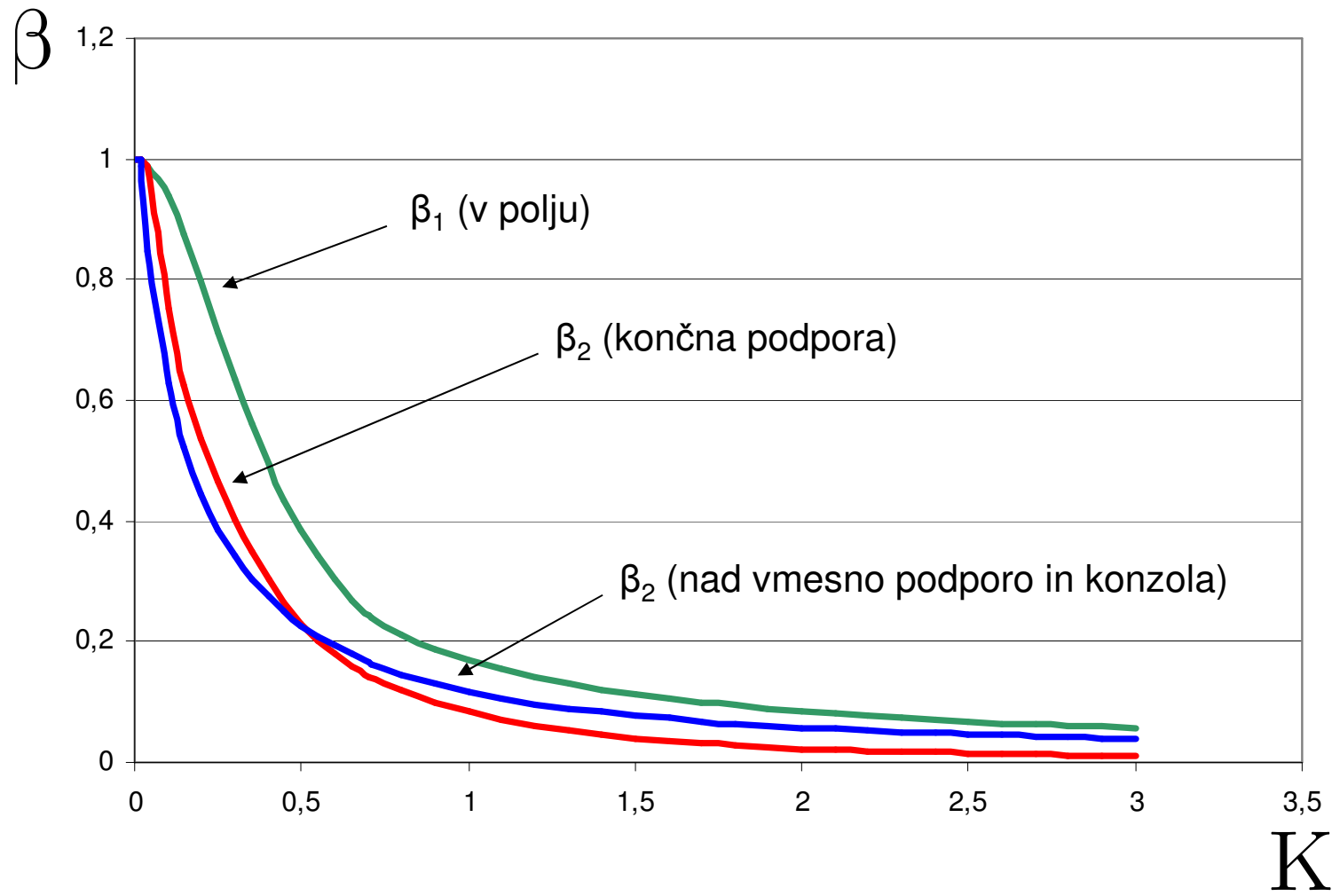
STRIŽNA PODAJNOST ELEMENTOV - MSU

$b_{\text{eff}} = \beta \cdot b \rightarrow$ efektivna širina

$$\kappa = \frac{\alpha_0 \cdot b_0}{L_e}$$

$$\alpha_0 = \sqrt{1 + \frac{A_{sl}}{b_0 \cdot t}}$$

κ	pozicija	vrednost β
$\kappa \leq 0,02$		$\beta = 1,0$
$0,02 < \kappa \leq 0,70$	v polju	$\beta = \beta_1 = \frac{1}{1 + 6,4 \cdot \kappa^2}$
	nad vmesno podpora	$\beta = \beta_2 = \frac{1}{1 + 6,0 \times \left(\kappa - \frac{1}{2500 \times \kappa} \right) + 1,6 \times \kappa^2}$
$\kappa > 0,70$	v polju	$\beta = \beta_1 = \frac{1}{5,9 \times \kappa}$
	nad vmesno podpora	$\beta = \beta_2 = \frac{1}{8,6 \times \kappa}$
vsi κ	končna podpora	$\beta_0 = (0,55 + 0,025/\kappa) \times \beta_1$, vendar $\beta_0 < \beta_1$
vsi κ	konzola	$\beta = \beta_2$ nad podpora in na koncu



STRIŽNA PODAJNOST ELEMENTOV

STRIŽNA PODAJNOST V MSN:

a) elastična, kot za MSU $\rightarrow b_{\text{eff}} = \beta \cdot b$

b) kombinacija efektov strižne podajnosti in izbočitve pločevine

$$A_{\text{eff}} = A_{\text{c,eff}} \cdot \beta_{\text{MSN}}$$

$$\alpha_0^* = \sqrt{\frac{A_{\text{c,eff}}}{b_0 \cdot t}}$$

c) elasto-plastična strižna podajnost

$$A_{\text{eff}} = A_{\text{c,eff}} \times \beta^k \geq A_{\text{c,eff}} \times \beta$$

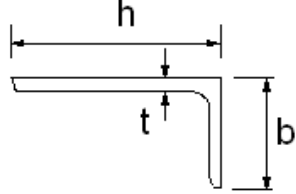
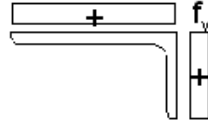
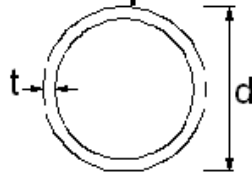
KOMPAKTOST

Internal compression parts						
				Axis of bending		
				Axis of bending		
Class	Part subject to bending	Part subject to compression	Part subject to bending and compression			
1	$c/t \leq 72\varepsilon$	$c/t \leq 33\varepsilon$	when $\alpha > 0,5$: $c/t \leq \frac{396\varepsilon}{13\alpha - 1}$ when $\alpha \leq 0,5$: $c/t \leq \frac{36\varepsilon}{\alpha}$			
2	$c/t \leq 83\varepsilon$	$c/t \leq 38\varepsilon$	when $\alpha > 0,5$: $c/t \leq \frac{456\varepsilon}{13\alpha - 1}$ when $\alpha \leq 0,5$: $c/t \leq \frac{41,5\varepsilon}{\alpha}$			
3	$c/t \leq 124\varepsilon$	$c/t \leq 42\varepsilon$	when $\psi > -1$: $c/t \leq \frac{42\varepsilon}{0,67 + 0,33\psi}$ when $\psi \leq -1^{*)}$: $c/t \leq 62\varepsilon(1 - \psi)\sqrt{(-\psi)}$			
$\varepsilon = \sqrt{235 / f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

KOMPAKTST

Outstand flanges						
Rolled sections			Welded sections			
Class	Part subject to compression	Part subject to bending and compression				
		Tip in compression		Tip in tension		
Stress distribution in parts (compression positive)						
1	$c/t \leq 9\varepsilon$	$c/t \leq \frac{9\varepsilon}{\alpha}$	$c/t \leq \frac{9\varepsilon}{\alpha\sqrt{\alpha}}$	$c/t \leq \frac{9\varepsilon}{\alpha\sqrt{\alpha}}$	$c/t \leq \frac{9\varepsilon}{\alpha\sqrt{\alpha}}$	$c/t \leq \frac{9\varepsilon}{\alpha\sqrt{\alpha}}$
2	$c/t \leq 10\varepsilon$	$c/t \leq \frac{10\varepsilon}{\alpha}$	$c/t \leq \frac{10\varepsilon}{\alpha\sqrt{\alpha}}$	$c/t \leq \frac{10\varepsilon}{\alpha\sqrt{\alpha}}$	$c/t \leq \frac{10\varepsilon}{\alpha\sqrt{\alpha}}$	$c/t \leq \frac{10\varepsilon}{\alpha\sqrt{\alpha}}$
Stress distribution in parts (compression positive)						
3	$c/t \leq 14\varepsilon$	$c/t \leq 21\varepsilon\sqrt{k_\sigma}$ For k_σ see EN 1993-1-5				
$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

KOMPAKTOST

Glej tudi "Previsni deli pasnic" (list 2 od 3)		<p style="text-align: center;">Kotniki</p> 		Ne velja za kotnike v zveznem kontaktu z ostalimi komponentami		
Razred kompaktnosti	Prerez v tlaku					
Razporeditev napetosti po prerezu (tlačne pozitivne)						
3	$h/t \leq 15\varepsilon : \frac{b+h}{2t} \leq 11,5\varepsilon$					
<p>Cevni prerezi</p> 						
Razred kompaktnosti	Prerez v tlaku in/ali v upogibu					
1	$d/t \leq 50\varepsilon^2$					
2	$d/t \leq 70\varepsilon^2$					
3	$d/t \leq 90\varepsilon^2$					
OPOMBA Za $d/t > 90\varepsilon^2$ glej EN 1993-1-6.						
$\varepsilon = \sqrt{235 / f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71
	ε^2	1,00	0,85	0,66	0,56	0,51

IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

NEOJAČENE PLOČEVINE

$$A_{c,eff} = \rho \times A_c$$

- notranji elementi prečnega prereza

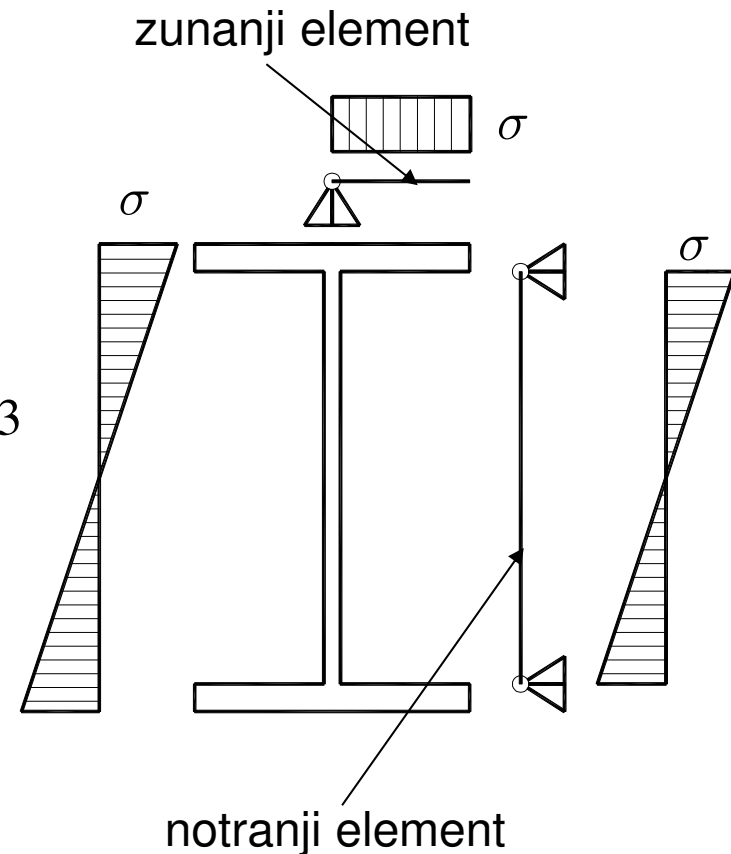
$$\rho = 1,0 \quad \text{za} \quad \bar{\lambda}_p \leq 0,673$$

$$\rho = \frac{\bar{\lambda}_p - 0,055 \times (3 + \psi)}{\bar{\lambda}_p^2} \leq 1,0 \quad \text{za} \quad \bar{\lambda}_p > 0,673$$

- zunanji elementi prečnega prereza

$$\rho = 1,0 \quad \text{za} \quad \bar{\lambda}_p \leq 0,748$$

$$\rho = \frac{\bar{\lambda}_p - 0,188}{\bar{\lambda}_p^2} \leq 1,0 \quad \text{za} \quad \bar{\lambda}_p > 0,748$$



IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

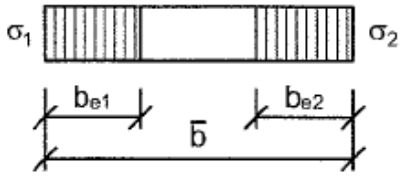
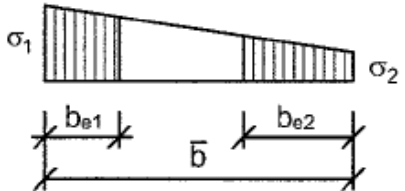
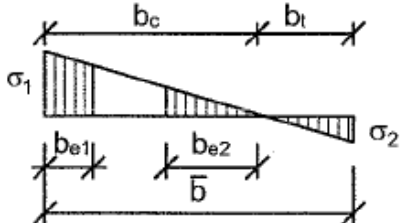
$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}}{t \times 28,4 \times \varepsilon \times \sqrt{k_\sigma}} \longrightarrow \text{relativna vitkost}$$

$$\sigma_{cr} = k_\sigma \times \sigma_E = k_\sigma \frac{\pi^2 \times E}{12 \times (1 - \nu^2)} \left(\frac{t}{b} \right)^2 \longrightarrow \text{el. kritična napetost}$$

$$\varepsilon = \sqrt{\frac{235}{f_y \left[N / mm^2 \right]}} \longrightarrow \text{materialni faktor}$$

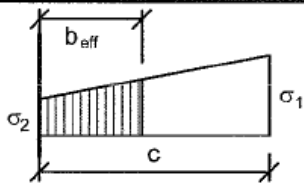
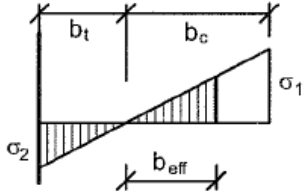
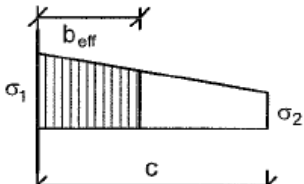
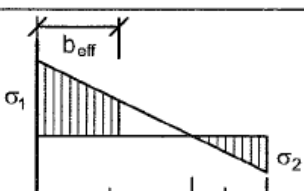
IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

NOTRANJI TLAČENI ELEMENTI

Stress distribution (compression positive)				Effective ^p width b_{eff}		
				$\underline{\psi = 1:}$ $b_{eff} = \rho \bar{b}$ $b_{e1} = 0,5 b_{eff} \quad b_{e2} = 0,5 b_{eff}$		
				$\underline{1 > \psi \geq 0:}$ $b_{eff} = \rho \bar{b}$ $b_{e1} = \frac{2}{5 - \psi} b_{eff} \quad b_{e2} = b_{eff} - b_{e1}$		
				$\underline{\psi < 0:}$ $b_{eff} = \rho b_c = \rho \bar{b} / (1 - \psi)$ $b_{e1} = 0,4 b_{eff} \quad b_{e2} = 0,6 b_{eff}$		
$\psi = \sigma_2 / \sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1	$-1 > \psi > -3$
Buckling factor k_σ	4,0	$8,2 / (1,05 + \psi)$	7,81	$7,81 - 6,29\psi + 9,78\psi^2$	23,9	$5,98 (1 - \psi)^2$

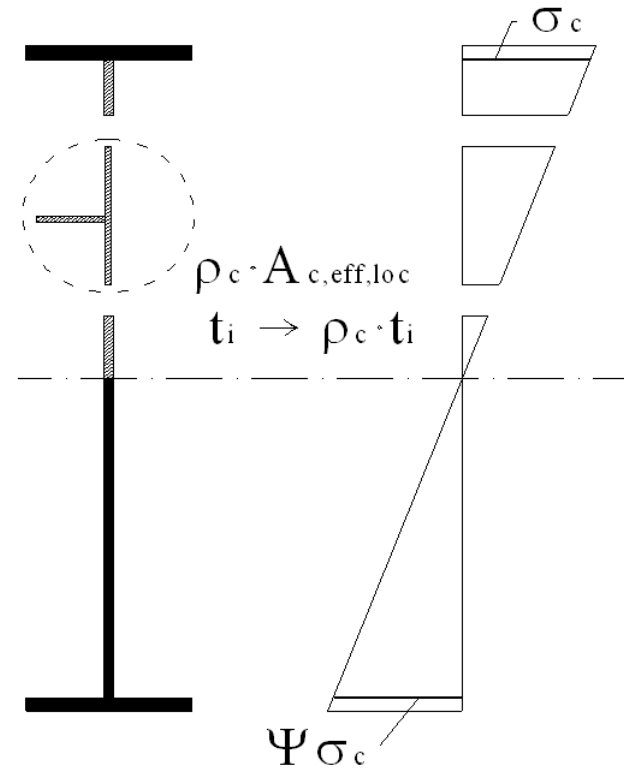
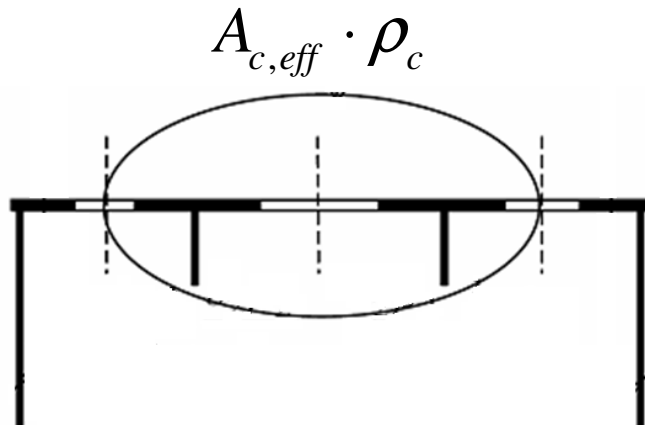
IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

ZUNANJI TLAČENI ELEMENTI

Stress distribution (compression positive)		Effective ^p width b_{eff}			
		$1 \geq \psi \geq 0:$ $b_{eff} = \rho c$			
		$\psi < 0:$ $b_{eff} = \rho b_c = \rho c / (1 - \psi)$			
$\psi = \sigma_2 / \sigma_1$	1	0	-1	$1 \geq \psi \geq -3$	
Buckling factor k_σ	0,43	0,57	0,85	$0,57 - 0,21\psi + 0,07\psi^2$	
		$1 \geq \psi \geq 0:$ $b_{eff} = \rho c$			
		$\psi < 0:$ $b_{eff} = \rho b_c = \rho c / (1 - \psi)$			
$\psi = \sigma_2 / \sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1
Buckling factor k_σ	0,43	$0,578 / (\psi + 0,34)$	1,70	$1,7 - 5\psi + 17,1\psi^2$	23,8

IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

$$\left. \begin{aligned} A_{c,eff} &= \rho_c \times A_{c,eff,loc} + \sum b_{edge,eff} \cdot t \\ A_{c,eff,loc} &= A_{sl,eff} + \sum_c \rho_{loc} \cdot b_{c,loc} \cdot t \end{aligned} \right\} \begin{array}{l} A_{eff} \\ W_{eff} \end{array}$$

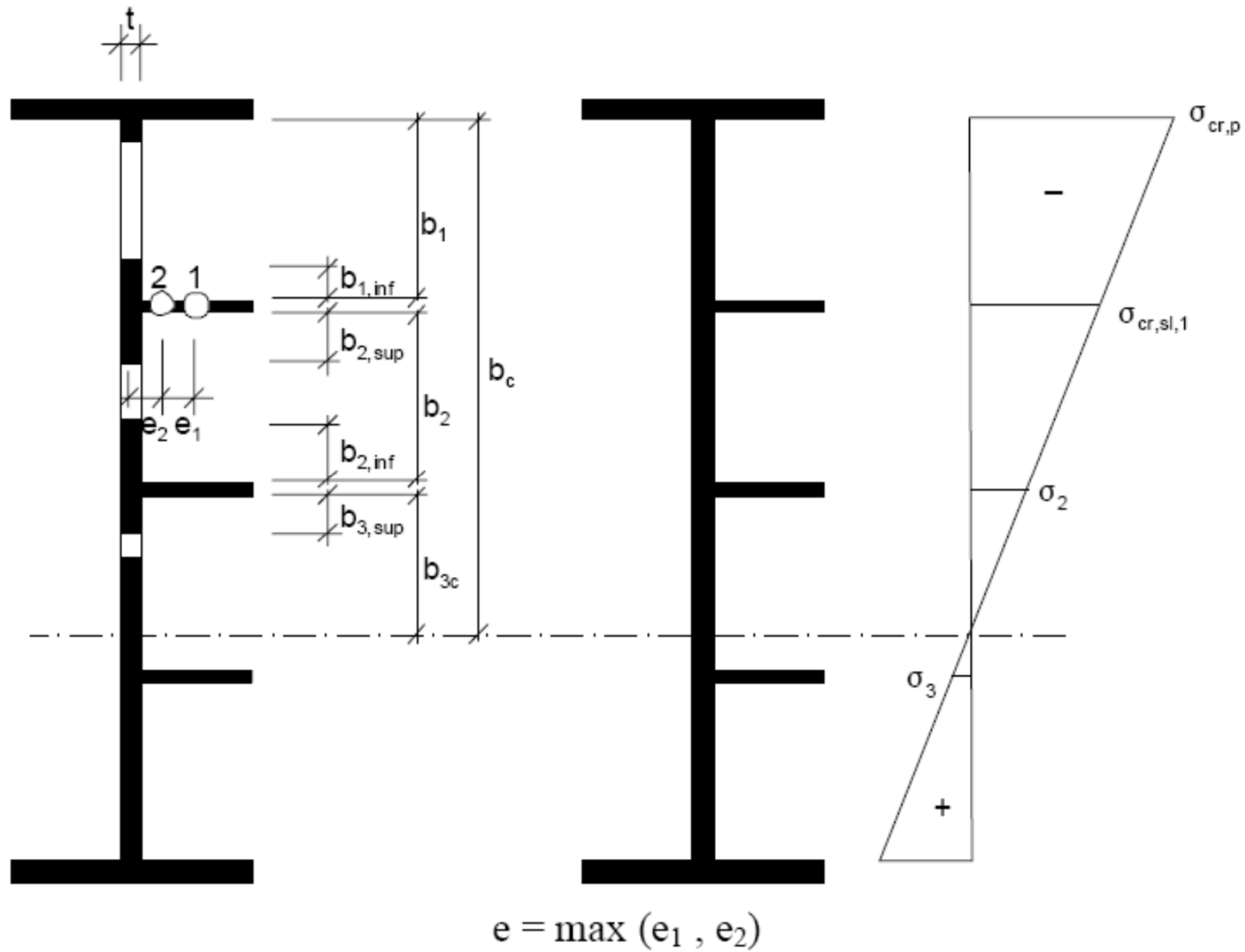


$$A_{c,eff} = \rho_c \cdot A_{c,eff,loc} + t \cdot b_{1,edge,eff} + t \cdot b_2$$

KONTROLA:
$$\eta_1 = \frac{N_{Ed}}{f_y \cdot A_{eff}} + \frac{M_{Ed} + N_{Ed} \cdot e_N}{f_y \cdot W_{y,eff}} \leq 1,0$$

γ_{M0} γ_{M0}

IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI



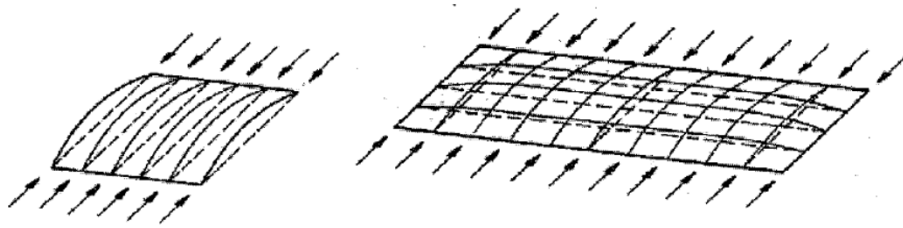
IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

DOLOČITEV PRIPADAJOČIH ŠIRIN PLOČEVINE

	width for gross area	width for effective area according to EN 1993-1-5, Table 4.1	condition for ψ_i
$b_{1,inf}$	$\frac{3 - \psi_1}{5 - \psi_1} b_1$	$\frac{3 - \psi_1}{5 - \psi_1} b_{1,eff}$	$\psi_1 = \frac{\sigma_{cr,sl,1}}{\sigma_{cr,p}} > 0$
$b_{2,sup}$	$\frac{2}{5 - \psi_2} b_2$	$\frac{2}{5 - \psi_2} b_{2,eff}$	$\psi_2 = \frac{\sigma_2}{\sigma_{cr,sl,1}} > 0$
$b_{2,inf}$	$\frac{3 - \psi_2}{5 - \psi_2} b_2$	$\frac{3 - \psi_2}{5 - \psi_2} b_{2,eff}$	$\psi_2 > 0$
$b_{3,sup}$	$0,4 b_{c3}$	$0,4 b_{c3,eff}$	$\psi_3 = \frac{\sigma_3}{\sigma_2} < 0$

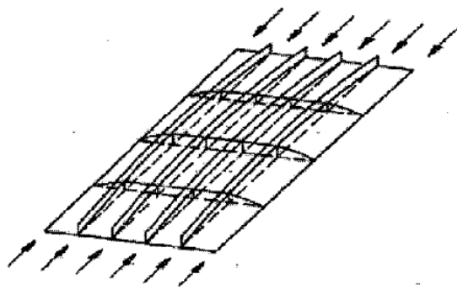
IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

INTERAKCIJA IZBOČITVE MED UPOGIBNIM UKLONOM IN OJAČENO PLOČEVINO



a) column-like behaviour of plates without longitudinal supports

b) column-like behaviour of an unstiffened plate with a small aspect ratio α

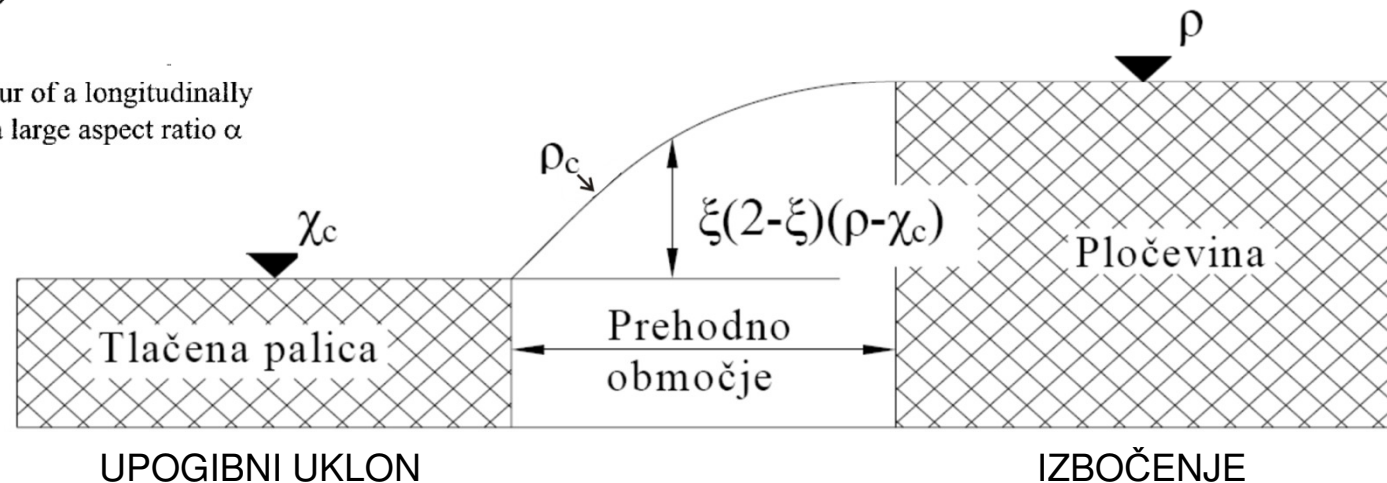


c) column-like behaviour of a longitudinally stiffened plate with a large aspect ratio α

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

↑ IZBOČENJE
↑ UKLON

$$\xi = \frac{\sigma_{cr,p}}{\sigma_{cr,c}} - 1, \text{ vendar } 0 \leq \xi \leq 1$$



IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

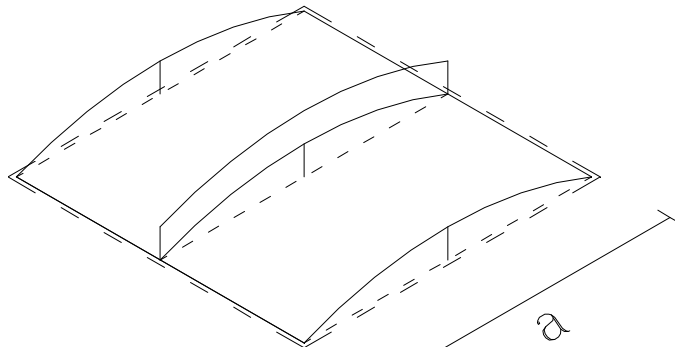
UKLON OJAČITVE

$$\chi_c = \chi_c(\bar{\lambda}_c, \alpha_e)$$

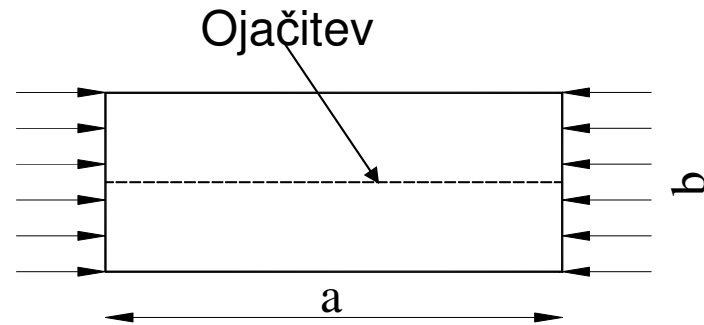
$$\bar{\lambda}_c = \sqrt{\frac{\beta_{A,c} \cdot f_y}{\sigma_{cr,c}}}$$

$$\beta_{A,c} = \frac{A_{sl,1,eff}}{A_{sl,1}}$$

$$\sigma_{cr,sl} = \frac{\pi^2 \cdot E \cdot I_{sl,1}}{A_{sl,1} \cdot a^2}$$



Upogibni uklon



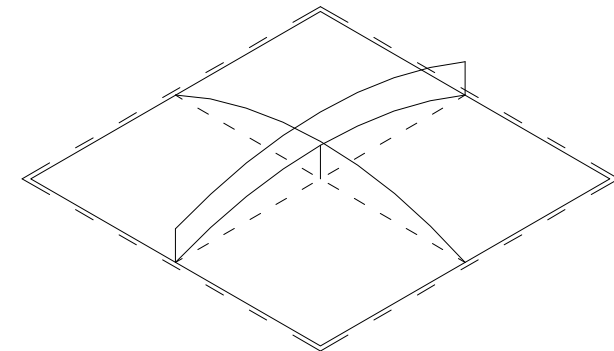
IZBOČITEV PANELA

$$\rho = \frac{\bar{\lambda}_p - 0,55(3 + \psi)}{\bar{\lambda}_p^2} \leq 1,0$$

$$\bar{\lambda}_p = \sqrt{\frac{\beta_{A,c} \cdot f_y}{\sigma_{cr,p}}}$$

$$\beta_{A,c} = \frac{A_{c,eff,loc}}{A_c}$$

$$\sigma_{cr,p} = k_{\sigma,p} \cdot \sigma_E$$



Izbočenje

IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

KRITIČNA UKLONSKA NAPETOST

Neojačena pločevina

$$\sigma_{cr,c} = \frac{\pi^2 Et^3}{12(1-\nu^2)a^2}$$

Ojačena pločevina

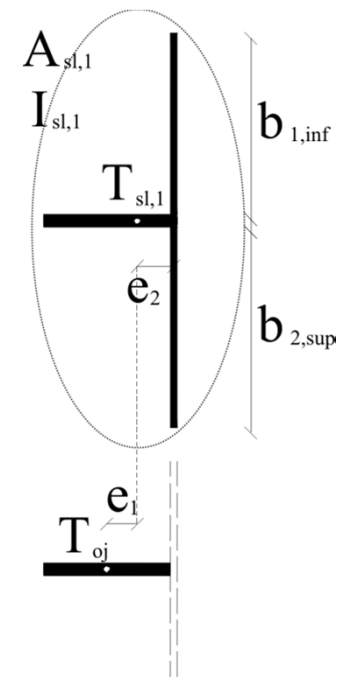
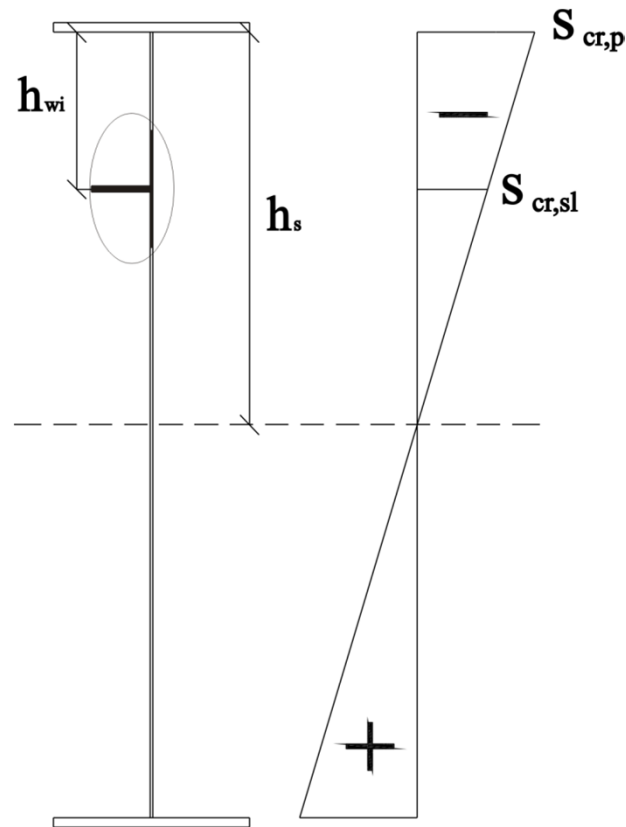
$$\sigma_{cr,sl} = \frac{\pi^2 EI_{sl,1}}{A_{sl,1}a^2}$$

$$\sigma_{cr,c} = \frac{h_s}{h_s - h_{wi}} \sigma_{cr,sl}$$

$$\alpha_e = \alpha + \frac{0,09}{i/e}$$

$$i = \sqrt{\frac{I_{sl,1}}{A_{sl,1}}} \quad ; \quad e = \max(e_1, e_2)$$

$$\alpha = \begin{cases} 0,34 & \text{(krivulja b) za zaprte ojačitve} \\ 0,49 & \text{(krivulja c) za odprte ojačitve} \end{cases}$$



IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

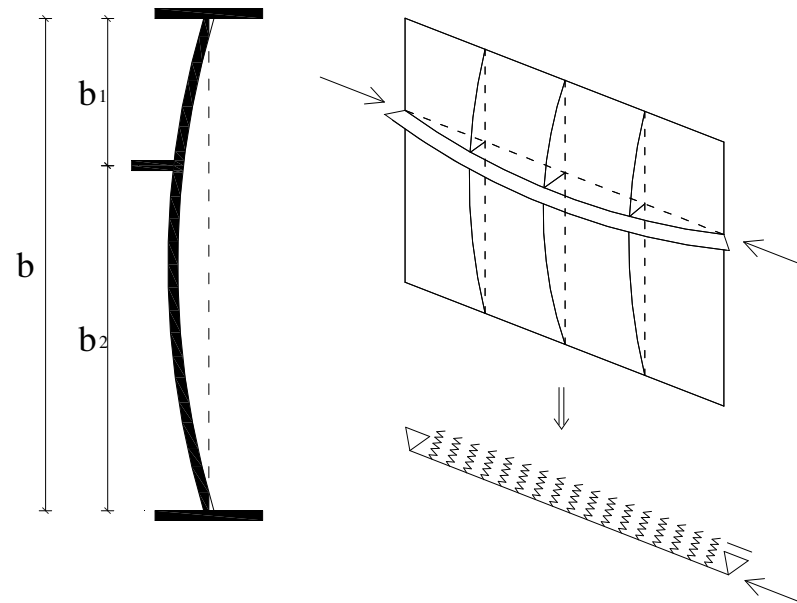
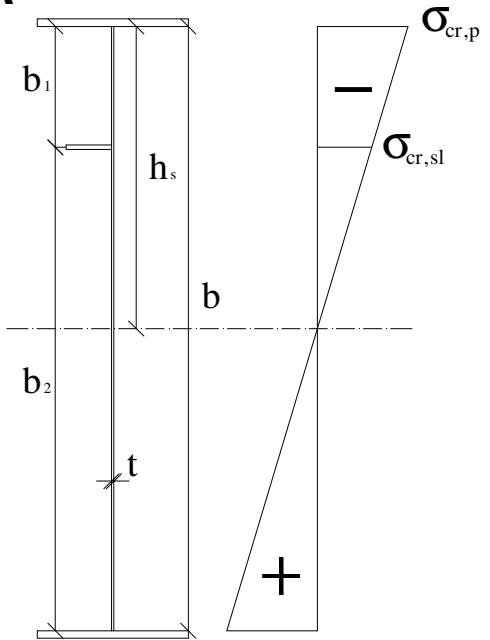
KRITIČNA NAPETOST IZBOČITVE PANELA

Ena ali dve vzdolžni ojačitvi (nosilec na el. podlagi)

$$\sigma_{cr,sl} = \frac{1,05E}{A_{sl,i}} \frac{\sqrt{I_{sl,i} t^3 b}}{b_1 b_2} \quad \text{če } a > a_c$$

$$\sigma_{cr,sl} = \frac{\pi^2 E I_{sl,i}}{A_{sl,i} a^2} + \frac{E t^3 b a^2}{4\pi^2 (1-\nu^2) A_{sl,i} b_1^2 b_2^2} \quad \text{če } a \leq a_c \rightarrow \sigma_{cr,p} = \frac{h_s}{h_s - h_1} \sigma_{cr,sl}$$

$$a_c = 4,33 \sqrt[4]{\frac{I_{sl,i} b_1^2 b_2^2}{t^3 b}}$$



IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

KRITIČNA NAPETOST IZBOČITVE PANELA

Tri ali več enakomerno razporejenih vzdolžnih ojačitev (ortotropna plošča)

$$k_{\sigma,p} = \frac{2\left((1+\alpha^2)^2 + \gamma - 1\right)}{\alpha^2(\psi+1)(1+\delta)} \quad \text{če } \alpha \leq \sqrt[4]{\gamma}$$

$$k_{\sigma,p} = \frac{4(1+\sqrt{\gamma})}{(\psi+1)(1+\delta)} \quad \text{če } \alpha > \sqrt[4]{\gamma}$$

$$\alpha = \frac{a}{b} \geq 0,5 \quad ; \quad \gamma = \frac{I_{sl}}{I_p} \quad ; \quad I_p = \frac{b \cdot t^3}{12 \cdot (1-\nu^2)}$$

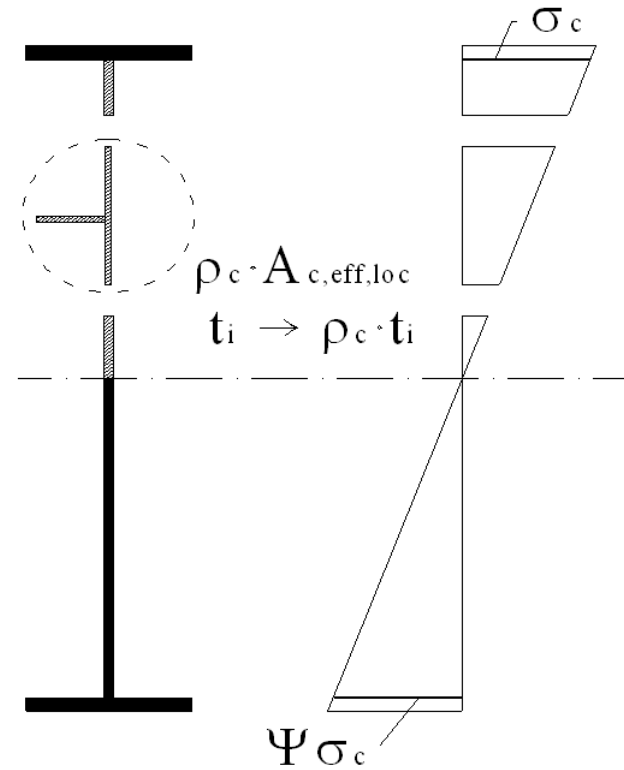
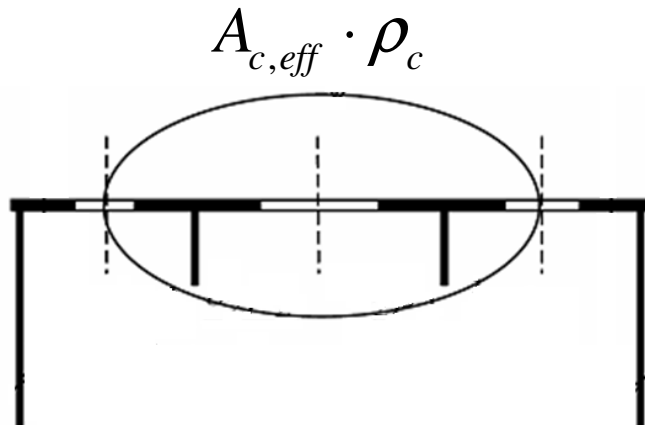
$$\longrightarrow \sigma_{cr,p} = k_{\sigma,p} \sigma_E = k_{\sigma,p} \frac{\pi^2 E t^2}{12(1-\nu^2) b^2}$$

I_{sl} – vztrajnostni moment bruto prereza celotne pločevine



IZBOČENJE PLOČEVIN ZARADI NORMALNIH NAPETOSTI

$$\left. \begin{aligned} A_{c,eff} &= \rho_c \times A_{c,eff,loc} + \sum b_{edge,eff} \cdot t \\ A_{c,eff,loc} &= A_{sl,eff} + \sum_c \rho_{loc} \cdot b_{c,loc} \cdot t \end{aligned} \right\} \begin{array}{l} A_{eff} \\ W_{eff} \end{array}$$



$$A_{c,eff} = \rho_c \cdot A_{c,eff,loc} + t \cdot b_{1,edge,eff} + t \cdot b_2$$

KONTROLA:
$$\eta_1 = \frac{N_{Ed}}{f_y \cdot A_{eff}} + \frac{M_{Ed} + N_{Ed} \cdot e_N}{f_y \cdot W_{y,eff}} \leq 1,0$$

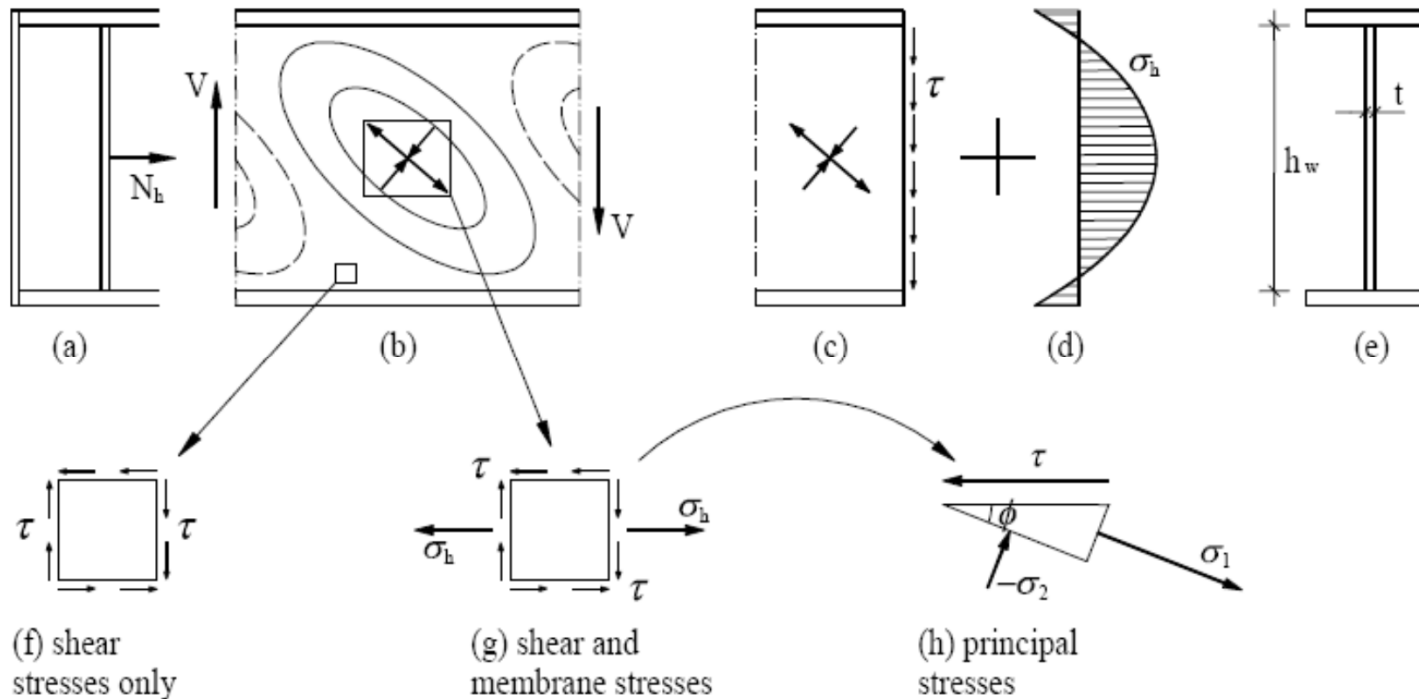
γ_{M0} γ_{M0}

IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI

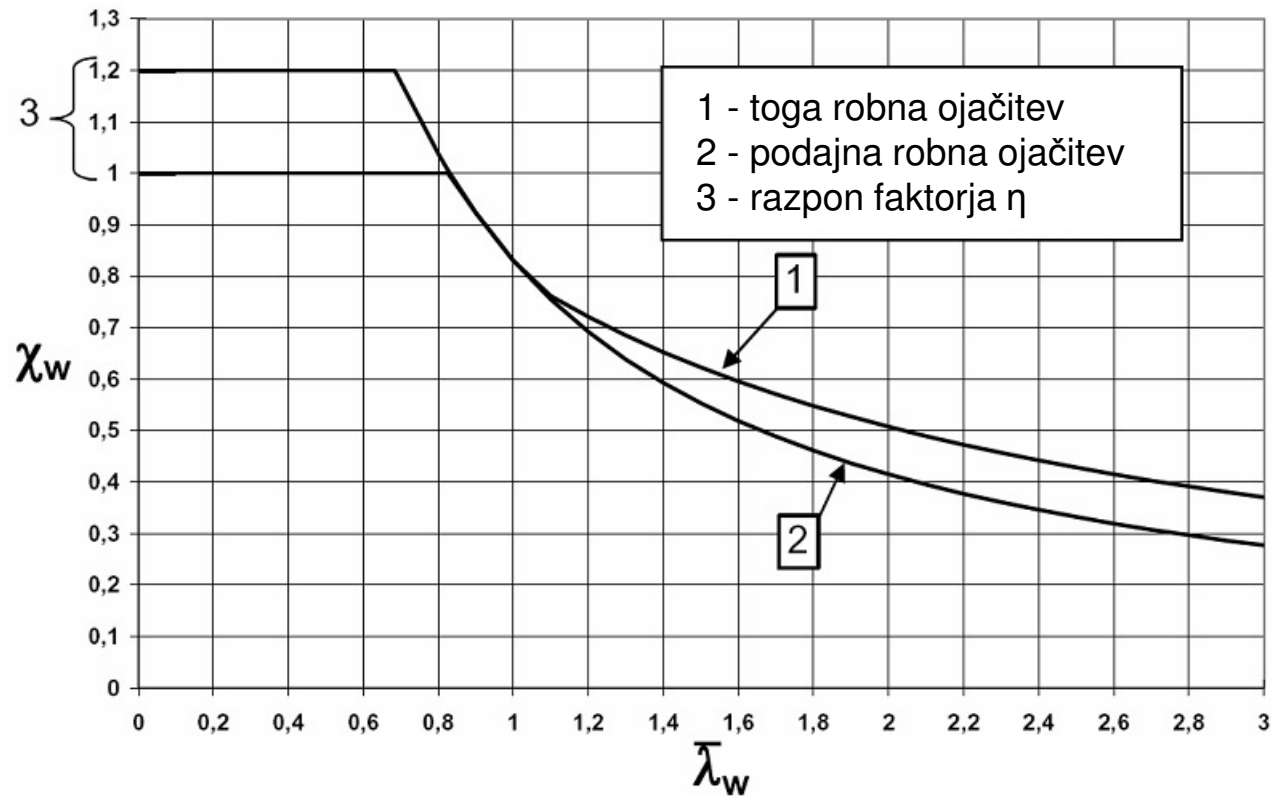
$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leq \frac{\eta \cdot f_{yw} \cdot h_w \cdot t_w}{\sqrt{3} \cdot \gamma_{M1}}$$

PRISPEVEK STOJINE

$$V_{bw,Rd} = \frac{\chi_w \cdot f_{yw} \cdot b \cdot t}{\sqrt{3} \cdot \gamma_{M1}}$$



IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI



Funkcija strižne nosilnosti stojine

$$\bar{\lambda}_w < 0,83/\eta \rightarrow \chi_w = \eta$$

$$0,83/\eta \leq \bar{\lambda}_w < 1,08 \rightarrow \chi_w = 0,83/\bar{\lambda}_w$$

$$\bar{\lambda}_w \geq 1,08 \rightarrow \begin{cases} \chi_w = 1,37/(0,7 + \bar{\lambda}_w) & \text{toga robna ojačitev} \\ \chi_w = 0,83/\bar{\lambda}_w & \text{podajna robna ojačitev} \end{cases}$$

IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI

$$\bar{\lambda}_w = \sqrt{\frac{f_y}{\tau_{cr} \sqrt{3}}} = \frac{h_w}{37,4 \varepsilon \sqrt{k_\tau}} \Rightarrow \chi_w \Rightarrow V_{bw,Rd} = \frac{\chi_w f_{yw} h_w t}{\gamma_{M1} \sqrt{3}}$$

PRISPEVEK STOJINE

Pločevina z ali brez vzdolžnih ojačitev

$$k_\tau = 5,34 + 4,00 \left(\frac{h_w}{a} \right)^2 + k_{\tau st} \quad \text{če } a/h_w \geq 1$$

$$k_\tau = 4,00 + 5,34 \left(\frac{h_w}{a} \right)^2 + k_{\tau st} \quad \text{če } a/h_w < 1$$

$$k_{\tau st} = \max \left(9 \left(\frac{h_w}{a} \right)^2 \sqrt[4]{\left(\frac{I_{sl}}{t^3 h_w} \right)^3}; \quad \frac{2,1}{t} \sqrt[3]{\frac{I_{sl}}{h_w}} \right)$$

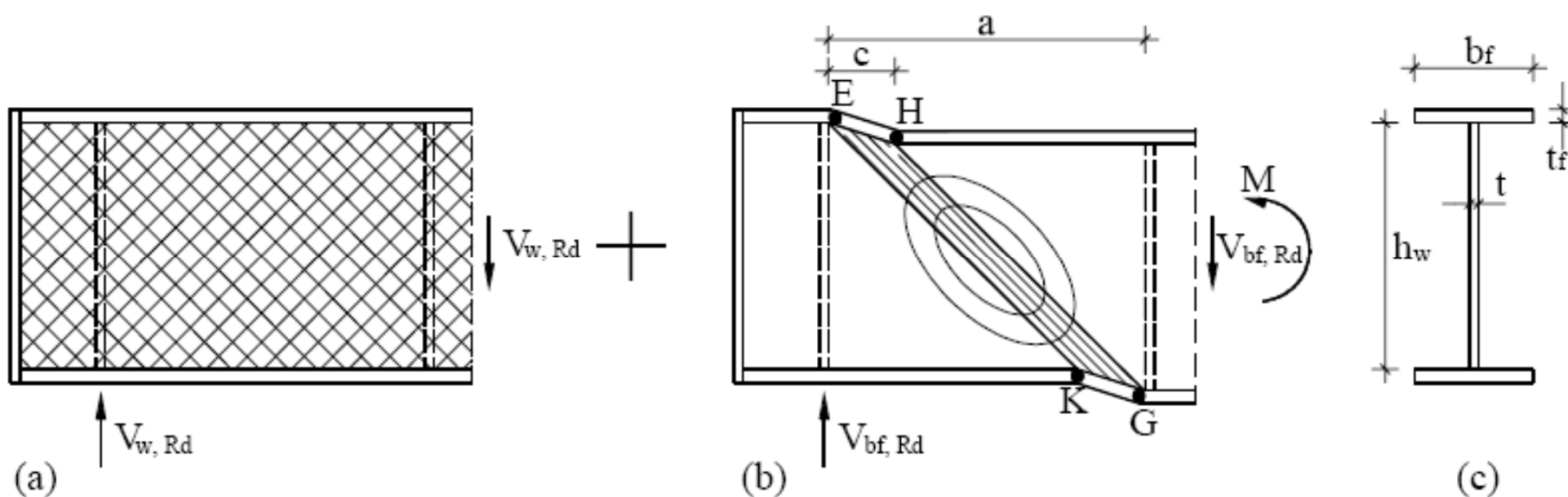
Pločevina z eno ali dvema vzdolžnima ojačitvama, pri pogoju $\alpha < 3$

$$k_\tau = 4,1 + \frac{6,3 + 0,18 \frac{I_{sl}}{t^3 h_w}}{\alpha^2} + 2,2 \sqrt[3]{\frac{I_{sl}}{t^3 h_w}}$$

IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI

PRISPEVEK PASNIC

$$V_{bf,Rd} = \frac{b_f \cdot t_f \cdot f_{yf}}{c \cdot \gamma_{M1}} \left(1 - \left(\frac{M_{Ed}}{M_{f,Rd}} \right)^2 \right) \quad c = a \left(0,25 + 1,6 \frac{M_{pl,f}}{M_{pl,w}} \right)$$



- ustrezna redukcija v primeru dodatnih osnih sil, ki jih prevzamejo pasnice

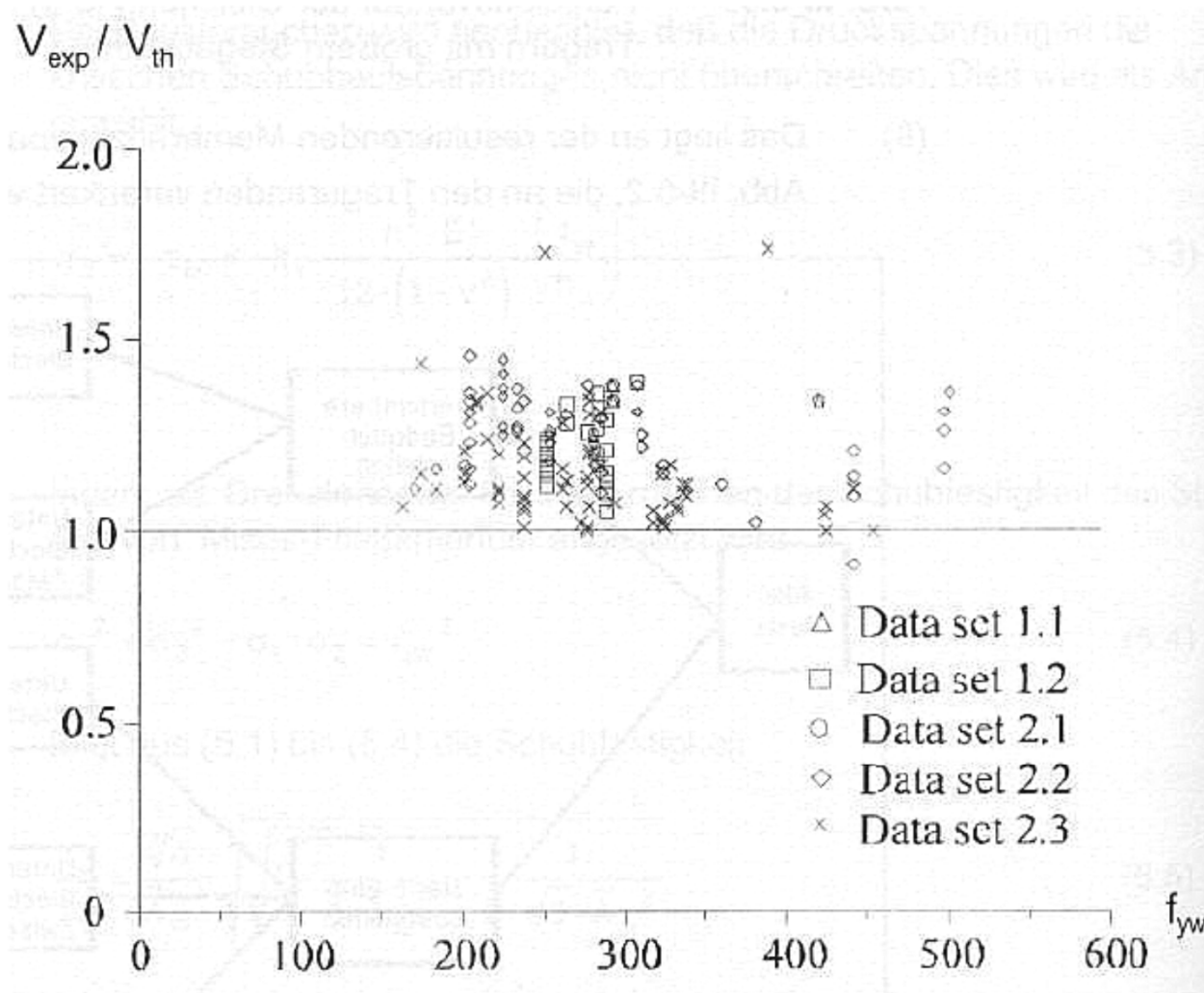
IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI

KONTROLA

$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leq \frac{\eta \cdot f_{yw} \cdot h_w \cdot t_w}{\sqrt{3} \cdot \gamma_{M1}}$$

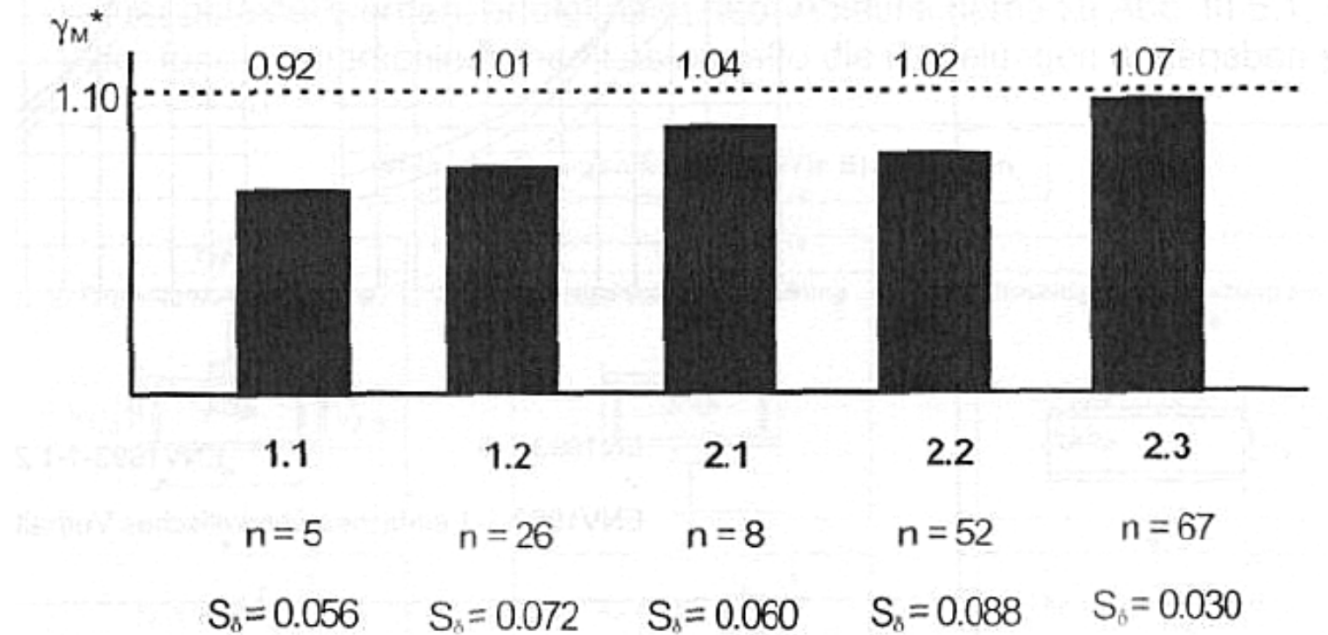
$$\eta_3 = \frac{V_{Ed}}{V_{b,Rd}} \leq 1,0$$

IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI



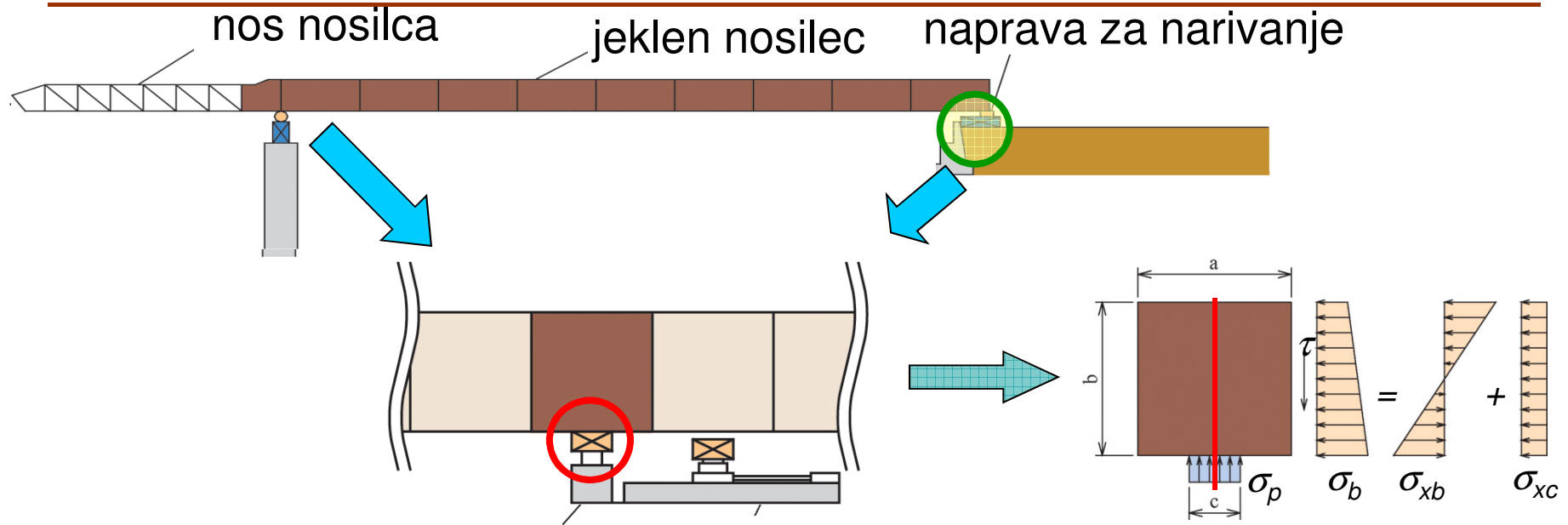
Primerjava eksperimentalnih in teoretičnih vrednosti strižne nosilnosti pločevin

IZBOČENJE PLOČEVIN ZARADI STRIŽNIH NAPETOSTI



Delni varnostni faktor γ_{M1} za strižno nosilnost pločevin

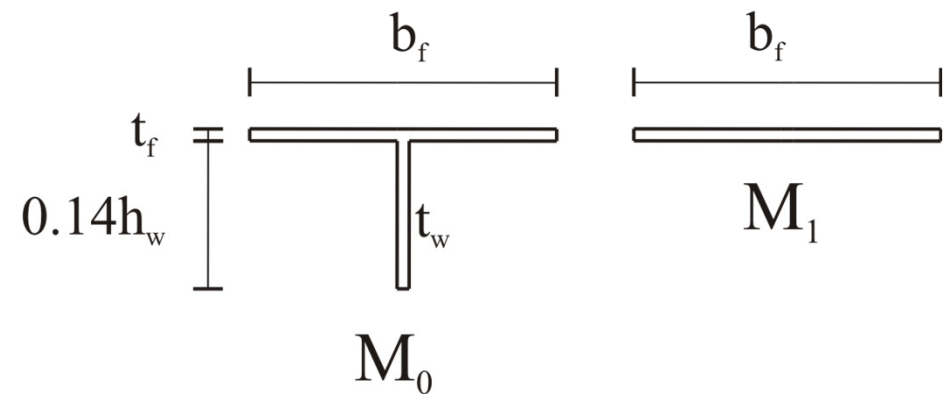
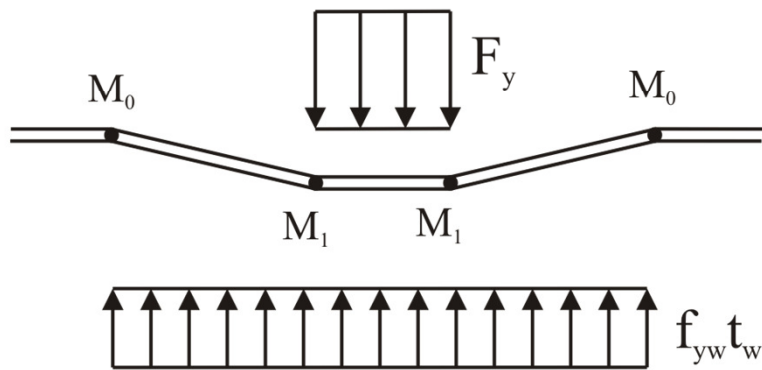
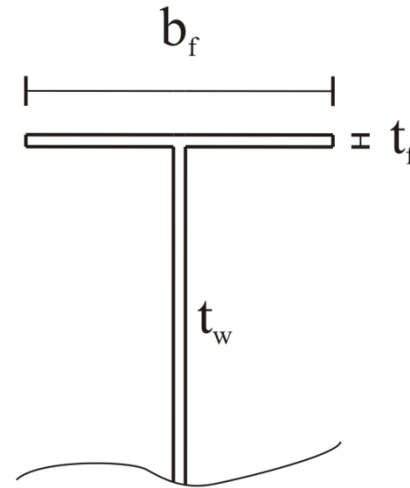
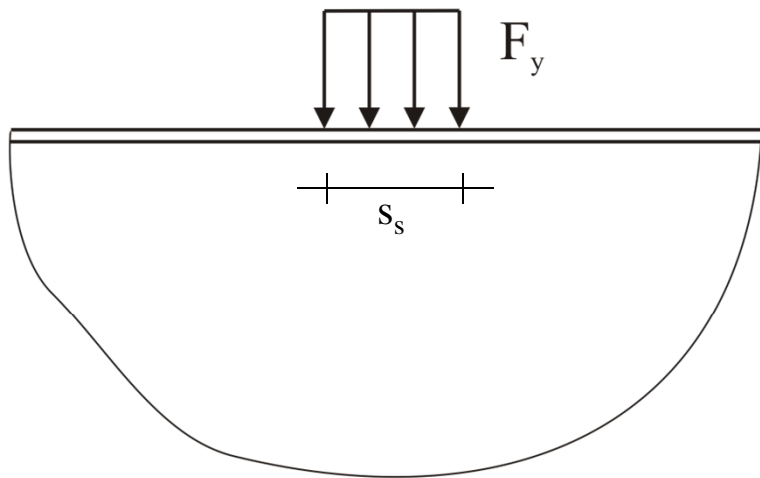
VNOS KONCENTRIRANE SILE



vnos koncentrirane sile



VNOS KONCENTRIRANE SILE



Mehanski model plastične nosilnosti pri vnosu koncentrirane sile v stojino

VNOS KONCENTRIRANE SILE

Vnos obtežbe:

- (a) preko pasnice in prevzem s strižnimi silami v stojini
- (b) preko ene pasnice in prenos preko stojine direktno do druge pasnice
- (c) preko ene pasnice ob neojačenem robu

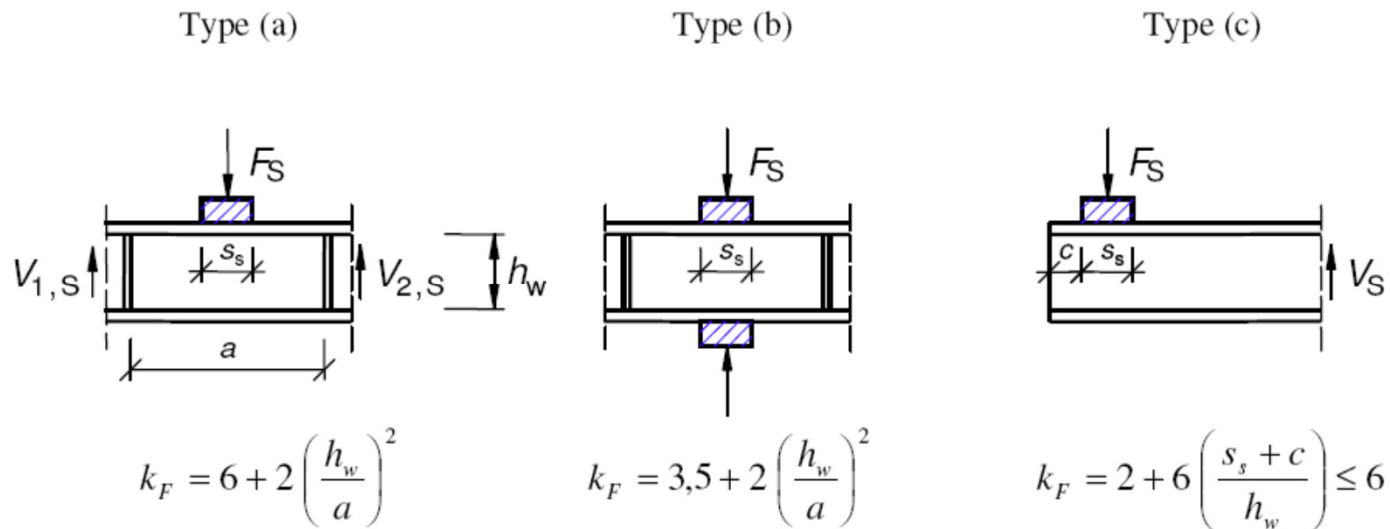


Figure 6.1: Buckling coefficients for different types of load application

VNOS KONCENTRIRANE SILE

Dolžina vnosa sile s_s :

- raznos sile v razmerju 1:1
- $s_s < h_w$
- v primeru več koncentriranih sil je potrebna kontrola individualnih sil in skupne obtežbe, kjer je s_s razdalja med krajnima silama

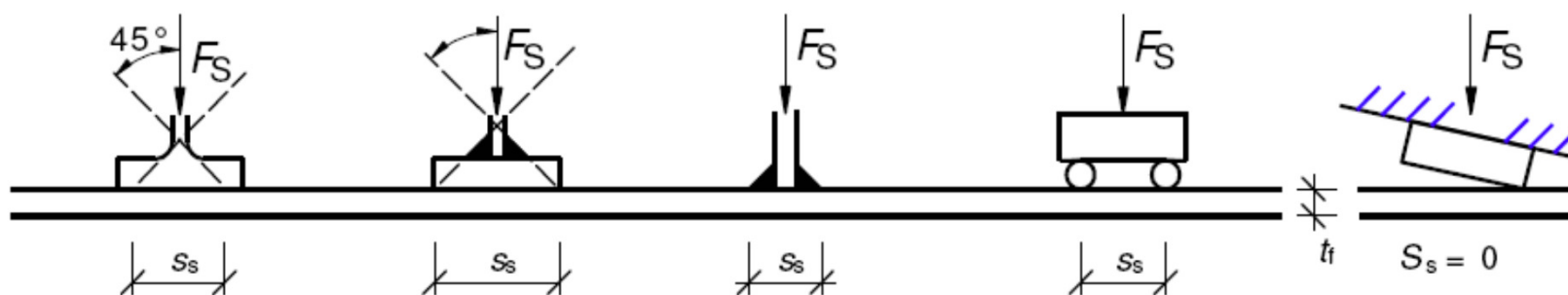


Figure 6.2: Length of stiff bearing

VNOS KONCENTRIRANE SILE

- Redukcijski faktor χ_F

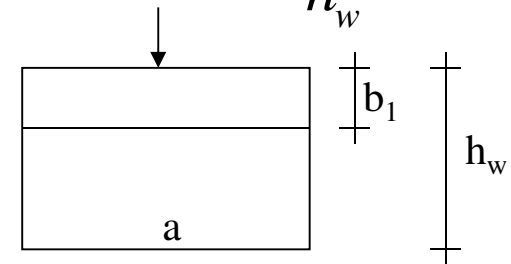
$$\chi_F = \frac{0,5}{\bar{\lambda}_F} \leq 1,0 \quad \bar{\lambda}_F = \sqrt{\frac{F_y}{F_{cr}}}$$

$$F_y = l_y \cdot t_w \cdot f_{yw}$$

$$F_{cr} = 0,9 \cdot k_F \cdot E \cdot \frac{t_w^3}{h_w}$$

Stojine brez vzdolžnih ojačitev: $k_F \rightarrow$ slika 6.1

Stojine z vzdolžnimi ojačitvami:



$$k_F = 6 + 2 \left[\frac{h_w}{a} \right]^2 + \left[5,44 \frac{b_1}{a} - 0,21 \right] \sqrt{\gamma_s} \quad \text{za} \quad 0,05 \leq \frac{b_1}{a} \leq 0,3 \text{ in } \frac{b_1}{h_w} \leq 0,3 \text{ in tip obte\u017ebe (a)}$$

$$\gamma_s = 10,9 \frac{l_{st,1}}{h_w t_w^3} \leq 13 \left[\frac{a}{h_w} \right]^3 + 210 \left[0,3 - \frac{b_1}{a} \right]$$

b_1 širina obremenjenega podpanela, vzeta kot čista razdalja med obremenjeno pasnico in ojačitvijo

VNOS KONCENTRIRANE SILE

- Efektivno obremenjena dolžina l_y

$$l_y = s_s + 2 t_f (1 + \sqrt{m_1 + m_2}) \leq a \quad \text{za tip obtežba (a) in (b)}$$

$$l_y = \min \begin{cases} l_e + t_f \sqrt{\frac{m_1}{2} + \left(\frac{l_e}{t_f}\right)^2 + m_2} \\ l_e + t_f \sqrt{m_1 + m_2} \end{cases} \quad \text{za tip obtežba (c)}$$

$$m_1 = \frac{f_{yf} b_f}{f_{yw} t_w}$$

$$m_2 = 0,02 \left(\frac{h_w}{t_f}\right)^2 \quad \text{za } \bar{\lambda}_F \geq 0,5$$

$$m_2 = 0 \quad \text{za } \bar{\lambda}_F \leq 0,5$$

Škatlasti nosilci: $b_f = 15 e t_f$

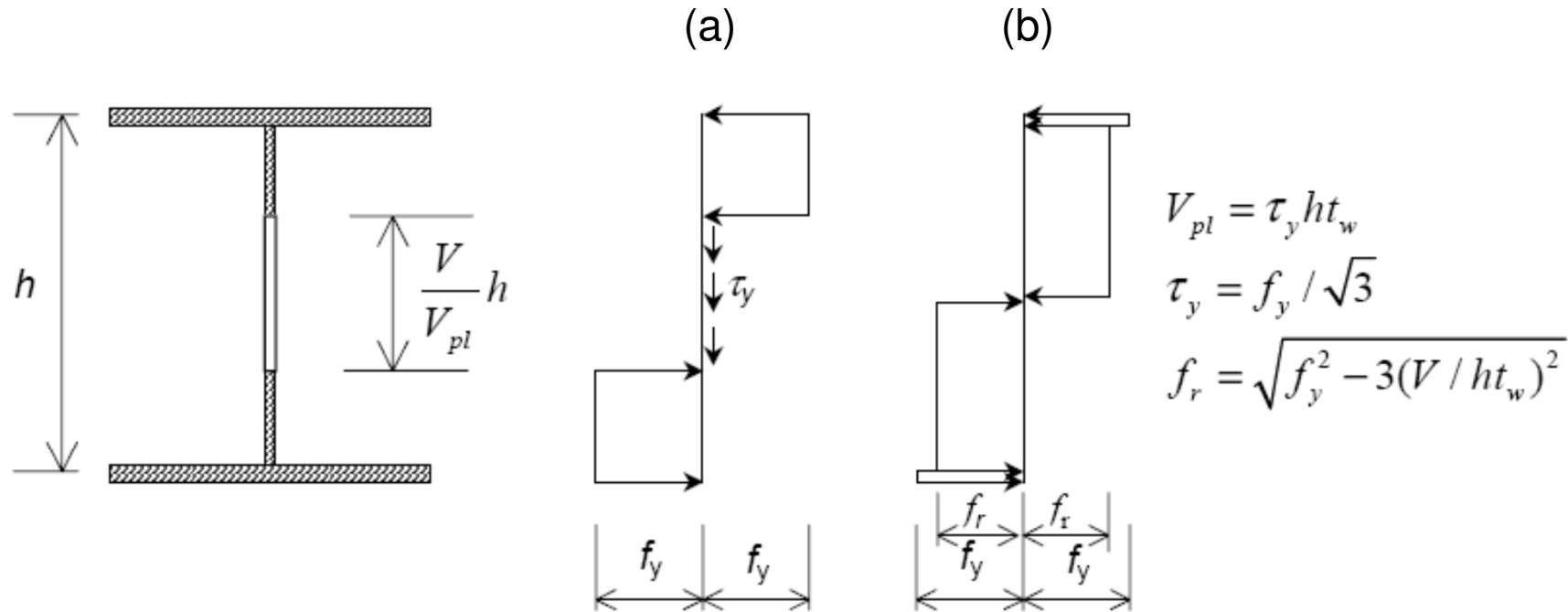
VNOS KONCENTRIRANE SILE

Kontrola:

$$F_{Rd} = \frac{\chi_F F_y}{\gamma_{M1}}$$

$$\eta_2 = \frac{F_{Ed}}{F_{Rd}} \leq 1,0$$

INTERAKCIJA MED STRIŽNIMI SILAMI, UPOGIBNIM MOMENTOM IN OSNO SILO



I profil v 1. ali 2. razredu kompaktnosti, podvržen upogibu in strigu in dve možni razporeditvi napetosti, kompatibilni z von Misesovim kriterijem tečenja

INTERAKCIJA MED STRIŽNIMI SILAMI, UPOGIBNIM MOMENTOM IN OSNO SILO

(a)

$$\frac{M_{Ed}}{M_{pl,Rd}} + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right) \cdot \left(\frac{V_{Ed}}{V_{pl,Rd}}\right)^2 = 1$$

(b)

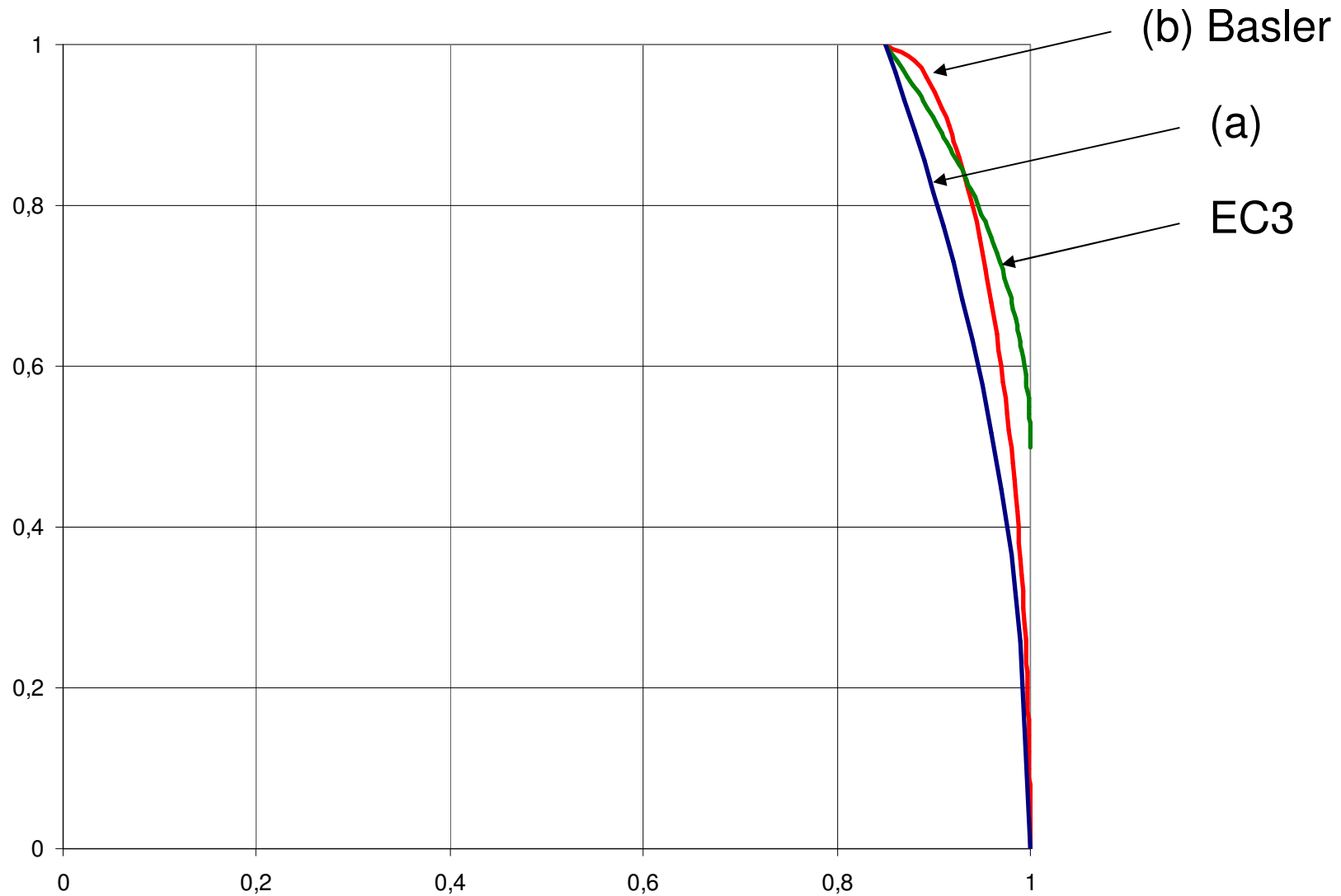
$$\frac{M_{Ed}}{M_{pl,Rd}} + \left(1 - \frac{M_{f,Ed}}{M_{pl,Rd}}\right) \cdot \left(1 - \sqrt{1 - \left(\frac{V_{Ed}}{V_{pl,Rd}}\right)^2}\right) = 1$$

EC3:

$$\frac{M_{Ed}}{M_{pl,Rd}} + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right) \cdot \left(\frac{2 \cdot V_{Ed}}{V_{pl,Rd}} - 1\right)^2 = 1 \quad \text{če } V > 0,5 \cdot V_{pl}$$

INTERAKCIJA MED STRIŽNIMI SILAMI, UPOGIBNIM MOMENTOM IN OSNO SILO

INTERAKCIJSKE KRIVULJE ZA KOMBINACIJO STRIGA IN UPOGIBA
NOSILCA V 1. oz. 2. RAZREDU KOMPAKTNOSTI



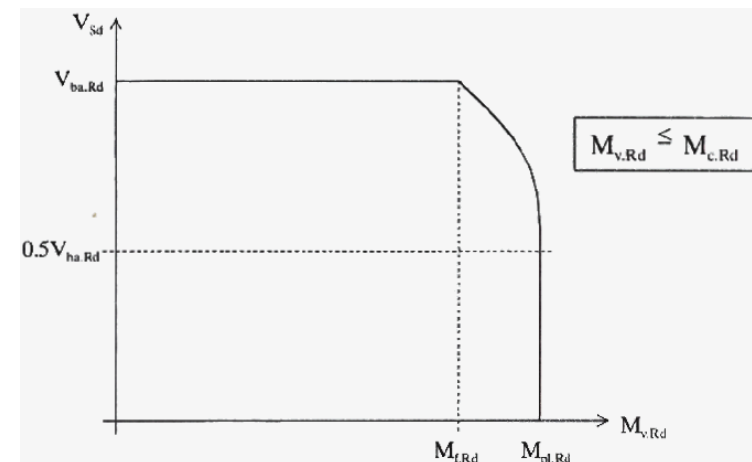
INTERAKCIJA MED STRIŽNIMI SILAMI, UPOGIBNIM MOMENTOM IN OSNO SILO

EC 3:

$$\frac{M_{Ed}}{M_{pl,Rd}} + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right) \cdot \left(\frac{2 \cdot V_{Ed}}{V_{pl,Rd}} - 1\right)^2 = 1 \quad \text{če} \quad V_{Ed} > 0,5 \cdot V_{pl,Rd}$$

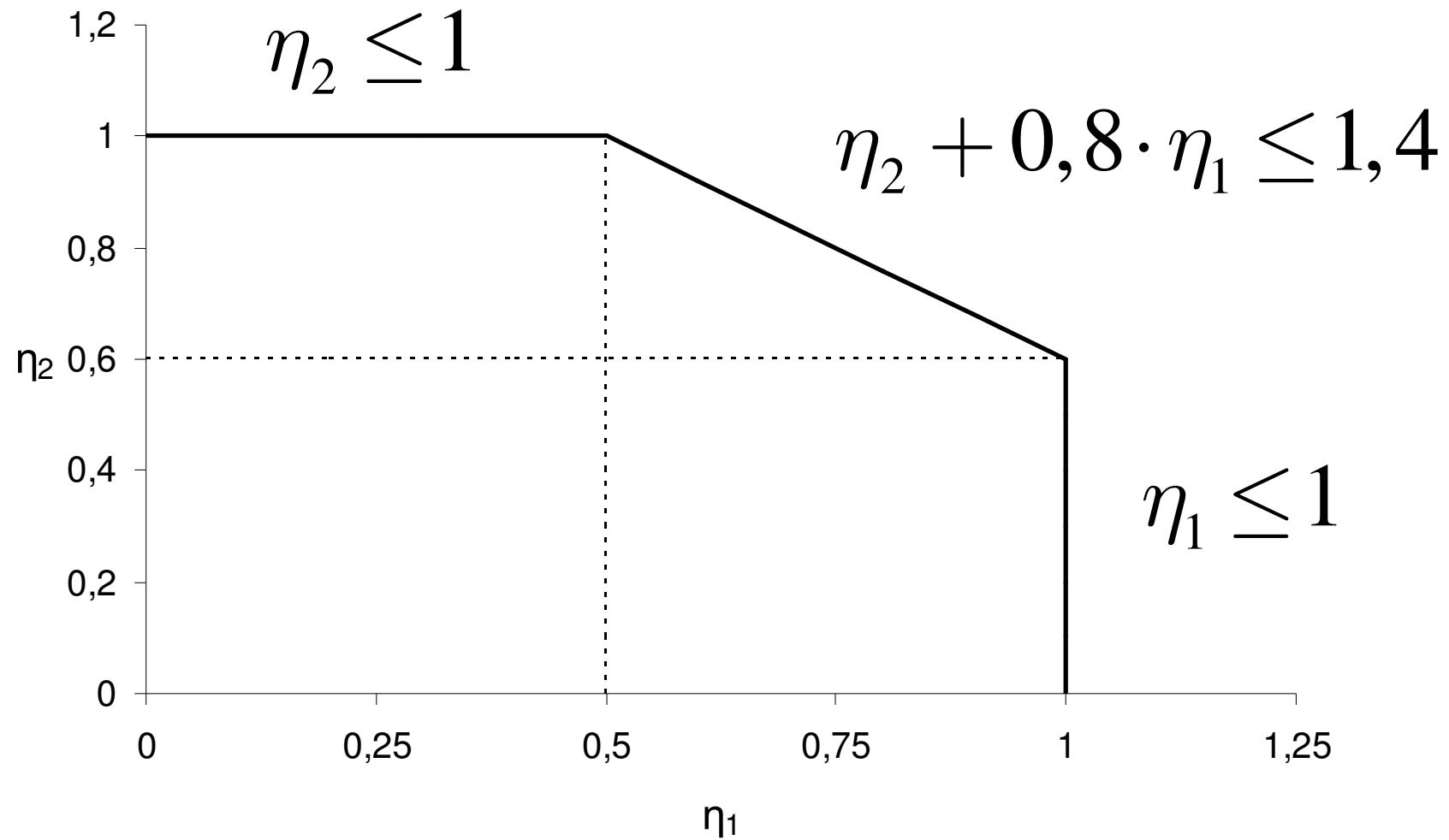
$$\bar{\eta}_1 + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right) \cdot (2 \cdot \bar{\eta}_3 - 1)^2 \leq 1,0$$

$$\bar{\eta}_1 = \frac{M_{Ed}}{M_{pl,Rd}}; \quad \bar{\eta}_3 = \frac{V_{Ed}}{V_{bw,Rd}}; \quad \rho = \left(\frac{2 \cdot V_{Ed}}{V_{pl}} - 1\right)^2$$

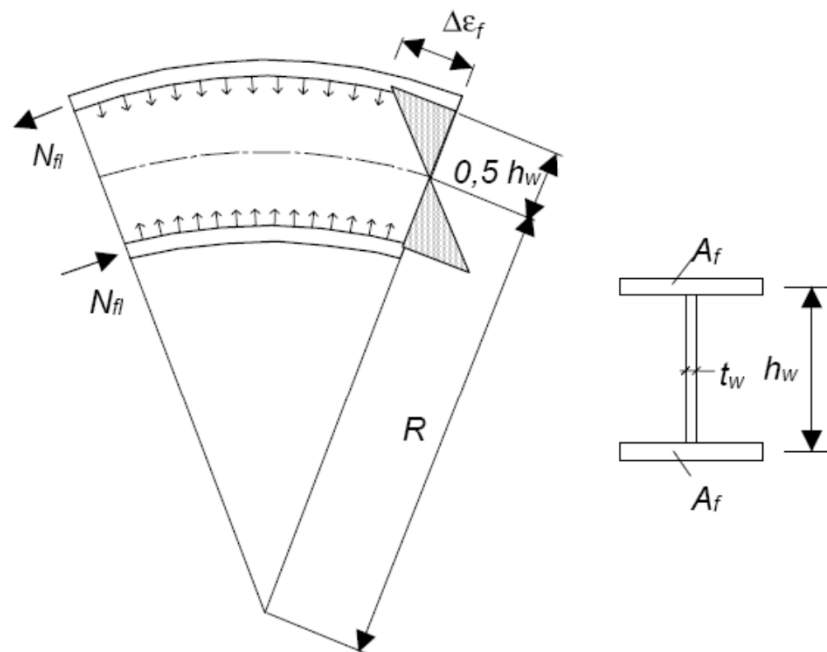


$$M_{Ed} \leq M_{v,Rd} = M_{f,Rd} + (M_{pl,Rd} - M_{f,Rd}) \cdot (1 - \rho) \leq M_{u,Rd}$$

INTERAKCIJA MED STRIŽNIMI SILAMI, UPOGIBNIM MOMENTOM IN OSNO SILO



VERTIKALNI UKLON PASNICE



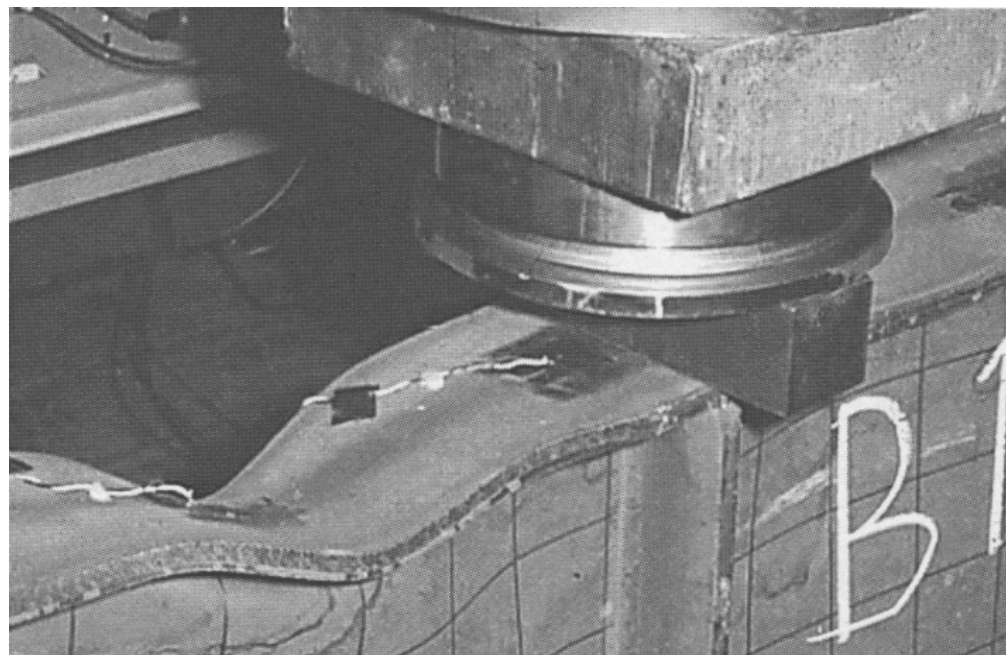
Prečni pritiski v upognjenem nosilcu pri čistem upogibu

$$\frac{h_w}{t_w} \leq k \cdot \frac{E}{f_{yf}} \sqrt{\frac{A_w}{A_{fc}}}$$

$k = 0,3$ - 1. razred kompaktnosti

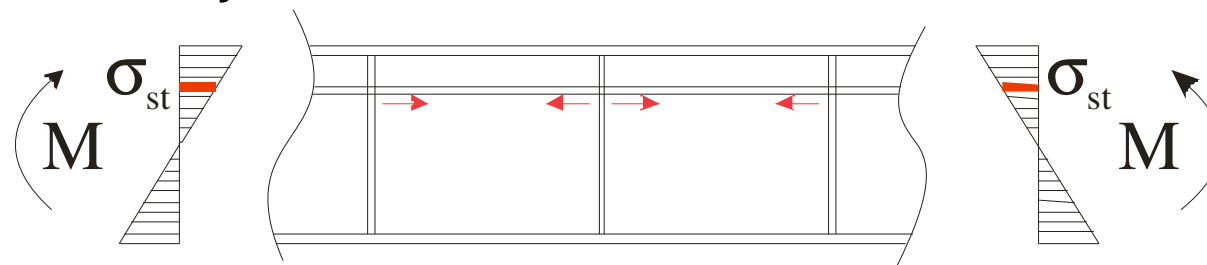
$k = 0,4$ - 2. razred kompaktnosti

$k = 0,55$ - 3. in 4. razred kompaktnosti

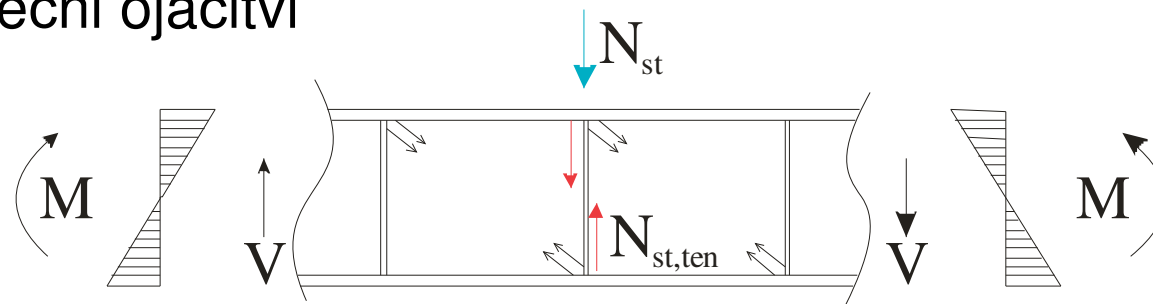


SILE V OJAČITVAH

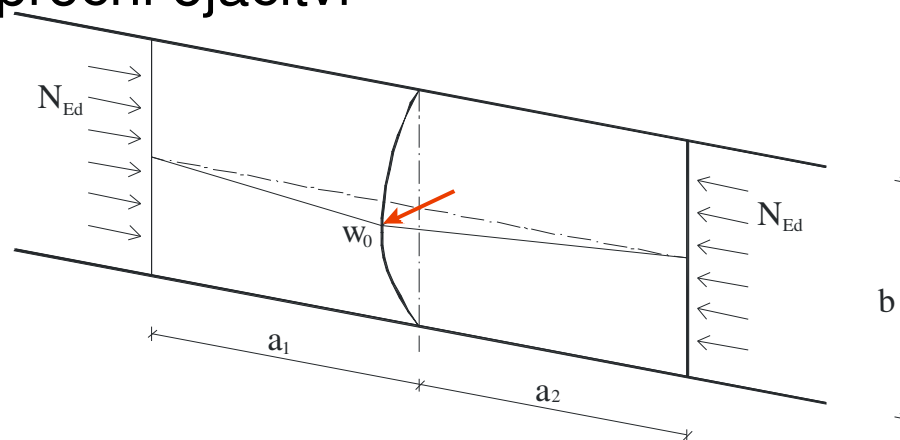
Osna sila v vzdolžni ojačitvi



Osna sila v prečni ojačitvi



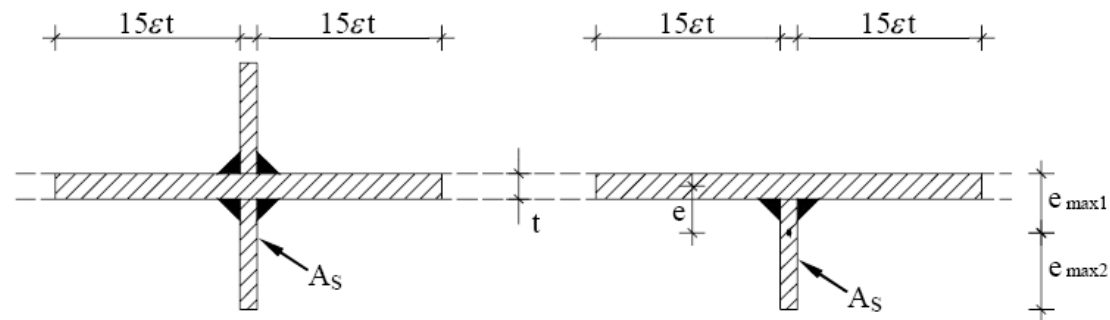
Izbočne sile v prečni ojačitvi



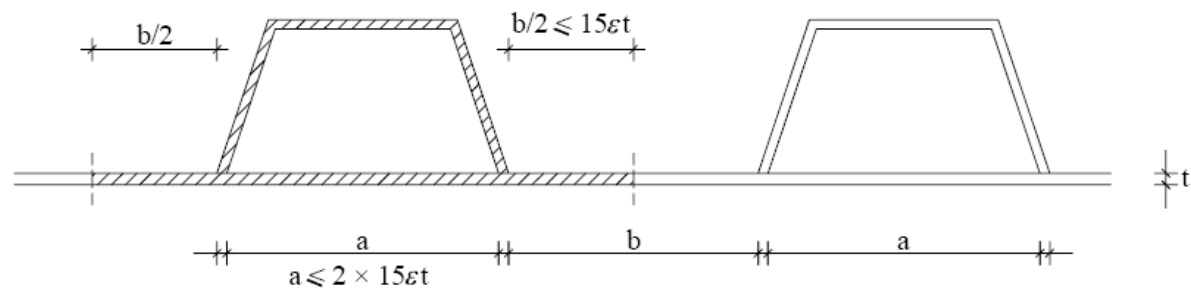
Kontrola prečnih ojačitev

- Prečne ojačitve naj bodo vedno toge (preprečujejo izbočitev pločevine v liniji ojačitve)
- Vzдолžne ojačitve so lahko podajne (ortotropna plošča)
- Prečne ojačitve nad podporami prenašajo velike sile (reakcije)
- Na zunanjih podporah prečne ojačitve pomagajo sidrati natezni pas, ki se razvije v stojini

Računski prečni prerez prečnih ojačitev



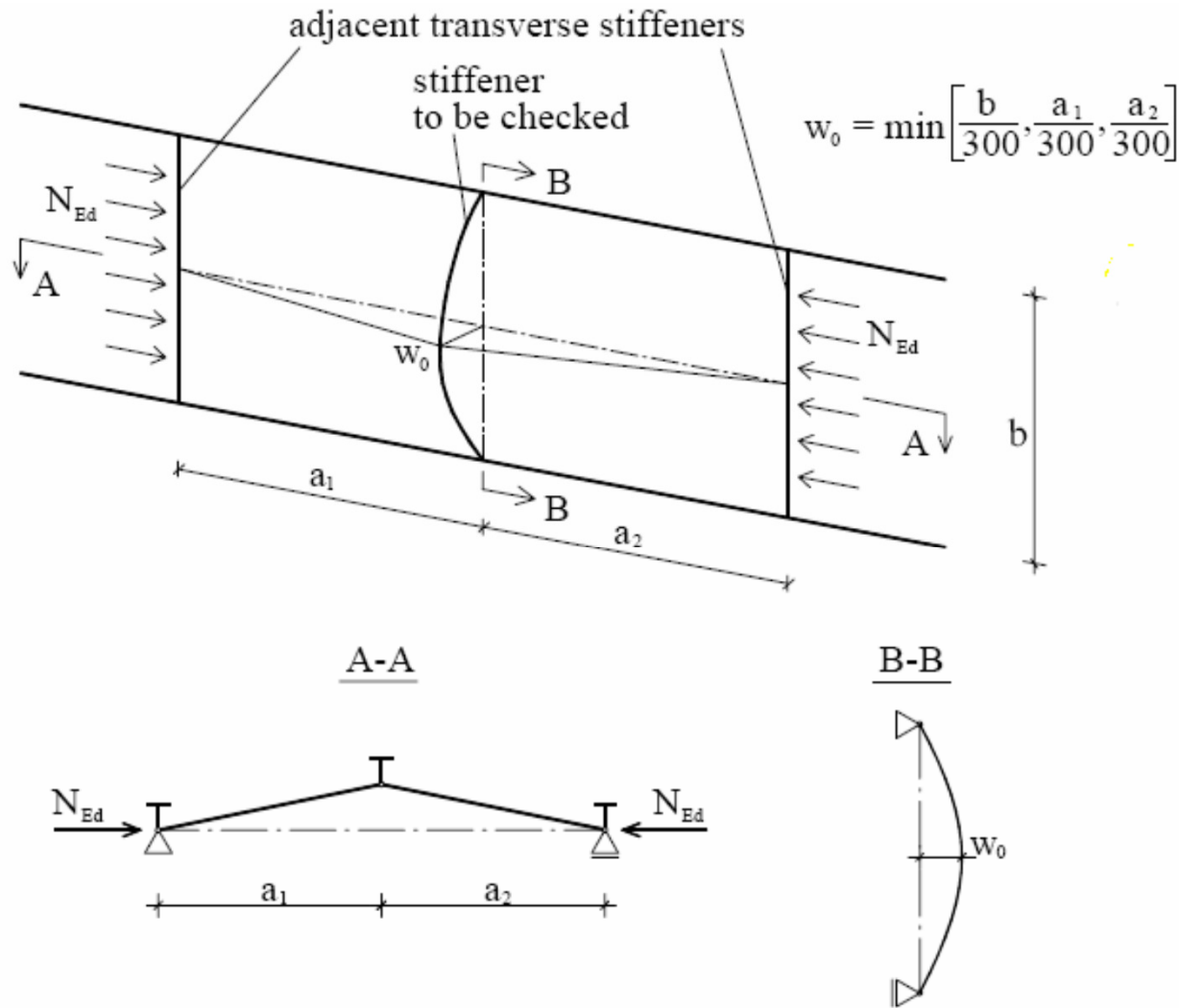
a) brez prekrivanja sodelujočih delov pločevin



b) prekrivanje sodelujočih delov pločevin

Slika 9.1: Sodelujoči prerezi ojačitev

Prečna ojačitev

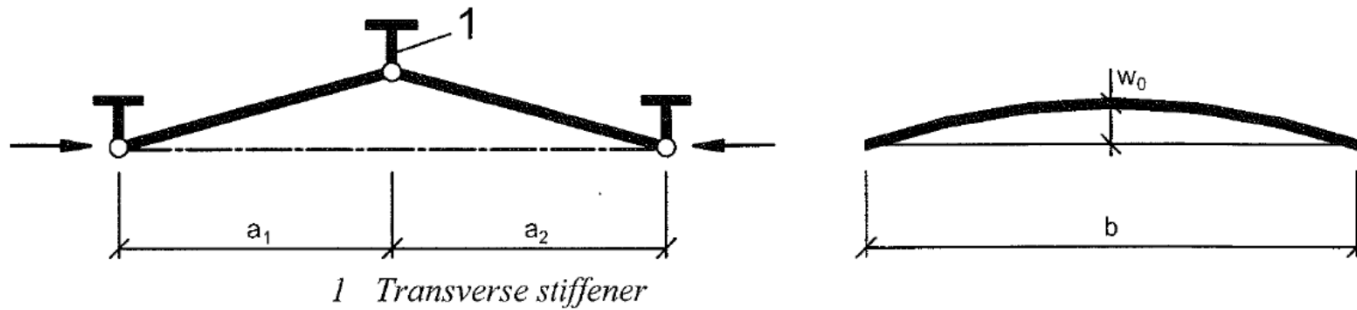


$$w \leq b / 300$$

$$\sigma_{\max} \leq \frac{f_y}{\gamma_{M1}}$$

Slika 9.2: Računski model za prečno ojačitev

Prečna ojačitev



$$I_{st} = \frac{\sigma_m}{E} \left(\frac{b}{\pi} \right)^4 \left(1 + w_0 \frac{300}{b} u \right)$$

$$\sigma_m = \frac{\sigma_{cr,c}}{\sigma_{cr,p}} \frac{N_{Ed}}{b} \left(\frac{1}{a_1} + \frac{1}{a_2} \right)$$

$$N_{Ed} = \int_{A_{c,eff}} \sigma_c \cdot dA_{c,eff} = \begin{cases} \sigma_c \cdot A_{c,eff} & \dots \dots \dots \text{čisti tlak} \\ \frac{\sigma_{c,max} \cdot A_{c,eff}}{2} & \dots \dots \dots \text{čisti upogib} \end{cases}$$

$$u = \frac{\pi^2 E \cdot e_{max}}{f_y \cdot 300 \cdot b} \geq 1,0$$

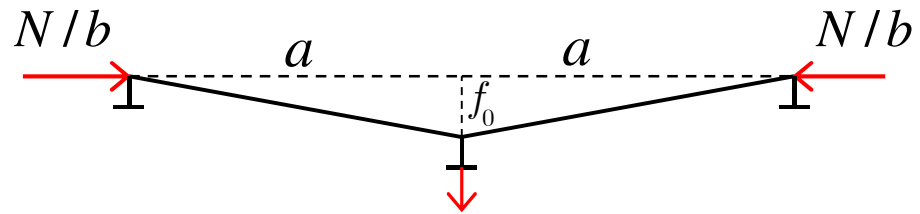
γ_{M1}

TRANSVERSE STIFFENERS – DEVIATION FORCE q_{dev}

$$q_{dev}(x) = (\bar{w}_0(x) + \bar{w}(x)) \sigma_m = \bar{f}_0(x) \left(\frac{1}{a_1} + \frac{1}{a_2} \right) \frac{N_{Ed}}{b} \frac{\sigma_{cr,c}}{\sigma_{cr,p}}$$

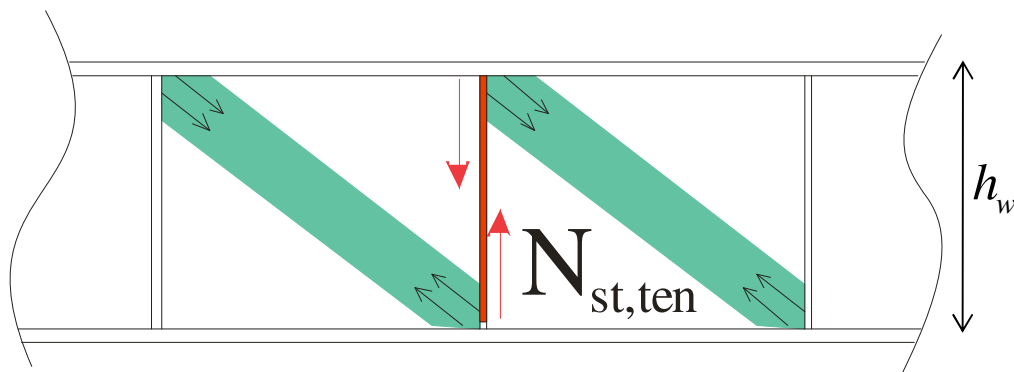
$$\sigma_m = \frac{\sigma_{cr,c}}{\sigma_{cr,p}} \frac{N_{Ed}}{b} \left(\frac{1}{a_1} + \frac{1}{a_2} \right)$$

$$\bar{w}_0(x) = w_0 \sin \left(\frac{\pi x}{b} \right)$$



$$q_{dev}(x) = \frac{2f_0}{a} \frac{N}{b}$$

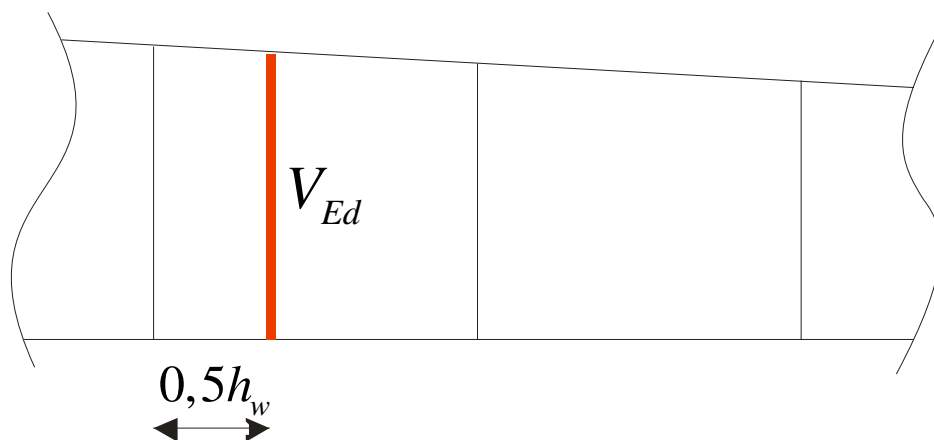
PREČNA OJAČITEV – SILA V NATEZNEM POLJU $N_{st,ten}$



SIST EN 1993-1-5:

$$N_{st,ten} = V_{Ed} - \frac{1}{\lambda_w^2} \cdot t \cdot h_w \frac{f_{yw}}{\sqrt{3}}$$

$[V_{Ed}]$

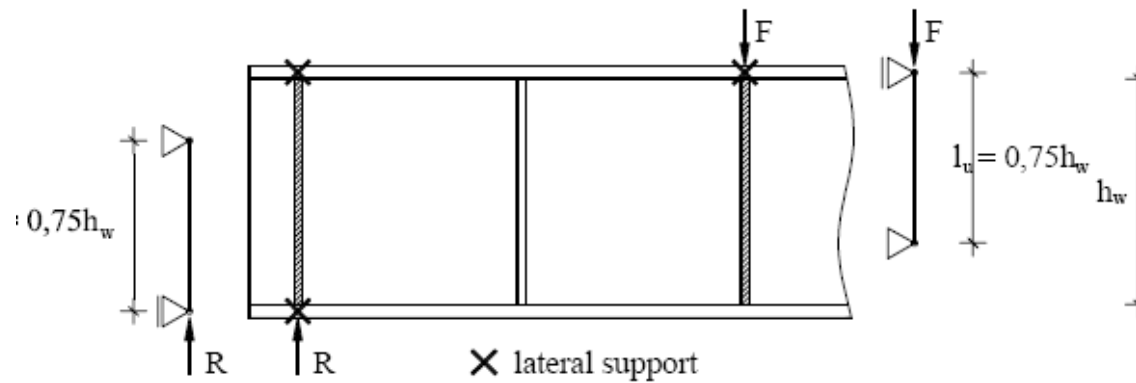


Stiffnes criteria:

$$I_{st} \geq 1,5 \frac{h_w^3 t^3}{a^2} \quad \text{for} \quad a / h_w < \sqrt{2}$$

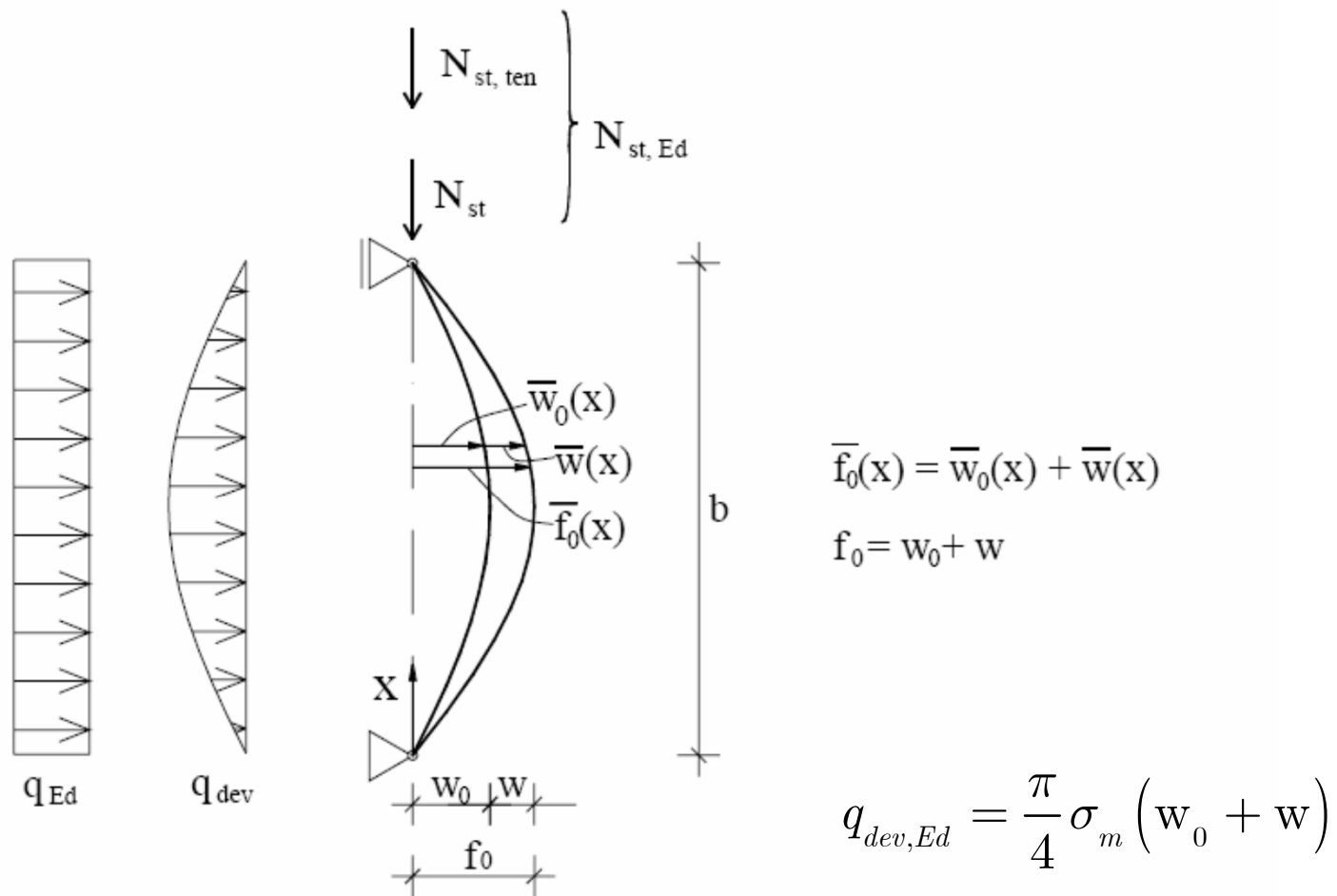
$$I_{st} \geq 0,75 h_w t^3 \quad \text{for} \quad a / h_w \geq \sqrt{2}$$

Prečna ojačitev



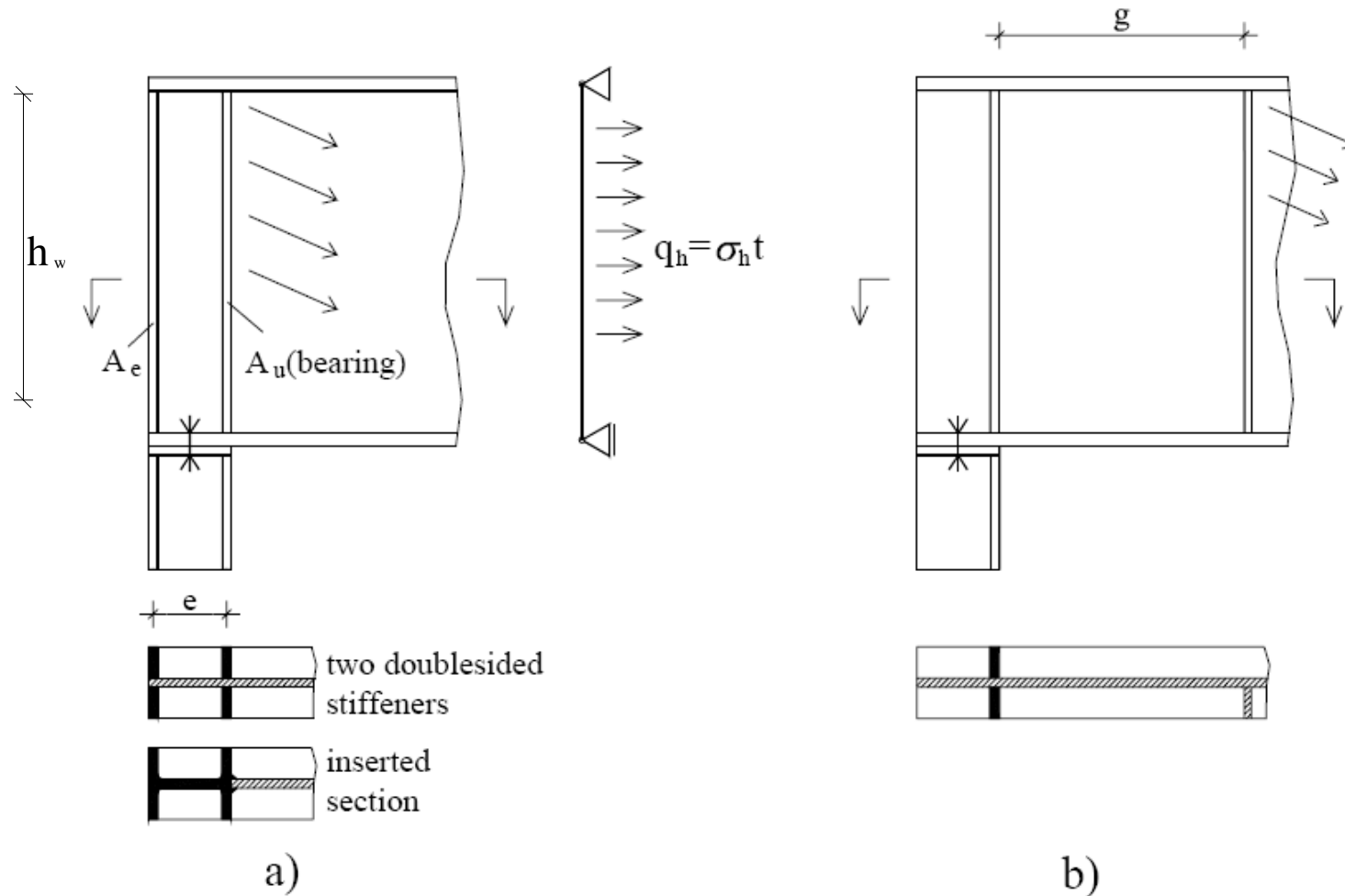
Kontrola uklona prečnih ojačitev pod vplivom prečne obremenitve

Obremenitev prečne ojačitve – splošni primer



Slika 9.3: Splošna obremenitev prečnih ojačitev

Robna prečna ojačitev



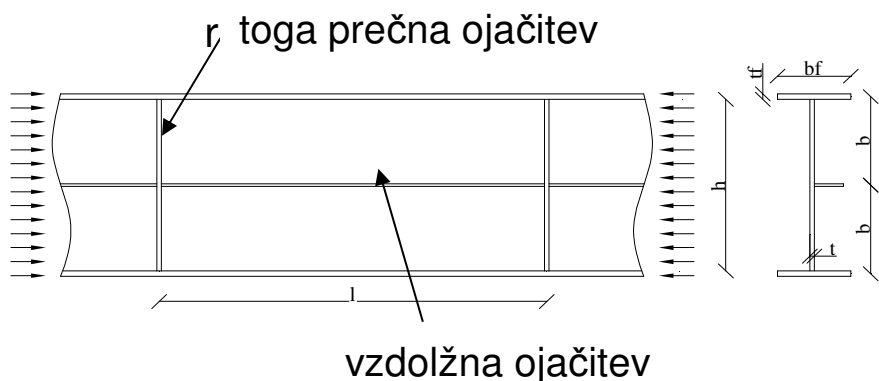
Slika 9.12: Detajl robnega panela

$$a \geq 0,1 \cdot h_w$$

$$A_e \geq 4 \cdot h_w \cdot t_w / e$$

TORZIJSKA NOSILNOST OJAČITVE ODPRTEGA PREČNEGA PREREZA

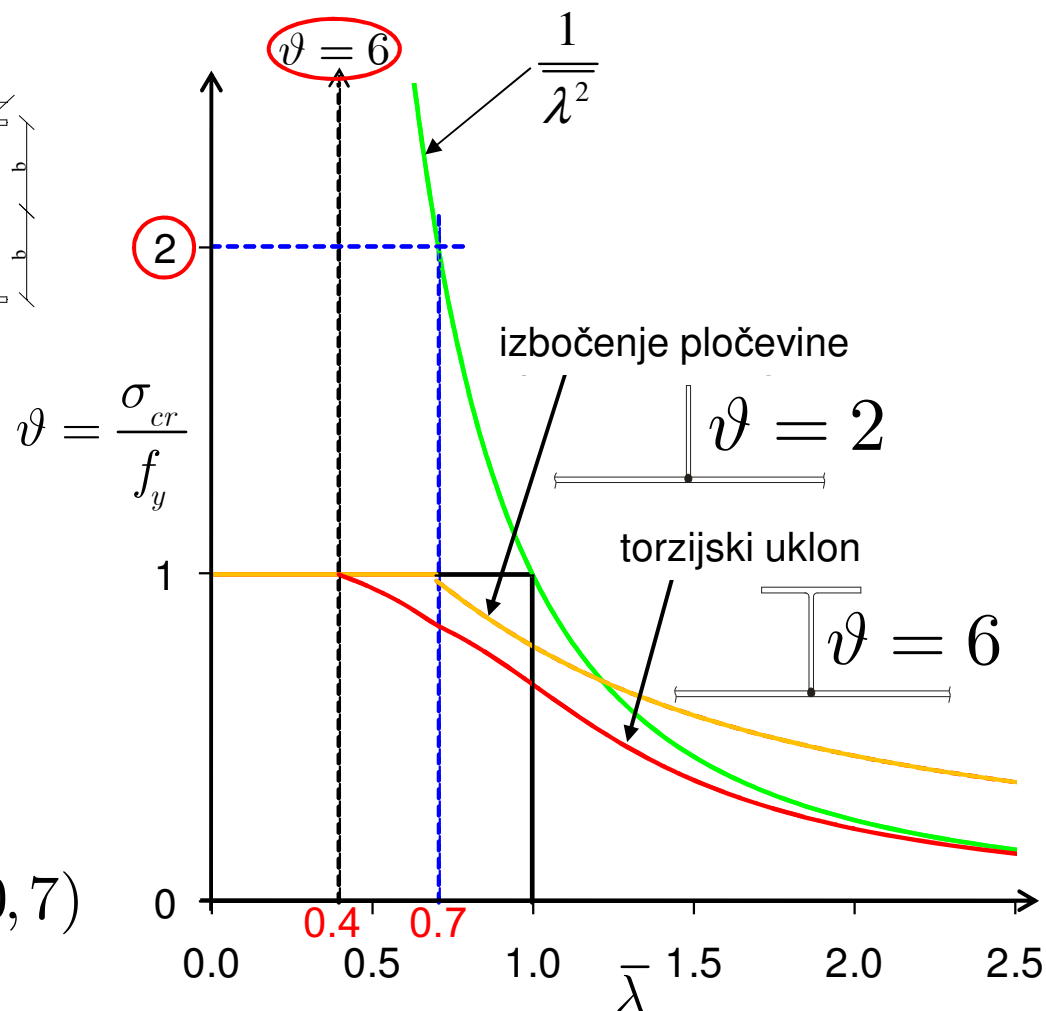
Torzijskemu uklonu se izognemo z omejitvijo elastične kritične napetosti



$$\sigma_{cr} \geq \vartheta f_y, \quad \text{EC3}$$

PLATO:

$$\bar{\lambda}_{PLATO} = \sqrt{\frac{f_y}{\sigma_{cr}}} \leq \frac{1}{\sqrt{\vartheta}} = 0,4 \quad (0,7)$$



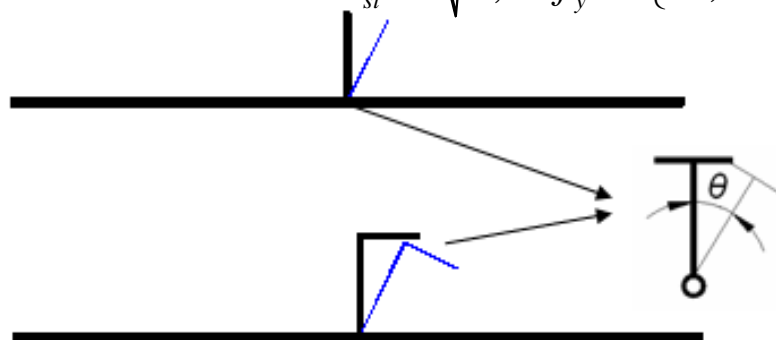
Različne možnosti za izračun elastične kritične napetosti

- Samo Saint-Venantova torzija

$$\sigma_{cr} = \frac{1}{I_p} [G \cdot I_t]$$

Formula je podana v EN 1993-1-5 in velja samo za ploščate ojačitve

$$\frac{b_{st}}{t_{st}} \leq \sqrt{\frac{E}{5,3 \cdot f_y}} = \begin{cases} 13,0 & (S235) \\ 10,5 & (S355) \end{cases}$$

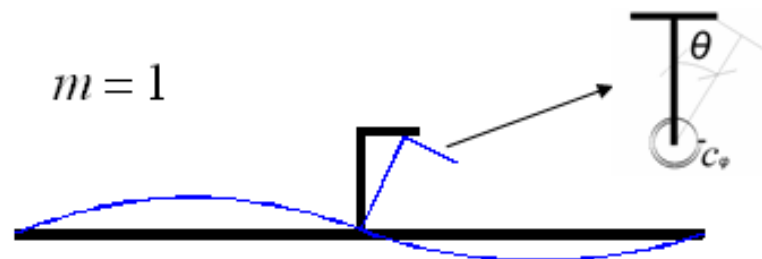


- Upoštevanje ovirane torzije

$$\sigma_{cr} = \frac{1}{I_p} \left[\frac{\pi^2 \cdot E \cdot I_w}{l^2} + G \cdot I_t \right]$$

- Upoštevanje podpiranja pločevine v obliki elastične podpore s togostjo C_φ

$$\sigma_{cr} = \frac{1}{I_p} \left[E \cdot I_w \frac{m^2 \cdot \pi^2}{l^2} + \frac{c_\varphi \cdot l^2}{m^2 \cdot \pi^2} + G \cdot I_t \right] \quad m = 1$$

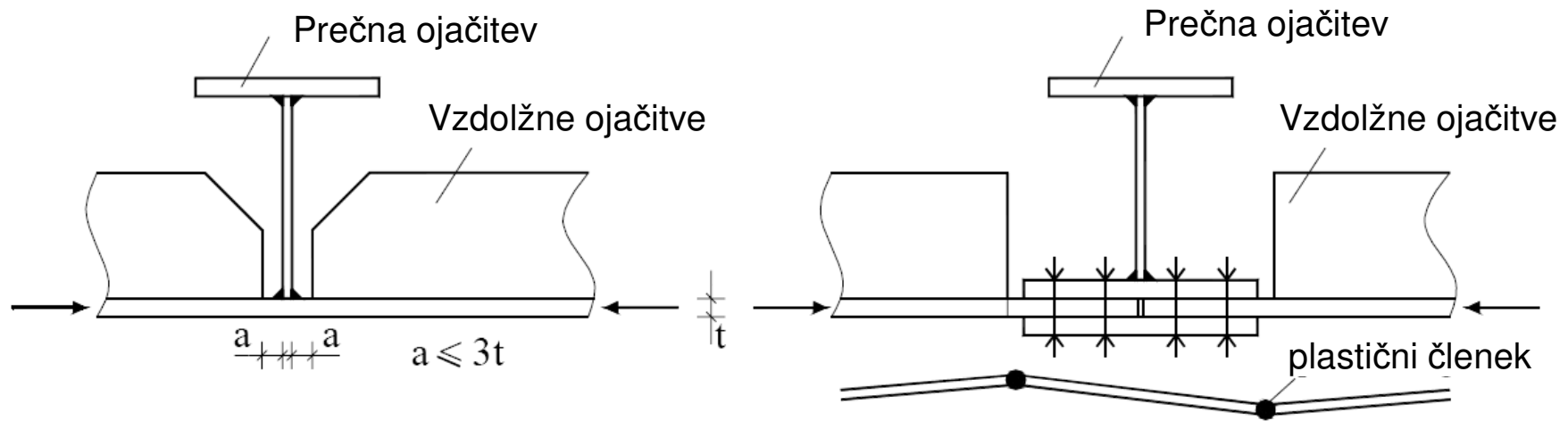


$$\sigma_{cr} = \frac{1}{I_p} \left[2 \sqrt{c_\varphi \cdot E \cdot I_w} + G \cdot I_t \right] \quad m \geq 2$$

m = število uklonskih valov

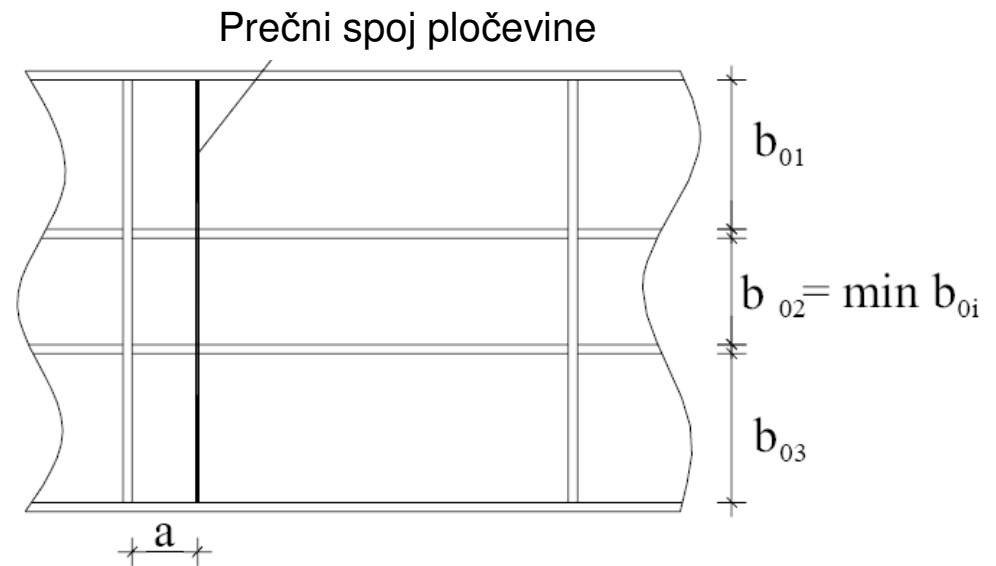
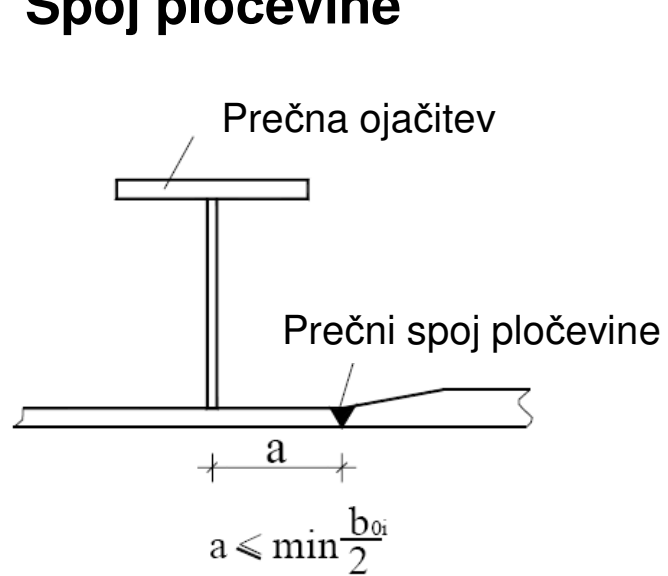
DETAJLI OJAČITEV

Nekontinuirnost vzdolžnih ojačitev

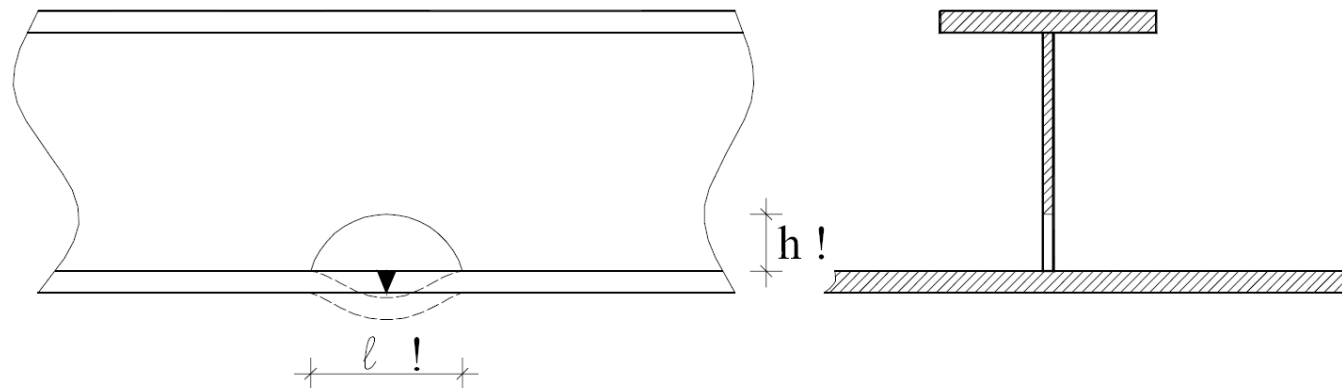


DETAJLI OJAČITEV

Spoj pločevine



Izrezi v vzdolžnih ojačitvah



Izrezi v prečnih ojačitvah

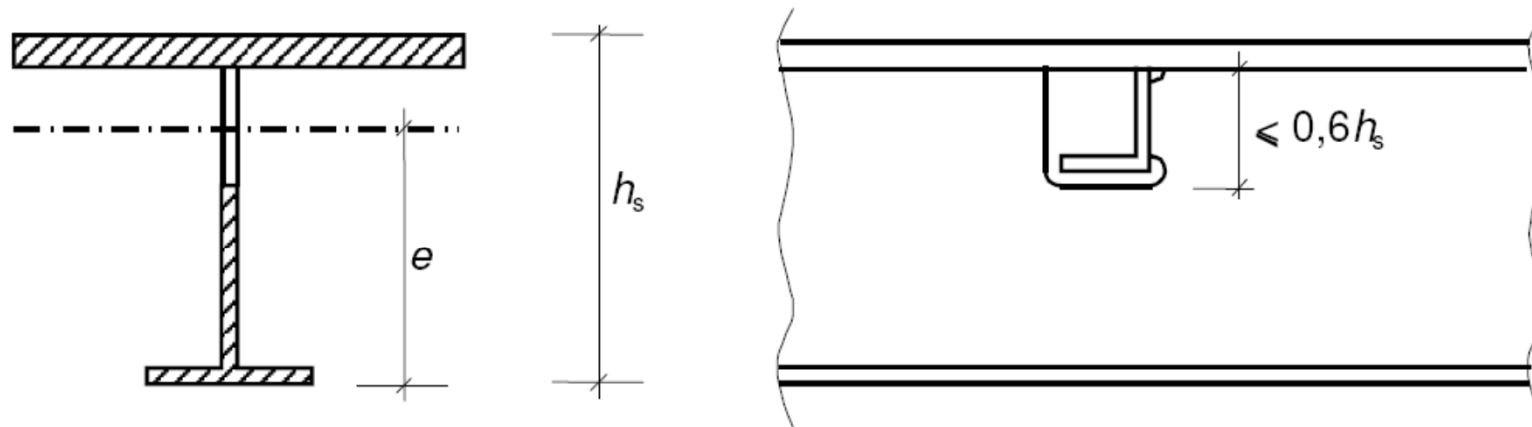


Figure 9.5: Cut outs in transverse stiffeners

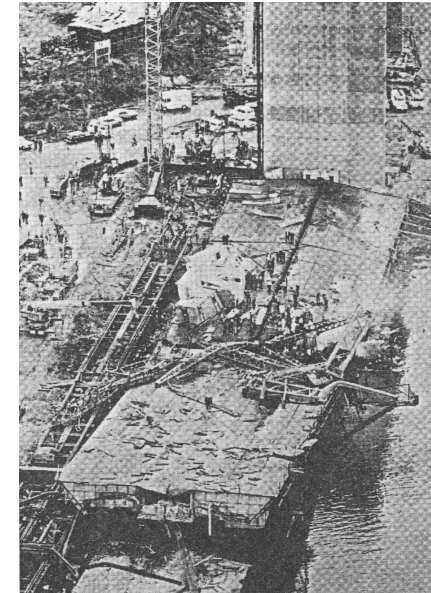
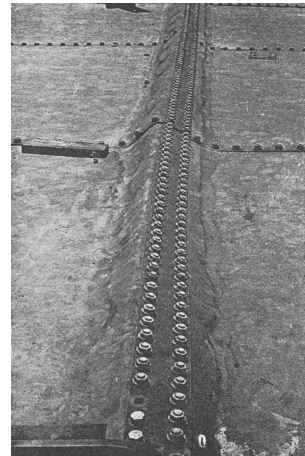
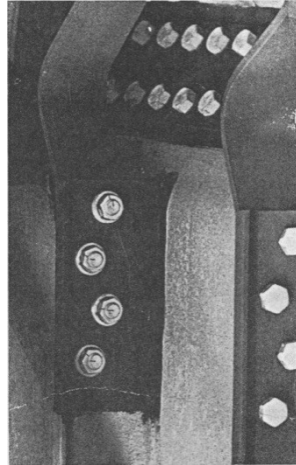
Bruto stojina prečne ojačitve ob izrezu mora prenesti strižno silo:

$$V_{Ed} = \frac{I_{net}}{e} \frac{f_{yk}}{\gamma_{M0}} \frac{\pi}{b_G},$$

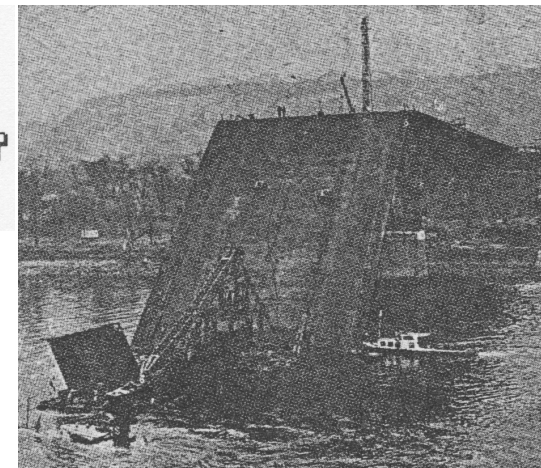
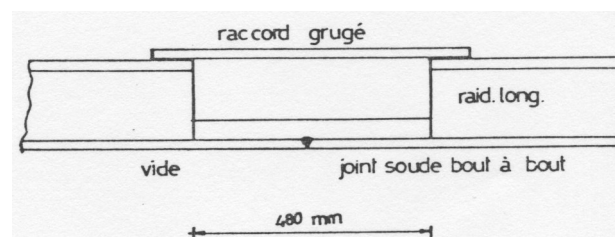
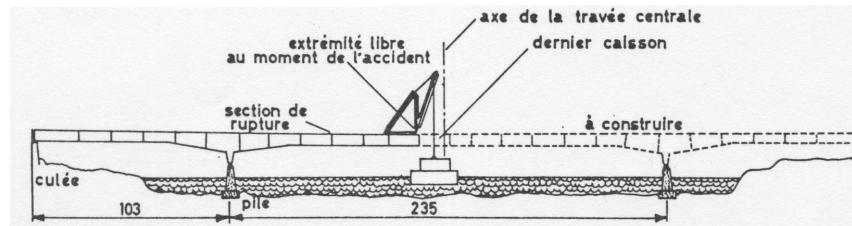
- I_{net} vztrajnostni moment neto prereza prečne ojačitve
 e maksimalna razdalja med spodnjim robom pasnice ojačitve in težiščem izrezanega dela
 b_G dolžina prečne ojačitve

DETAJLI OJAČITEV

MOST WEST-GATE (MELBOURNE, 1970)



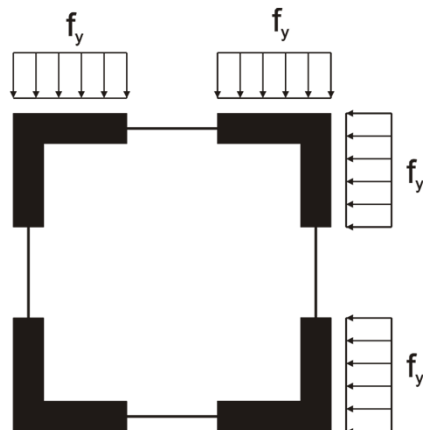
MOST KOBLENZ (1971)



Metoda reduciranih napetosti

- Določitev mejnih napetosti pri ojačenih in neojačenih pločevinah
- Alternativna metoda metodi sodelujočih širin
- Predpostavimo, da $\sigma_{x,Ed}$, $\sigma_{z,Ed}$, τ_{Ed} delujejo sočasno
- Pri neojačenih ali ojačenih pločevinah lahko predpostavimo lastnosti prereza, ki veljajo za 3. razred kompaktnosti, če velja $\frac{\rho \alpha_{ult,k}}{\gamma_{M1}} \geq 1$

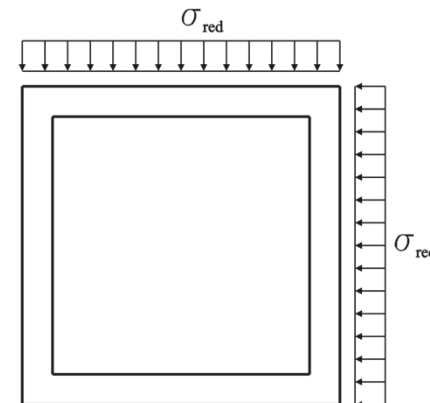
Metoda sodelujočih širin



$$A_{\text{eff}} f_y = A \sigma_{\text{red}}$$

$$\sigma_{\text{red}} \leq f_y$$

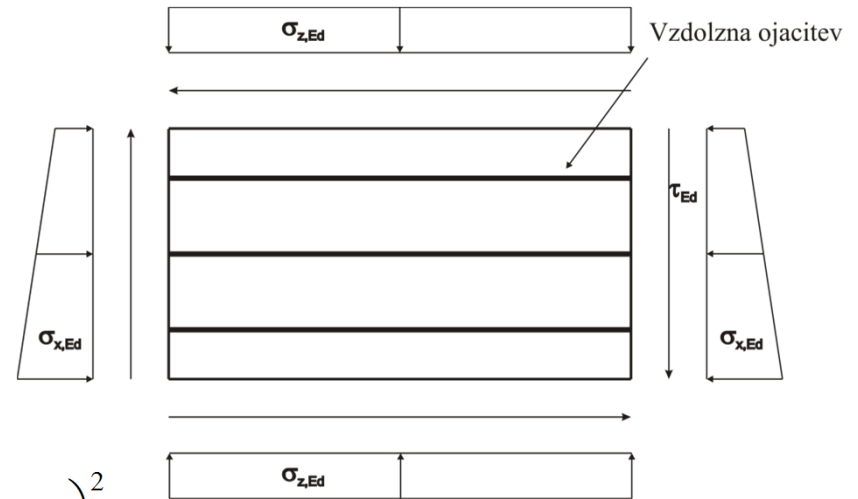
Metoda reduciranih napetosti



Metoda reduciranih napetosti

- Vitkost pločevine

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



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

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

$$\alpha_{cr,x} = \frac{\sigma_{cr,x}}{\sigma_{x,Ed}}, \alpha_{cr,z} = \frac{\sigma_{cr,z}}{\sigma_{z,Ed}}, \alpha_{cr,\tau} = \frac{\tau_{cr,\tau}}{\tau_{\tau,Ed}}$$

$\alpha_{ult,k}$	najmanjši množitelj projektne obtežbe s katerim dosežemo karakteristično nosilnost najbolj kritične točke pločevine
$\alpha_{cr,k}$	najmanjši množitelj projektne obtežbe s katerim dosežemo elastično kritično obtežbo pločevine

Metoda reduciranih napetosti

- Kontrola nosilnosti - Metoda 1 (zelo konzervativna)

$$\left(\frac{\sigma_{x,Ed}}{f_y / \gamma_{M1}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{f_y / \gamma_{M1}}\right)^2 - \left(\frac{\sigma_{x,Ed}}{f_y / \gamma_{M1}}\right)\left(\frac{\sigma_{z,Ed}}{f_y / \gamma_{M1}}\right) + 3\left(\frac{\tau_{Ed}}{f_y / \gamma_{M1}}\right)^2 \leq \rho^2$$

$$\rho = \min(\rho_x, \rho_z, \chi_w)$$

- Kontrola nosilnosti - Metoda 2

$$\left(\frac{\sigma_{x,Ed}}{\rho_x f_y / \gamma_{M1}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{\rho_z f_y / \gamma_{M1}}\right)^2 - \left(\frac{\sigma_{x,Ed}}{\rho_x f_y / \gamma_{M1}}\right)\left(\frac{\sigma_{z,Ed}}{\rho_z f_y / \gamma_{M1}}\right) + 3\left(\frac{\tau_{Ed}}{\chi_w f_y / \gamma_{M1}}\right)^2 \leq 1$$

Metoda reduciranih napetosti – Primer

Obravnavamo neojačen panel dimenzij 1000mm×1000mm, debelina pločevine je 10 mm. Napetosti v panelu so $\sigma_{x,Ed} = \sigma_{z,Ed} = 70$ MPa in $\tau_{Ed} = 70$ MPa.

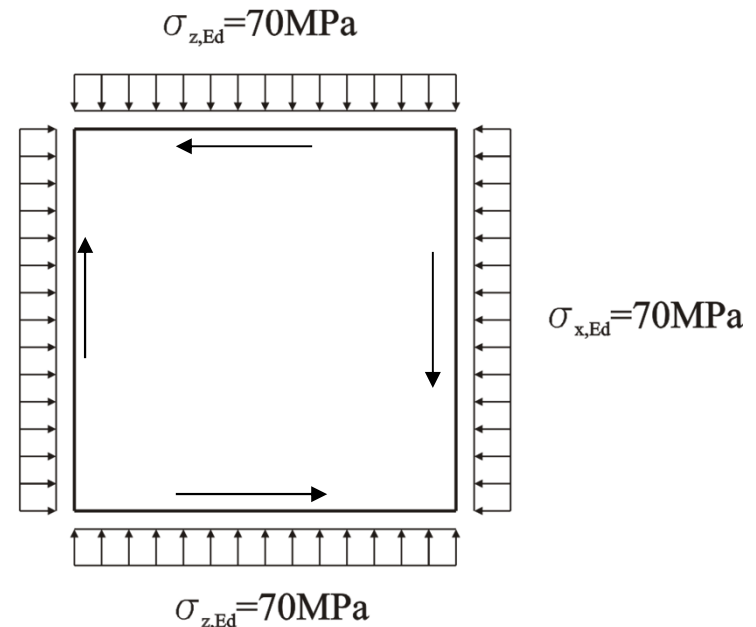
Direktne in strižne kritične napetosti:

$$\sigma_{cr,x} = \sigma_{cr,z} = \frac{k_{\sigma} \pi^2 E t^2}{12 (1-\nu^2) \bar{b}^2} = \frac{4 \cdot \pi^2 \cdot 210 \cdot 10^3 \cdot 10^2}{12 \cdot (1-0,3^2) \cdot 1000^2} = 75,9 \text{ MPa}$$

$$\tau_{cr} = \frac{k_{\tau} \pi^2 E t^2}{12 (1-\nu^2) \bar{b}^2} = \frac{9,34 \cdot \pi^2 \cdot 210 \cdot 10^3 \cdot 10^2}{12 \cdot (1-0,3^2) \cdot 1000^2} = 177,3 \text{ MPa}$$

$$k_{\tau} = 5,34 + 4,00 \left(\frac{\bar{b}}{a} \right)^2 = 5,34 + 4,00 \cdot \left(\frac{1000}{1000} \right)^2 = 9,34$$

$\sigma_{x,Ed} = 70$ MPa



Metoda reduciranih napetosti – Primer

Faktor za doseg karakteristične nosilnosti

$$\begin{aligned}\frac{1}{\alpha_{ult,k}^2} &= \left(\frac{\sigma_{x,Ed}}{f_y}\right)^2 + \left(\frac{\sigma_{z,Ed}}{f_y}\right)^2 - \left(\frac{\sigma_{x,Ed}}{f_y}\right)\left(\frac{\sigma_{z,Ed}}{f_y}\right) + 3\left(\frac{\tau_{Ed}}{f_y}\right)^2 = \\ &= \left(\frac{70}{355}\right)^2 + \left(\frac{70}{355}\right)^2 - \left(\frac{70}{355}\right)\left(\frac{70}{355}\right) + 3\left(\frac{70}{355}\right)^2 = 0,156 \rightarrow \alpha_{ult,k} = 2,536\end{aligned}$$

Ločeno in vzajemno obravnavane napetosti:

$$\alpha_{cr,x} = \alpha_{cr,z} = \frac{\sigma_{cr,x}}{\sigma_{x,Ed}} = \frac{75,9}{70} = 1,084, \quad \alpha_{cr,\tau} = \frac{\tau_{cr}}{\tau_{Ed}} = \frac{179}{70} = 2,531$$

$$\begin{aligned}\frac{1}{\alpha_{cr}} &= \frac{1+\psi_x}{4\alpha_{cr,x}} + \frac{1+\psi_z}{4\alpha_{cr,z}} + \left[\left(\frac{1+\psi_x}{4\alpha_{cr,x}} + \frac{1+\psi_z}{4\alpha_{cr,z}} \right)^2 + \frac{1-\psi_x}{2\alpha_{cr,x}^2} + \frac{1-\psi_z}{2\alpha_{cr,z}^2} + \frac{1}{\alpha_{cr,\tau}^2} \right]^{1/2} = \\ &= \frac{1+1}{4 \cdot 1,084} + \frac{1+1}{4 \cdot 1,084} + \left[\left(\frac{1+1}{4 \cdot 1,084} + \frac{1+1}{4 \cdot 1,084} \right)^2 + 0 + 0 + \frac{1}{2,531^2} \right]^{1/2} = 1,926 \rightarrow \alpha_{cr} = 0,519\end{aligned}$$

Metoda reduciranih napetosti – Primer

Vitkost podpanela:

$$\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}} = \sqrt{\frac{2,536}{0,519}} = 2,210$$

Redukcijski faktor:

$$\rho_x = \rho_z = \frac{\bar{\lambda}_p - 0,055(3 + \psi)}{\bar{\lambda}_p^2} = \frac{2,210 - 0,055 \cdot (3 + 1)}{2,210^2} = 0,407$$

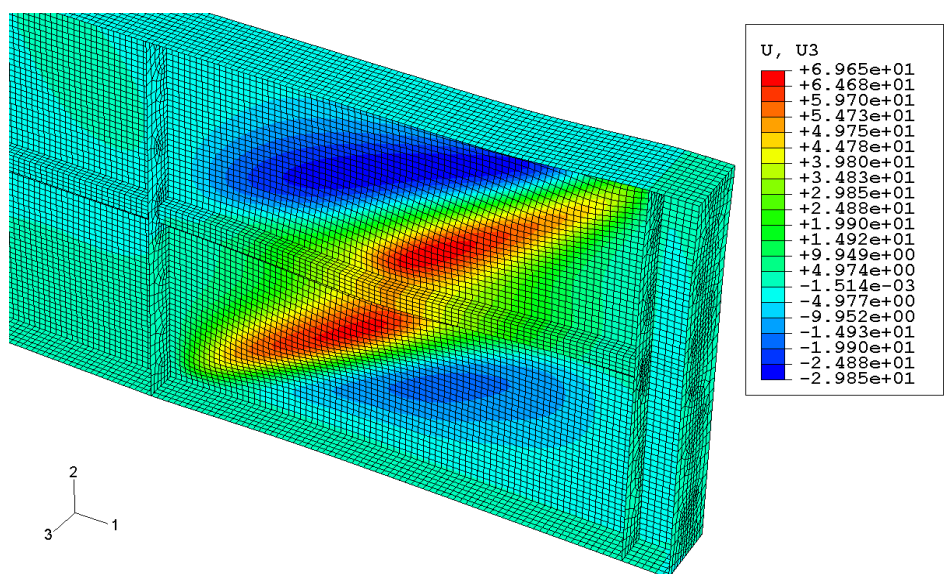
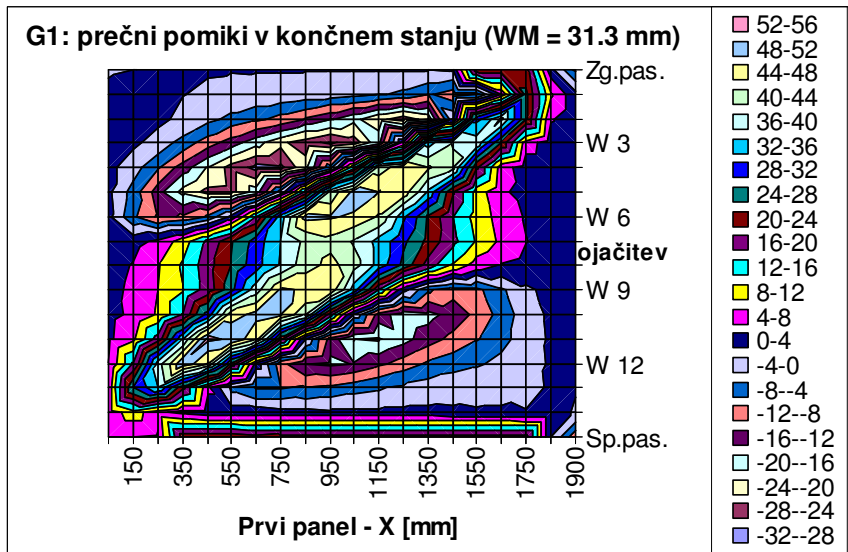
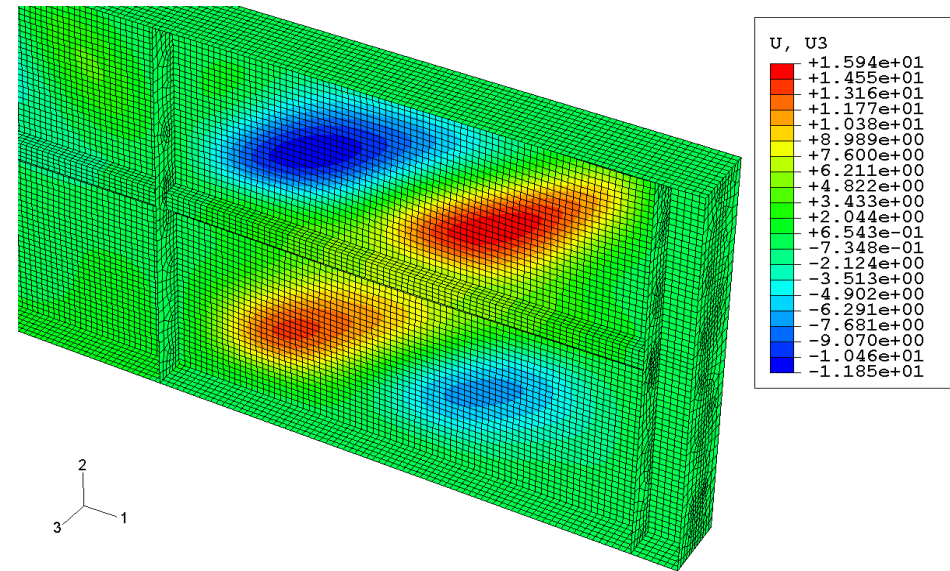
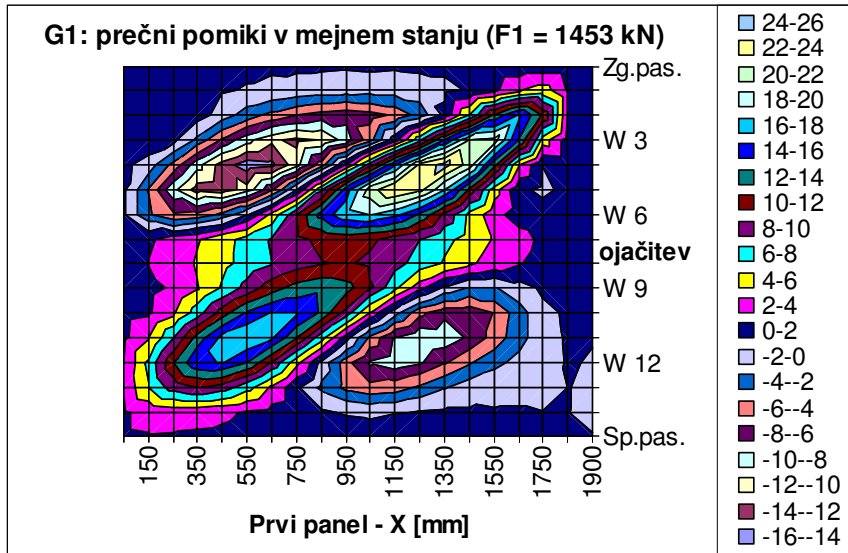
Redukcijski faktor za strižne napetosti (predpostavimo tog robni panel):

$$\chi_w = \frac{1,37}{(0,7 + \bar{\lambda}_w)} = \frac{1,37}{(0,7 + 2,210)} = 0,471$$

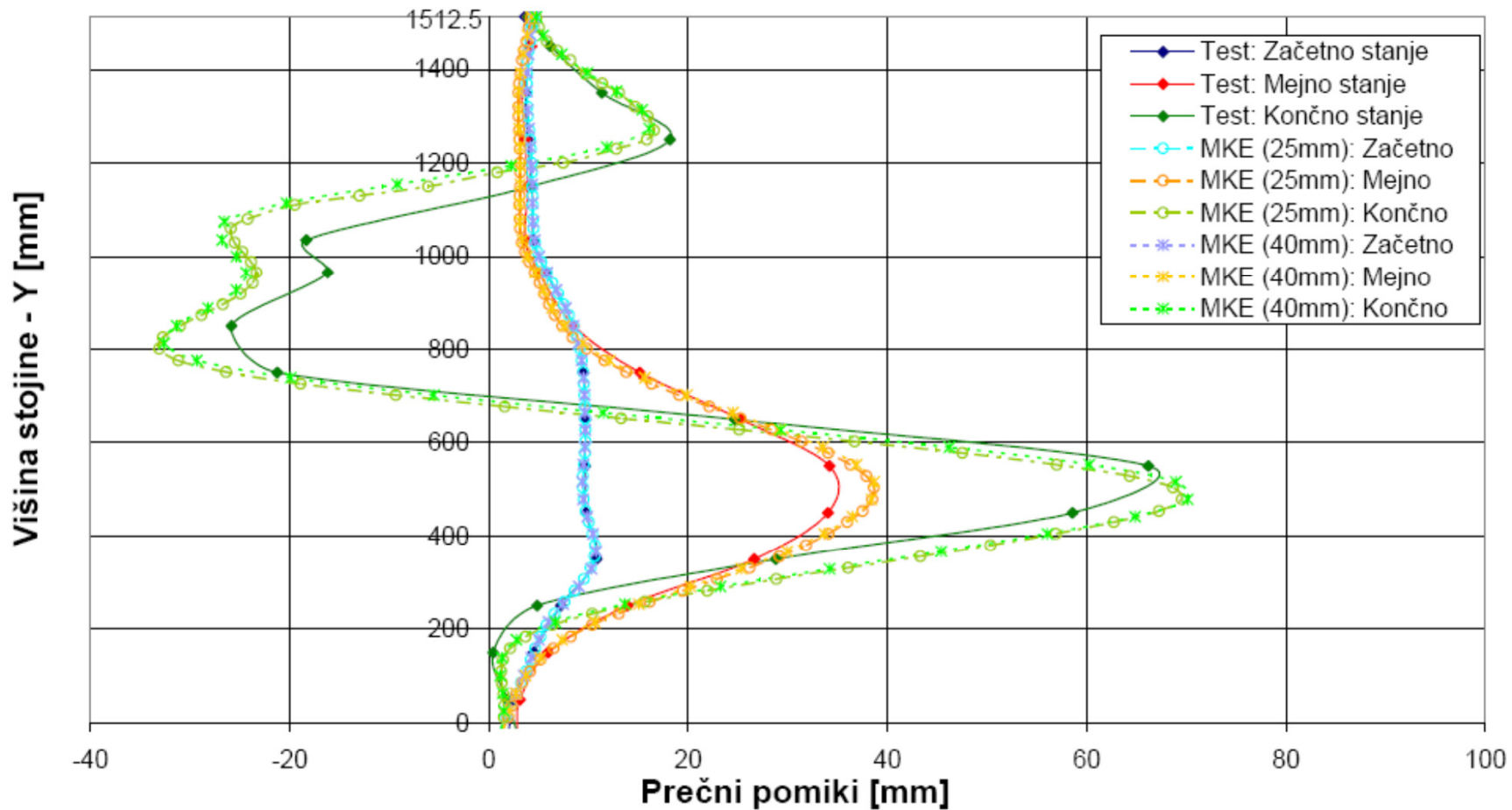
Kontrola:

$$\left(\frac{\sigma_{x,Ed}}{\rho_x f_y / \gamma_{M1}} \right)^2 + \left(\frac{\sigma_{z,Ed}}{\rho_z f_y / \gamma_{M1}} \right)^2 - \left(\frac{\sigma_{x,Ed}}{\rho_x f_y / \gamma_{M1}} \right) \left(\frac{\sigma_{z,Ed}}{\rho_z f_y / \gamma_{M1}} \right) + 3 \left(\frac{\tau_{Ed}}{\chi_w f_y / \gamma_{M1}} \right)^2 \leq 1$$
$$\left(\frac{70}{0,407 \cdot 355 / 1,1} \right)^2 + \left(\frac{70}{0,407 \cdot 355 / 1,1} \right)^2 - \left(\frac{70}{0,407 \cdot 355 / 1,1} \right) \left(\frac{70}{0,407 \cdot 355 / 1,1} \right) + 3 \left(\frac{70}{0,471 \cdot 355 / 1,1} \right)^2 = 0,92 < 1$$

MKE analiza ojačenih pločevin

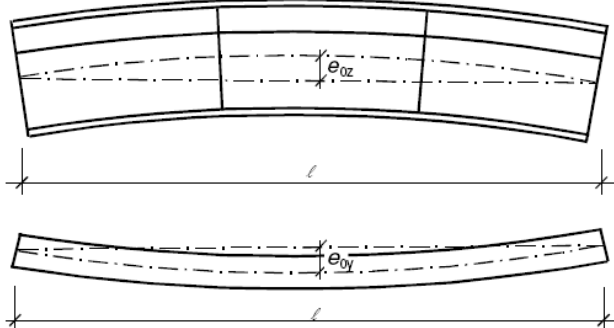
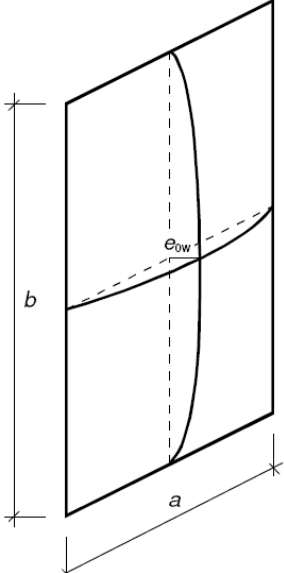
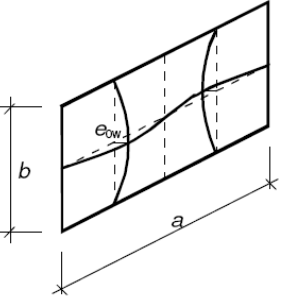
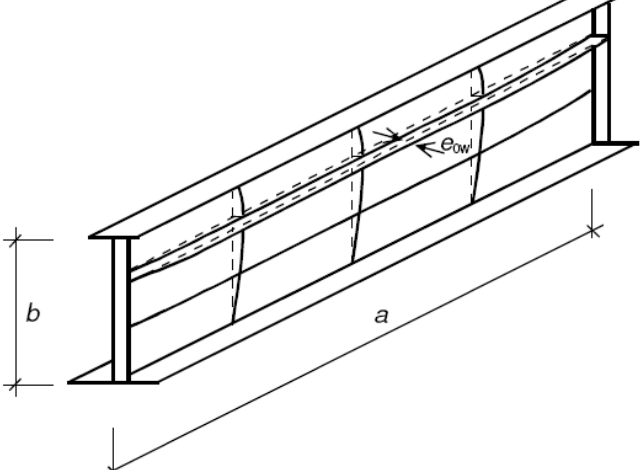
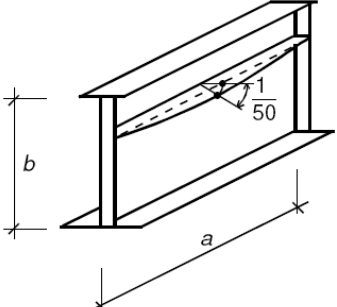


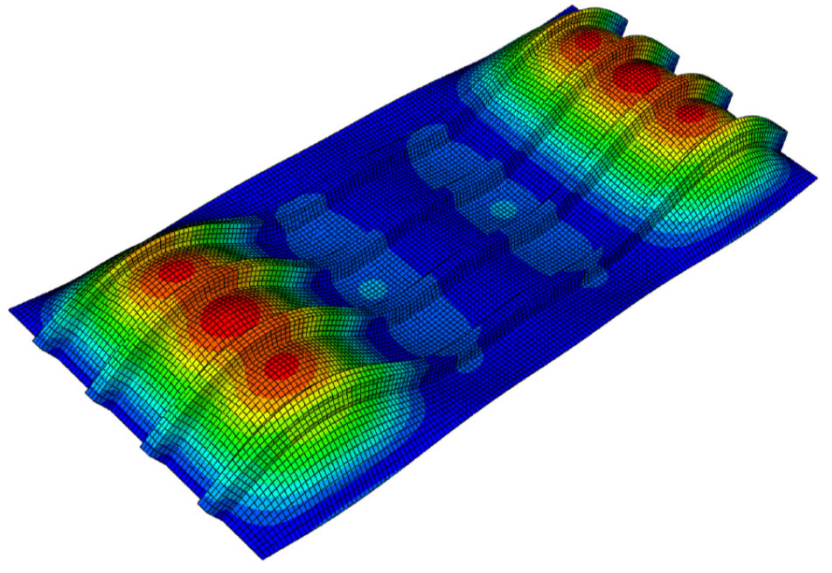
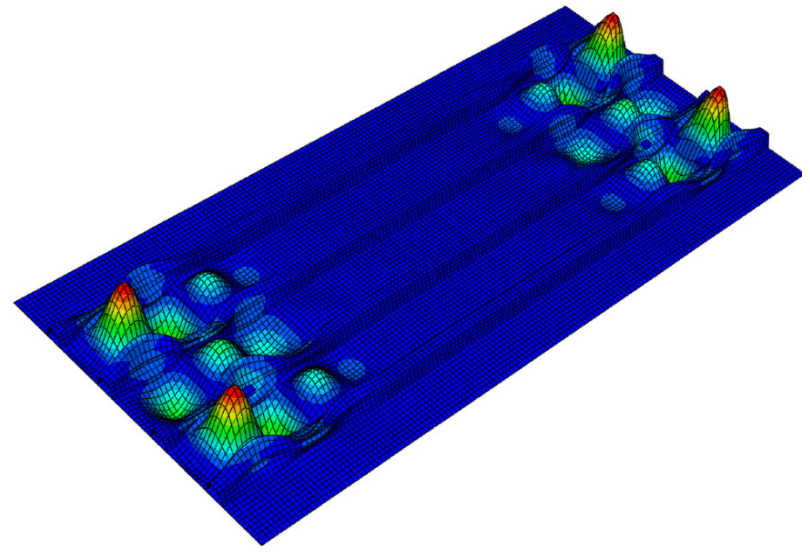
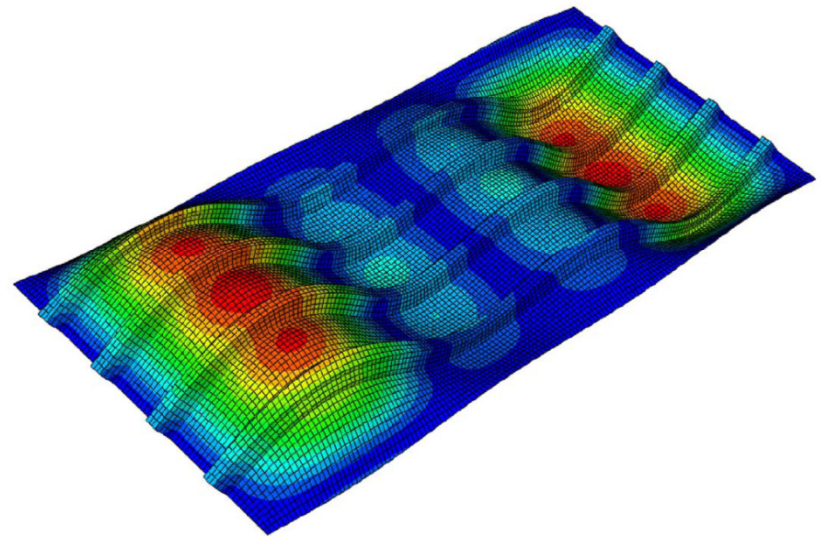
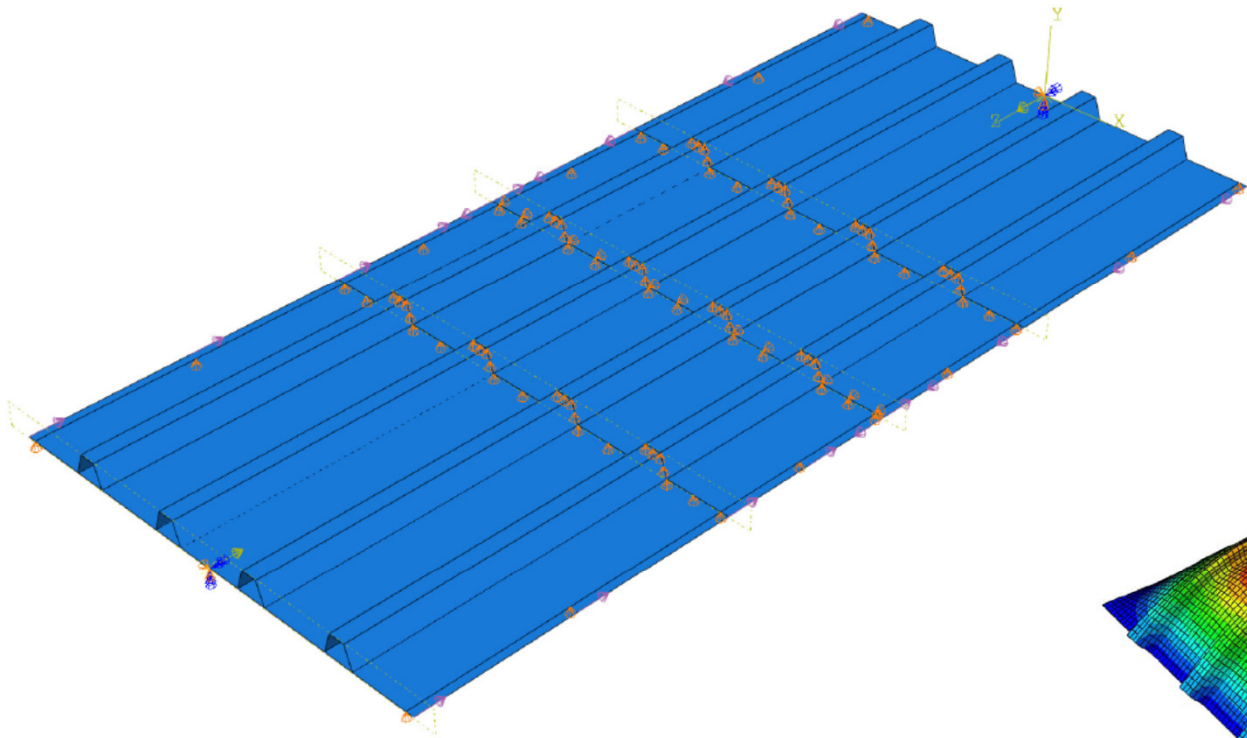
MKE analiza ojačenih pločevin

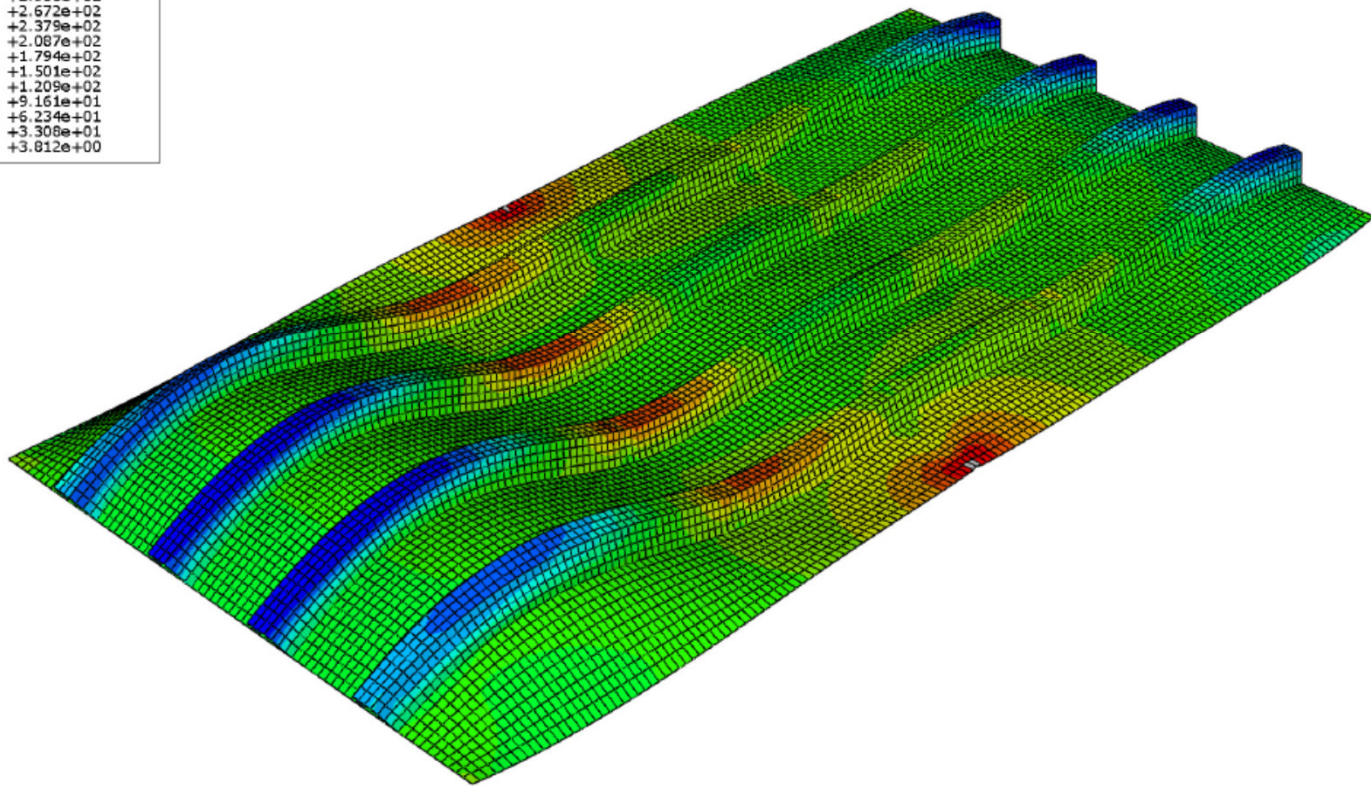
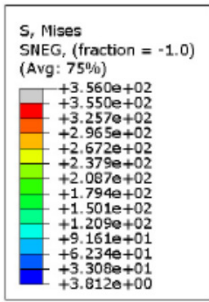


MKE analiza ojačenih pločevin

Material, mreža končnih elementov, geometrijske nepopolnosti, zaostale napetosti, robni pogoji, kalibracija s testi ...

Vrsta nepopolnosti	Element	Lokalni panel ali podpanel	
Globalni element dolžine l			
Globalni vzdolžna ojačitev dolžine a			





Tankostenski nosilci z valovitimi stojinami

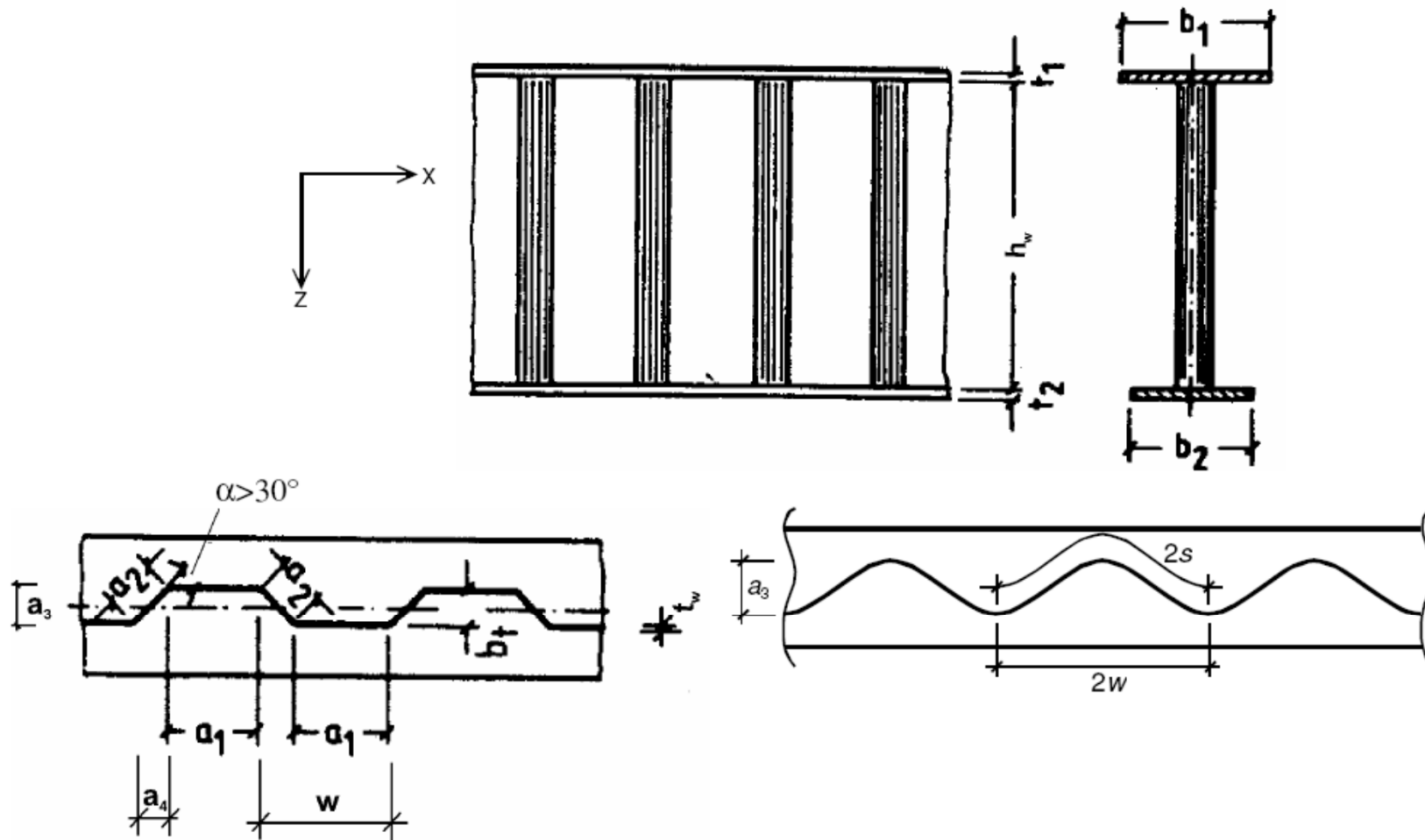


Figure D.1: Geometric notations

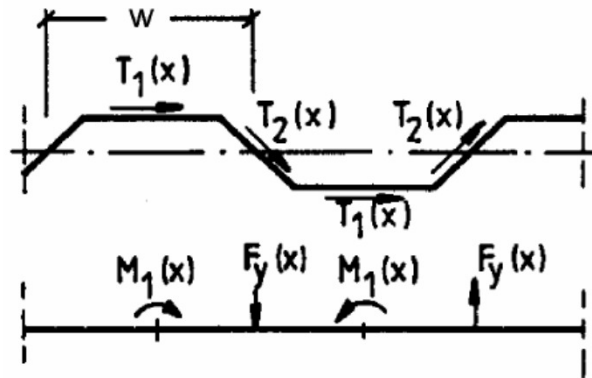
Tankostenski nosilci z valovitimi stojinami

- Upogibna nosilnost

$$M_{Rd} = \min \left\{ \underbrace{\frac{b_2 t_2 f_{yf,r}}{\gamma_{M0}} \left(h_w + \frac{t_1 + t_2}{2} \right)}_{\text{natezna pasnica}}; \underbrace{\frac{b_1 t_1 f_{yf,r}}{\gamma_{M0}} \left(h_w + \frac{t_1 + t_2}{2} \right)}_{\text{tlačena pasnica}}; \underbrace{\frac{b_1 t_1 \chi f_{yf}}{\gamma_{M1}} \left(h_w + \frac{t_1 + t_2}{2} \right)}_{\text{tlačena pasnica}} \right\}$$

$$f_{yf,r} = f_{yf} f_T$$

$$f_T = \begin{cases} 1 - 0,4 \sqrt{\frac{\sigma_x(M_z)}{f_{yf}}} & \text{valovi trapezne oblike} \\ 1,0 & \text{valovi sin usne oblike} \end{cases}$$



Moment M_z deluje v prečni smeri in je posledica strižnega toka v pasnicah.

Figure D.2: Transverse actions due to shear flow introduction into the flange

Tankostenski nosilci z valovitimi stojinami

- Strižna nosilnost

$$V_{Rd} = \chi_c \frac{f_{yw}}{\gamma_{M1} \sqrt{3}} h_w t_w$$

$$\chi_w = \min(\chi_{c,l}, \chi_{c,g})$$

$\chi_{c,l}$ redukcijski faktor za lokalni uklon

$\chi_{c,g}$ redukcijski faktor za globalni uklon

$$\chi_{c,l} = \frac{1,15}{0,9 + \bar{\lambda}_{c,l}} \leq 1,0 \quad \chi_{c,g} = \frac{1,5}{0,5 + \bar{\lambda}_{c,g}^2} \leq 1,0$$

$$\bar{\lambda}_{c,l} = \sqrt{\frac{f_y}{\tau_{cr,l} \sqrt{3}}} \quad \bar{\lambda}_{c,g} = \sqrt{\frac{f_y}{\tau_{cr,l} \sqrt{3}}}$$