

Univerza
v Ljubljani

Fakulteta
*za gradbeništvo
in geodezijo*



Katedra za metalne konstrukcije

JEKLENE KONSTRUKCIJE I

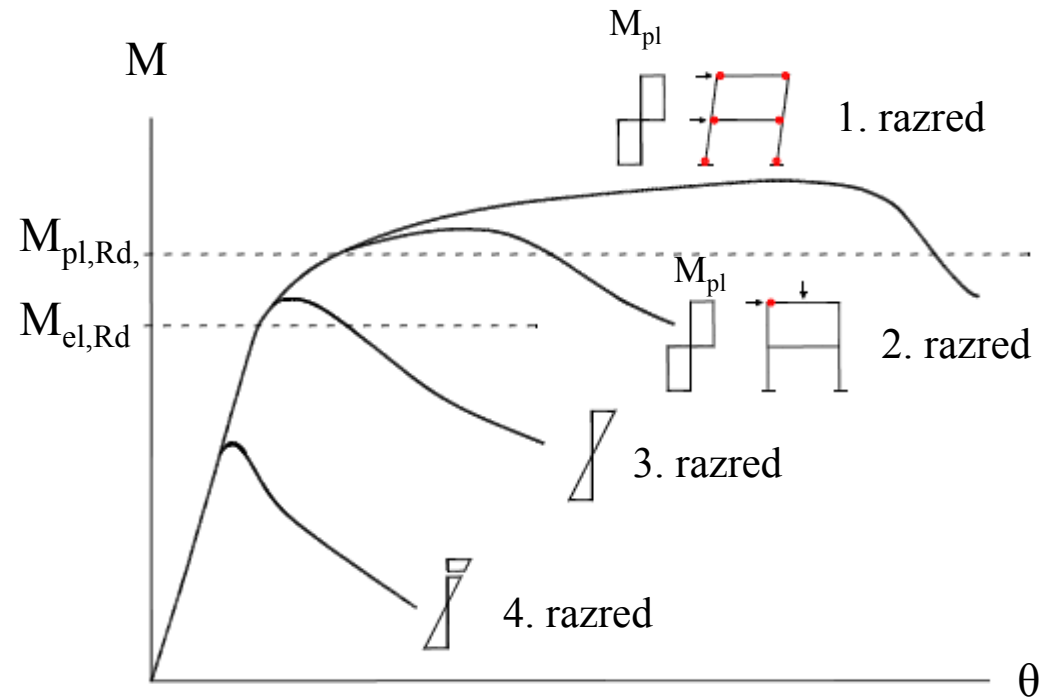
8.0 PREČNI PREREZI

prof. dr. Darko Beg
Sodelavec: Blaž Čermelj

Razvrščanje prečnih prerezov v štiri razrede kompaktnosti

Razred	Upogibna nosilnost prereza	Globalna analiza	Rotacijska kapaciteta
1. razred	plastična	plastična	dovolj velika, da omogoči razvoj porušnega mehanizma
2. razred	plastična	elastična	omejena, razvoj plastičnega členka (običajno razvoj prvega plastičnega členka)
3. razred	elastična	elastična	ne obstaja
4. razred	elastična na sodelujočem prerezu	elastična	ne obstaja

Razvrščanje prečnih prerezov v štiri razrede kompaktnosti

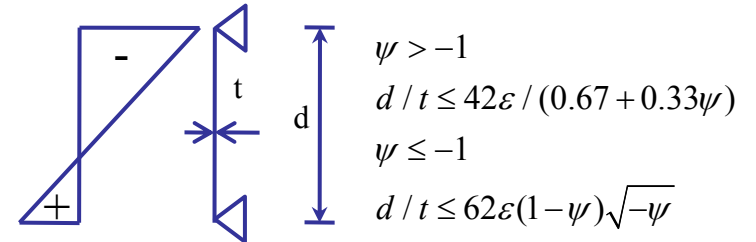


Razmejitev med vitkimi in semikompaktnimi prerezi

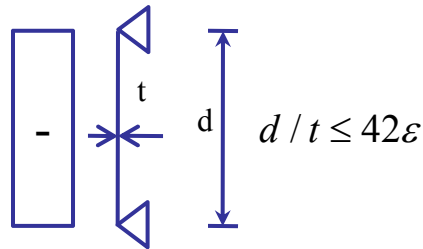
$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} \leq 0.673$ ni nevarnosti lokalnega izbočenja

$\bar{\lambda}_p = \sqrt{\frac{f_y}{\frac{\pi^2 E \cdot k_\sigma \cdot t^2}{12(1-\nu^2)b^2}}} = \frac{b}{t} / (28,4\varepsilon \cdot \sqrt{k_\sigma}) \leq 0.673 \quad \varepsilon = \sqrt{\frac{23,5}{f_y [kN/cm^2]}}$

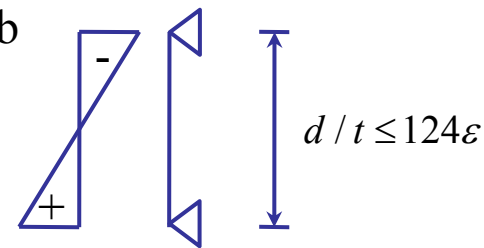
Upogib in tlak



Čisti tlak

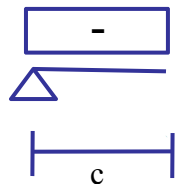


Čisti upogib



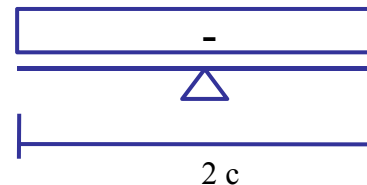
Tlačeni previsni del

$\frac{c}{t} \leq 14\varepsilon$



Pasnica (tlačena)

$\frac{2c}{t} \leq 28\varepsilon$

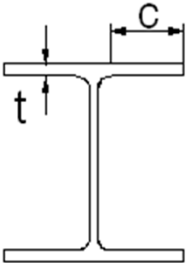
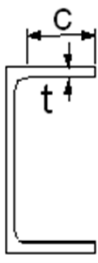
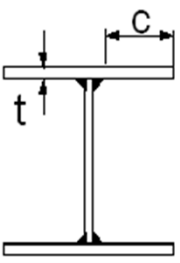
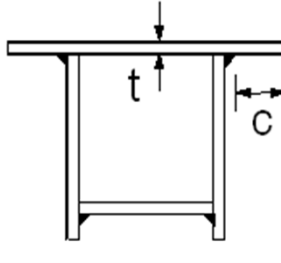
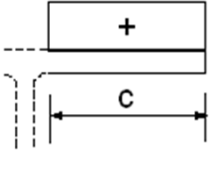
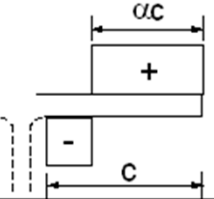
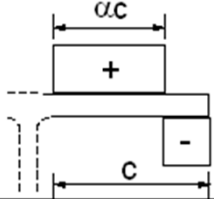
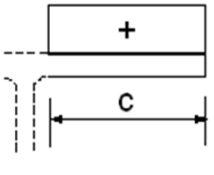
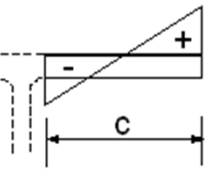
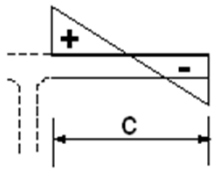


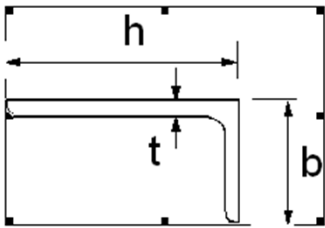
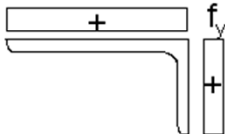
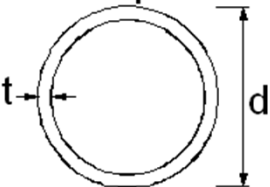
Preglednica 5.2 (list 1 od 3): Največje razmerje širine proti debelini tlačnih delov prečnih prerezov

Notranji tlačeni deli						
				Os upogiba		
				Os upogiba		
Razred kompaktnosti	Upogib	Tlak	Upogib in tlak			
Razpored napetost v delih prereza (tlačne pozitivne)						
1	$c/t \leq 72\varepsilon$	$c/t \leq 33\varepsilon$	pri $\alpha > 0,5$: $c/t \leq \frac{396\varepsilon}{13\alpha-1}$ pri $\alpha \leq 0,5$: $c/t \leq \frac{36\varepsilon}{\alpha}$			
2	$c/t \leq 83\varepsilon$	$c/t \leq 38\varepsilon$	pri $\alpha > 0,5$: $c/t \leq \frac{456\varepsilon}{13\alpha-1}$ pri $\alpha \leq 0,5$: $c/t \leq \frac{41,5\varepsilon}{\alpha}$			
Razpored napetost v delih prereza (tlačne pozitivne)						
3	$c/t \leq 124\varepsilon$	$c/t \leq 42\varepsilon$	pri $\psi > -1$: $c/t \leq \frac{42\varepsilon}{0,67+0,33\psi}$ pri $\psi \leq -1^*)$: $c/t \leq 62\varepsilon(1-\psi)\sqrt{(-\psi)}$			
$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

*) $\psi \leq -1$ pride v poštev, ko je tlačna napetost $\sigma < f_y$ ali natezna deformacija $\varepsilon_y > f_y/E$

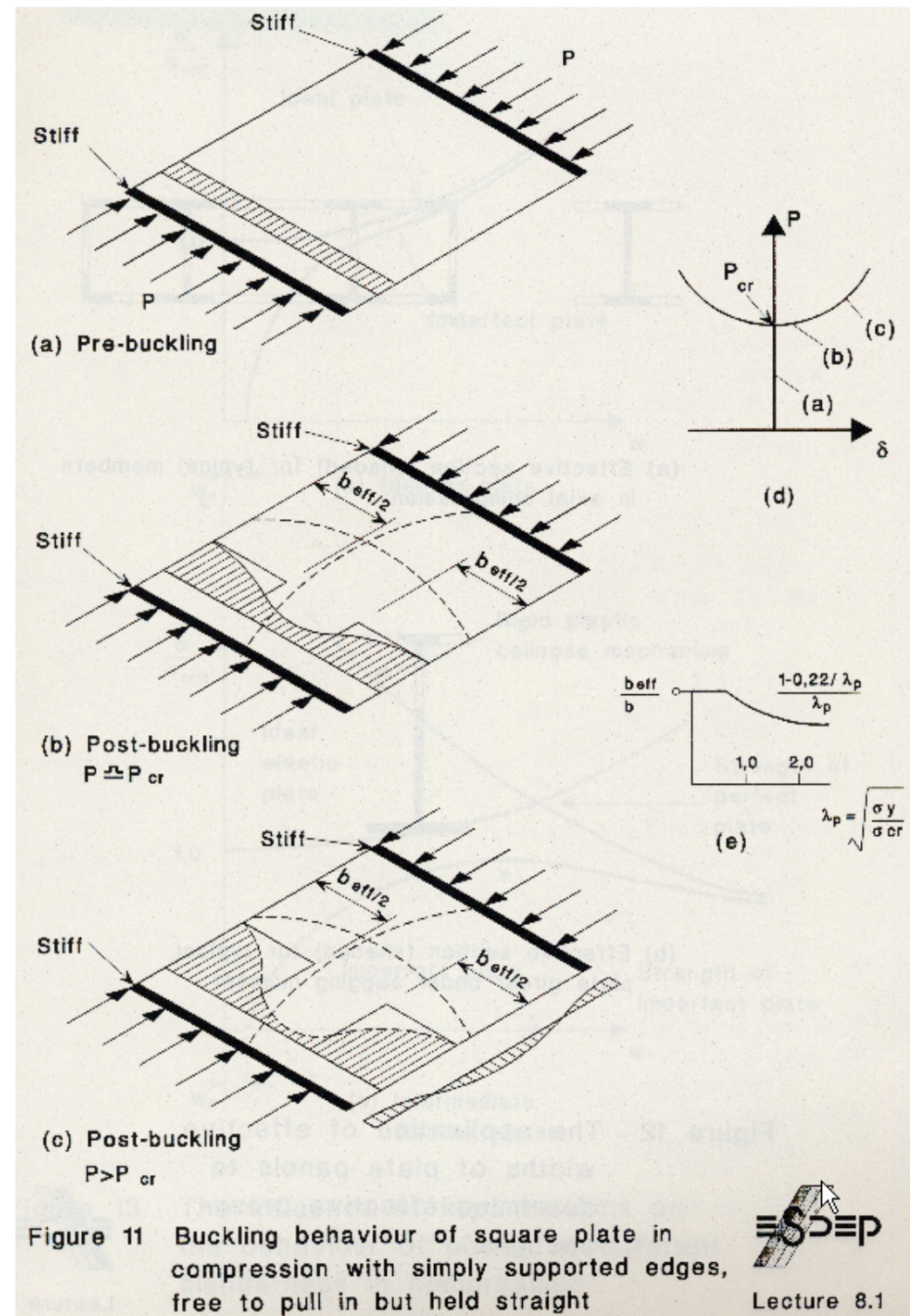
Previsni deli pasnic

Previsni deli pasnic						
						
Vroče valjani prerezi				Varjeni prerezi		
Razred kompaktnosti	Tlak		Upogib in tlak			
			Zunanji rob tlačén		Zunanji rob v nategu	
Razpored napetost v delih prereza (tlačne pozitivne)						
1	$c/t \leq 9\varepsilon$		$c/t \leq 9\varepsilon/\alpha$		$c/t \leq 10\varepsilon/(\alpha \sqrt{\alpha})$	
2	$c/t \leq 10\varepsilon$		$c/t \leq 10\varepsilon/\alpha$		$c/t \leq 10\varepsilon/(\alpha \sqrt{\alpha})$	
Razpored napetost v delih prereza (tlačne pozitivne)						
3	$c/t \leq 14\varepsilon$		$c/t \leq 21\varepsilon\sqrt{\kappa_o}$), za κ_o glej 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

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		

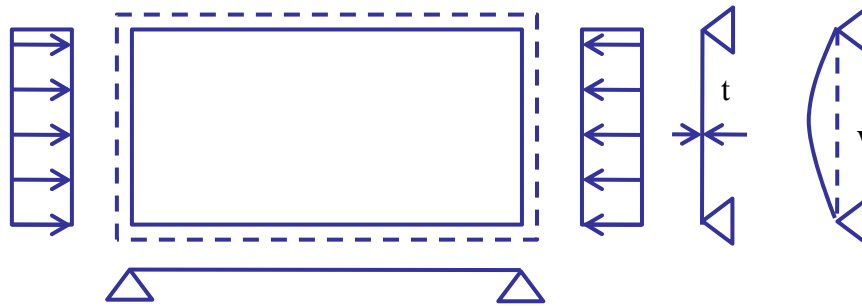
Vitki prerezi

- Metoda sodelujoče širine (lokalno izbočenje)
- $b_{\text{eff}} = \rho b$
- $\rho = \rho(\lambda)$



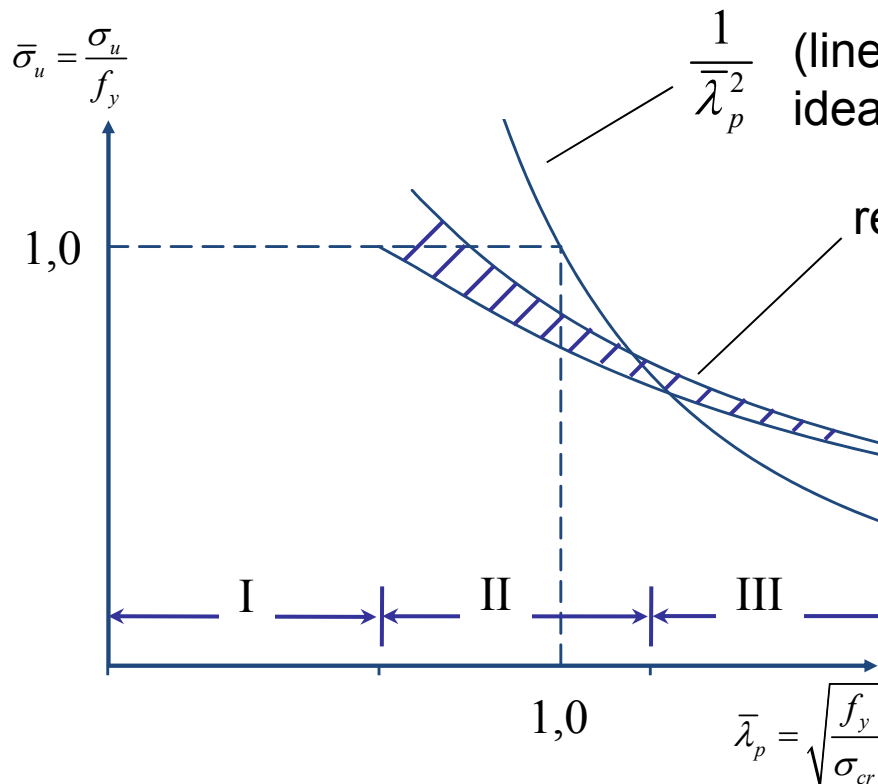
Lokalno izbočenje vitkih prerezov

Normalne napetosti



$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{f_y \cdot 12(1-\nu^2)b^2}{\pi^2 E \cdot t^2 K_\sigma}} = \frac{b}{t} \frac{1}{28.4 \varepsilon \sqrt{K_\sigma}}$$

$$\varepsilon = \sqrt{\frac{23,5}{f_y [kN/cm^2]}}$$



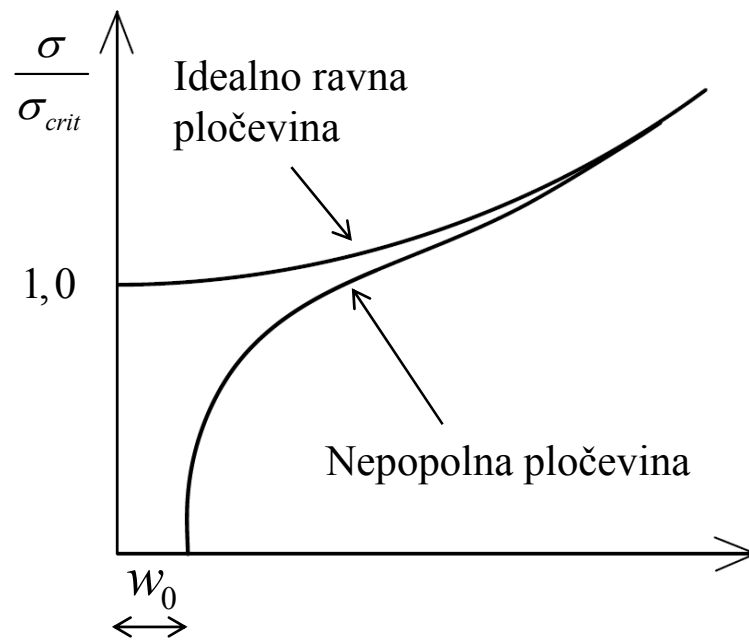
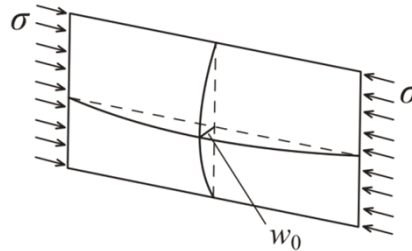
$\frac{1}{\bar{\lambda}_p^2}$ (linearna teorija izbočenja; idealno ravna, elastična pločevina)

realno obnašanje pločevin

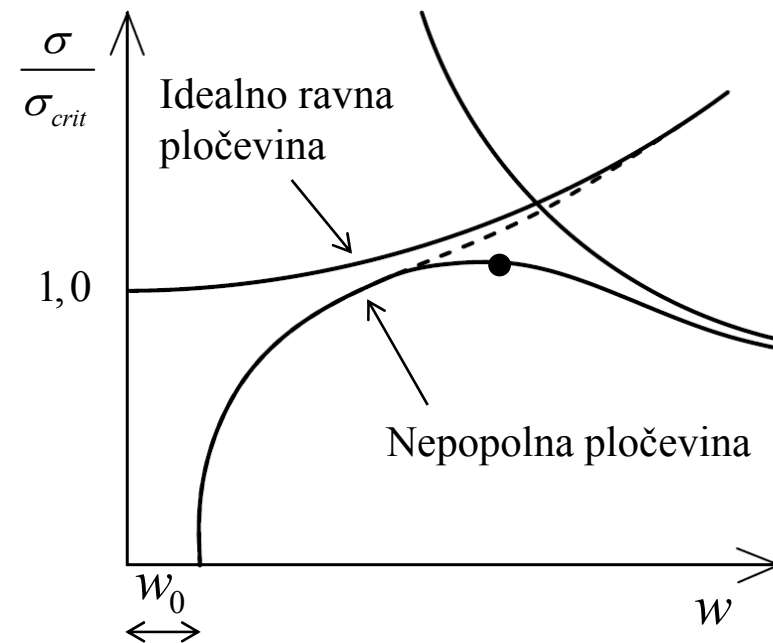
- nelinearna teorija izbočenja
- postkritična nosilnost

- I – ni lokalnega izbočenja, polna nosilnost f_y – majhne vitkosti
- II – zmanjšanje nosilnosti zaradi lokalnega izbočenja, vpliv zaostalih napetosti in w_0 – srednje vitkosti
- III – postkritična nosilnost – velike vitkosti, nosilnost višja kot pri linearni teoriji izbočenja

Vpliv geometrijske nepopolnosti pri vitkih pločevinah

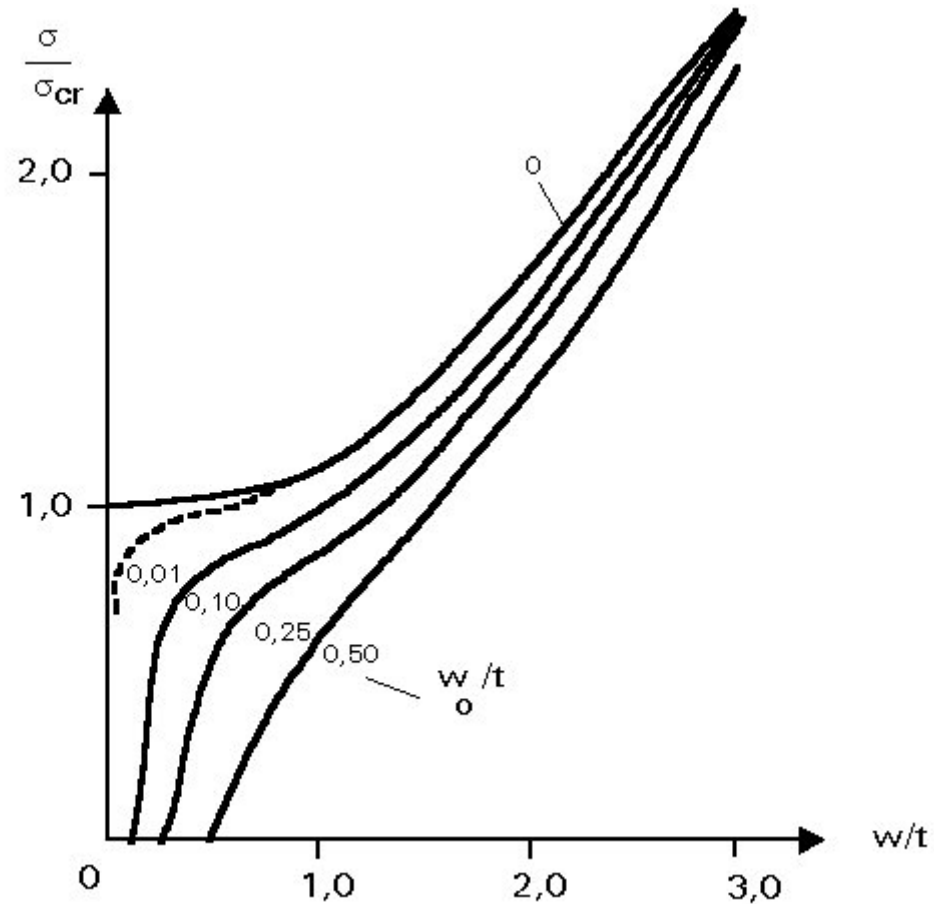


Elastični odziv vitkih pločevin



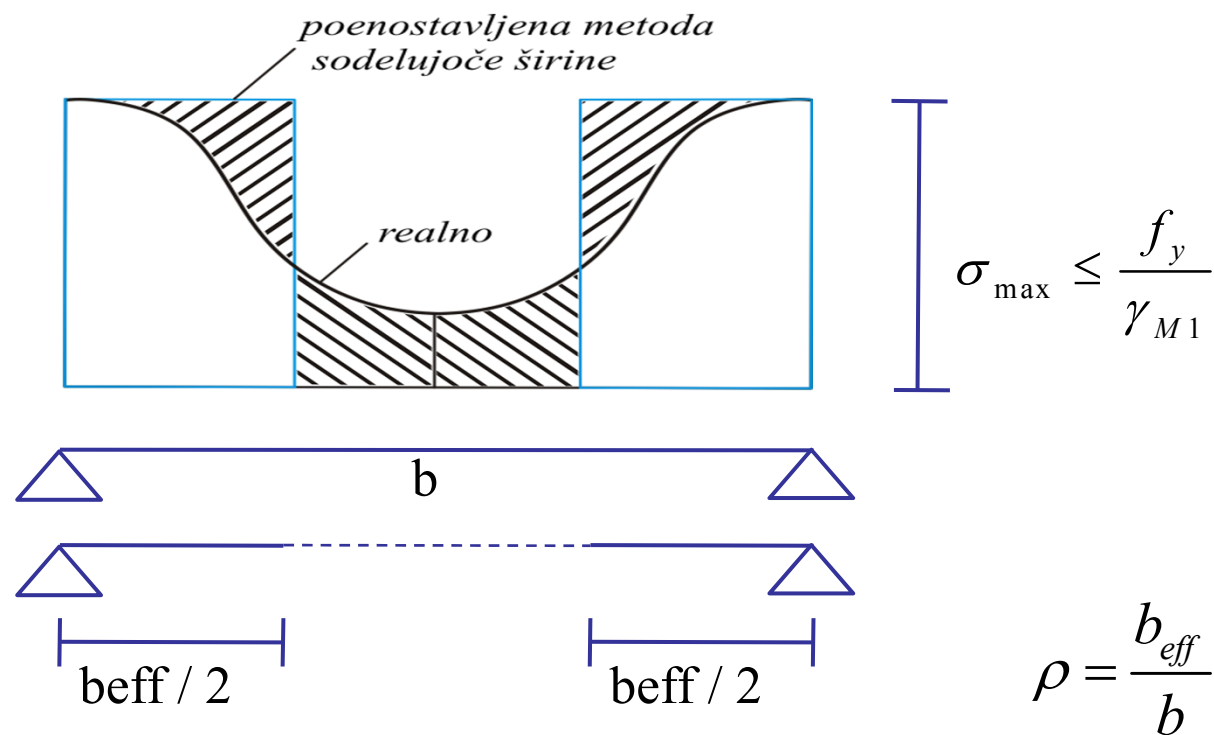
Elasto-plastični odziv pločevin

Vpliv nepopolnosti



Geometrijska nepopolnost - nelinearna teorija izbočenja pločevin

Pojem sodelujoče širine



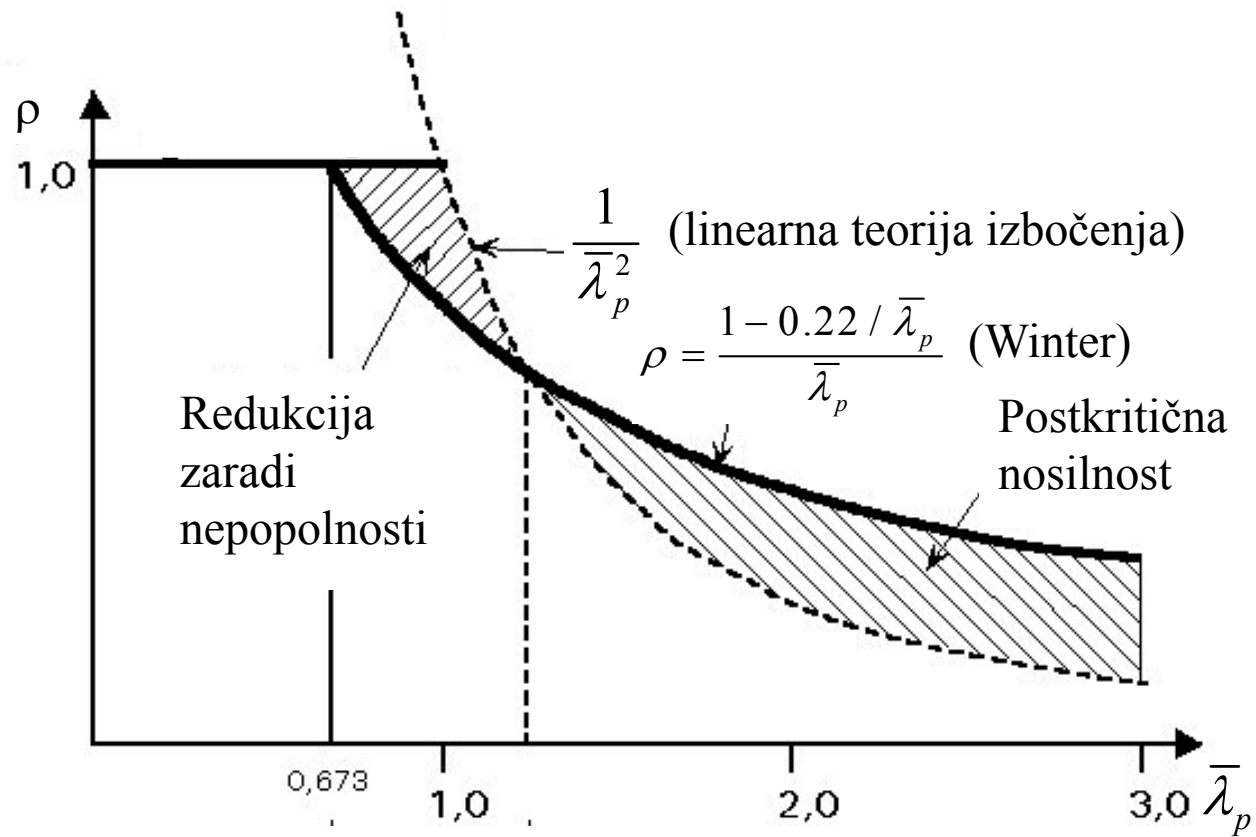
pri $\bar{\lambda}_p \leq 0.673$

$$\rho = 1.0$$

pri $\bar{\lambda}_p > 0.673$

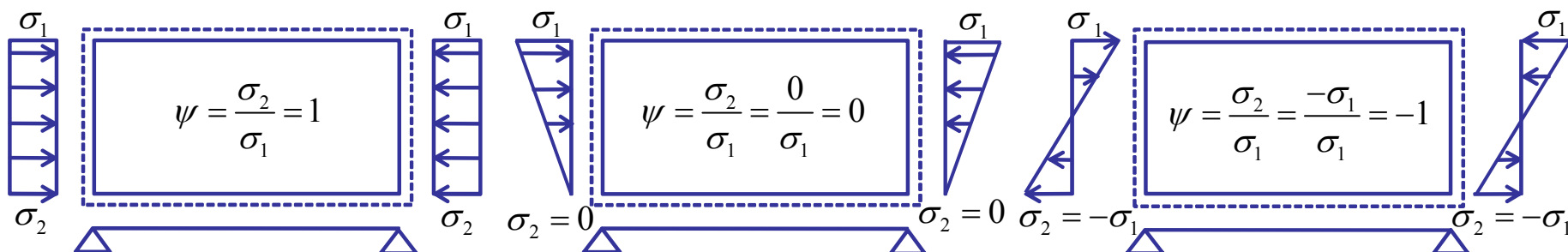
$$\rho = \frac{1}{\bar{\lambda}_p} \left(1 - \frac{0.22}{\bar{\lambda}_p} \right)$$

Winterjeva sodelujoča širina



Račun sodelujočih širin

- Pločevine, prečno podprte ob obeh vzdolžnih robovih:

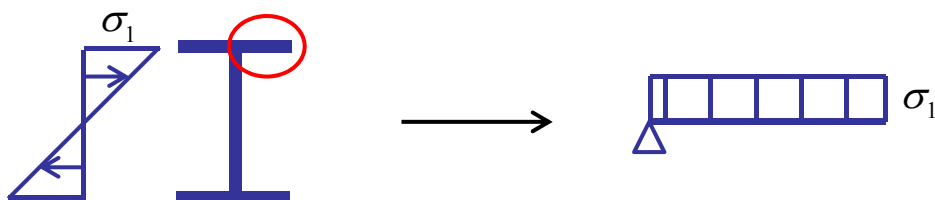


SIST EN 1993-1-5:

$$\rho = 1,0 \quad \text{pri} \quad \bar{\lambda}_p \leq 0,5 + \sqrt{0,085 - 0,055\psi}$$

$$\rho = \frac{\bar{\lambda}_p - 0,055(3 + \psi)}{\bar{\lambda}_p^2} \quad \text{pri} \quad \bar{\lambda}_p > 0,5 + \sqrt{0,085 - 0,055\psi}$$

- Pločevine z enim prostim vzdolžnim robom:

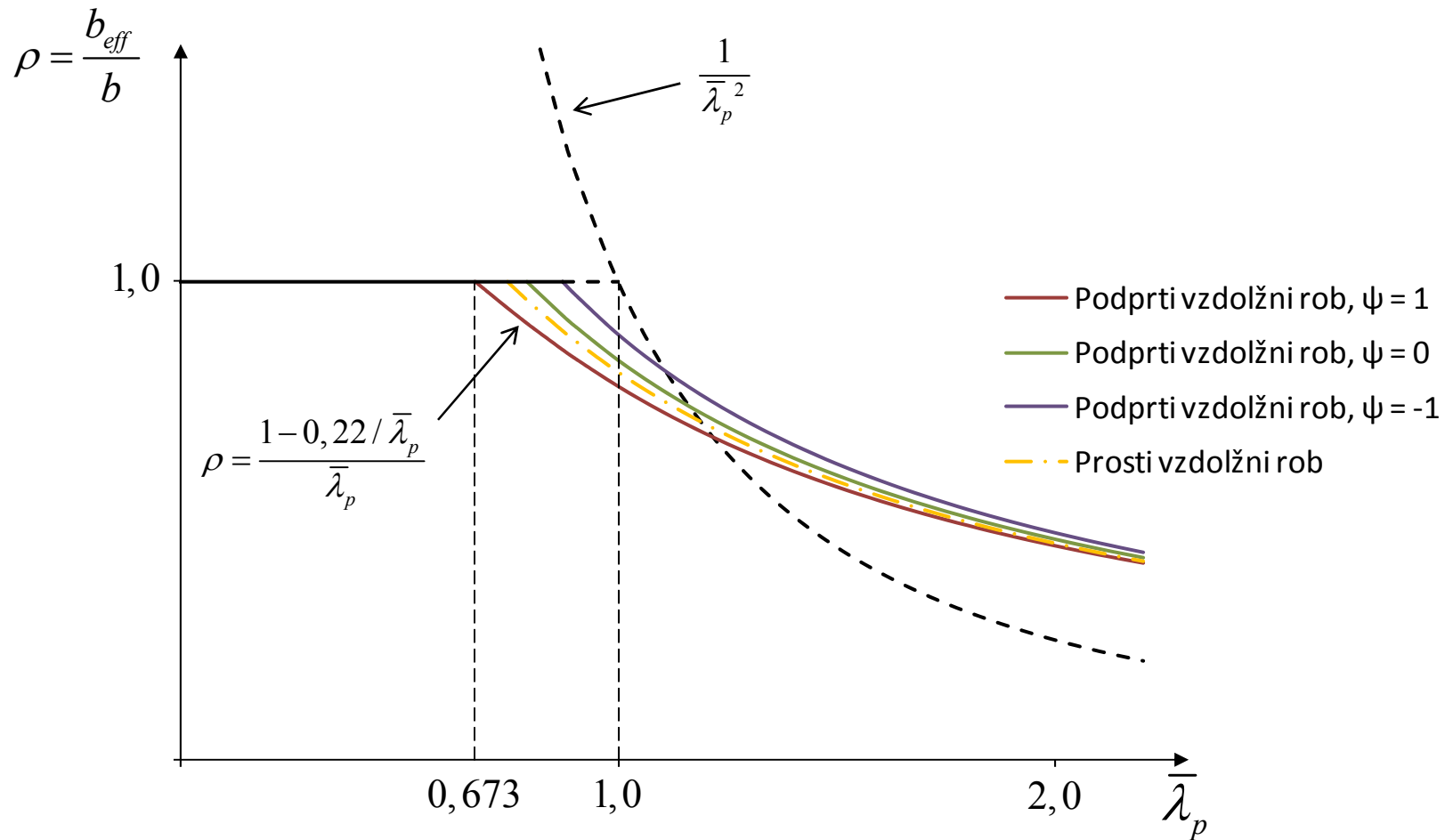


SIST EN 1993-1-5:

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

$$\rho = \frac{\bar{\lambda}_p - 0,188}{\bar{\lambda}_p} \quad \text{pri} \quad \bar{\lambda}_p > 0,748$$

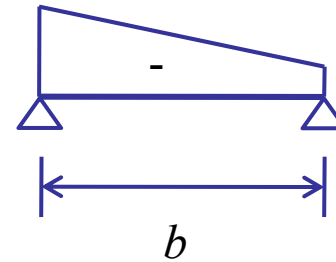
Zveza med $\rho = \frac{b_{eff}}{b}$ in vitkostjo pločevine $\bar{\lambda}_p$



Za razporeditve napetosti, ki niso konstantne

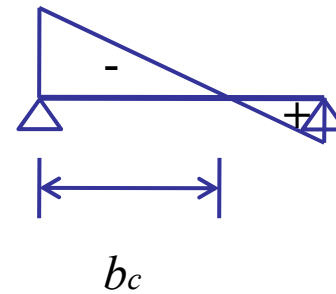
$$\rho = \frac{b_{eff}}{b}$$

(celotne širina je tlačena)



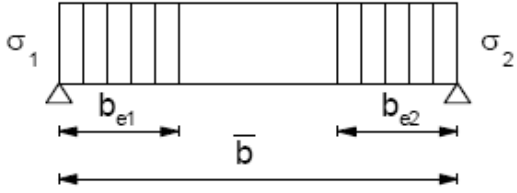
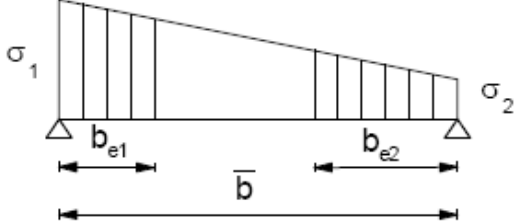
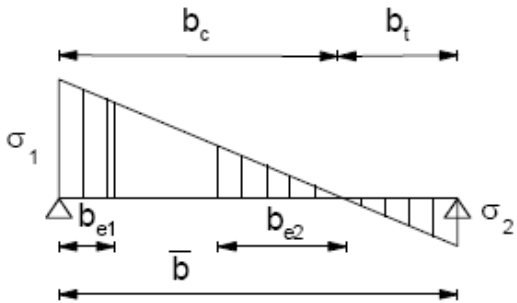
$$\rho = \frac{b_{eff}}{b_c}$$

(del širine je tlaččen - b_c)

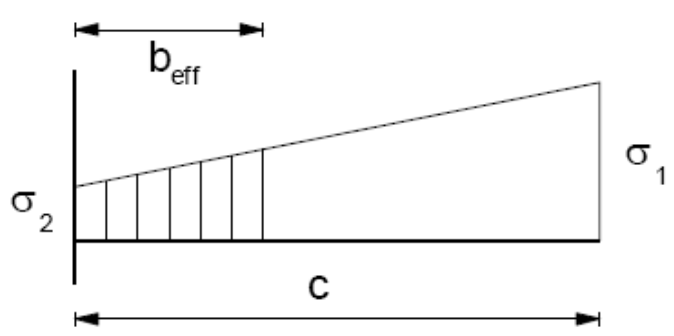
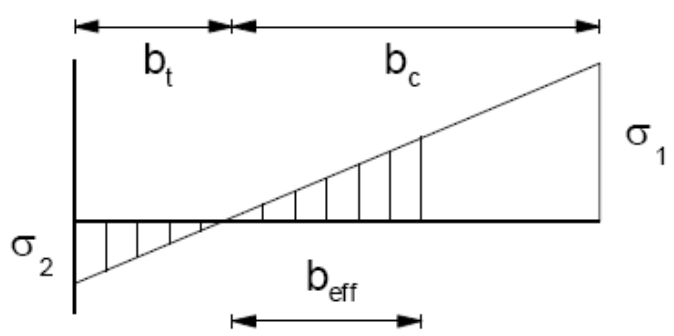


$$\left. \begin{array}{l} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right\} \bar{\lambda}_p = f(b)$$

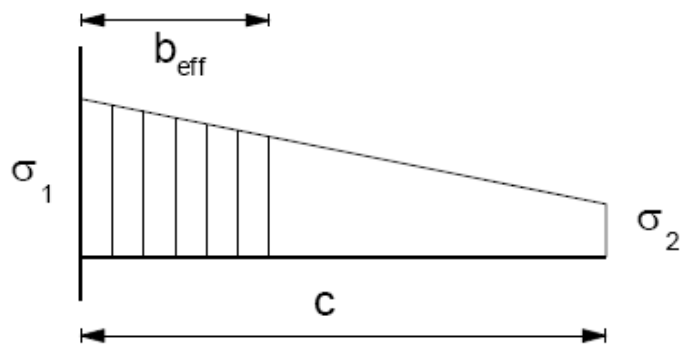
Sodelujoča širina pri pločevinah, podprtih ob obeh vzdolžnih robovih

Razporeditev napetosti				Sodelujoča širina b_{eff}		
				$\psi = 1:$ $b_{eff} = \rho \bar{b}$ $b_{e1} = 0.5 b_{eff}$ $b_{e2} = 0.5 b_{eff}$		
				$1 > \psi \geq 0:$ $b_{eff} = \rho \bar{b}$ $b_{e1} = \frac{2b_{eff}}{5 - \psi}$ $b_{e2} = b_{eff} - b_{e1}$		
				$\psi < 0:$ $b_{eff} = \rho b_c = \rho \bar{b} / (1 - \psi)$ $b_{e1} = 0.4 b_{eff}$ $b_{e2} = 0.6 b_{eff}$ $b_c = \{\text{širina tlačnega dela pločvine}\}$		
$\psi = \sigma_2 / \sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1	$-1 > \psi > -2$
k_σ	4.0	$\frac{8.2}{1.05 + \psi}$	7.81	$7.81 - 6.29\psi + 9.78\psi^2$	23.9	$5.98 (1 - \psi)^2$

Sodelujoča širina pri pločevinah z enim prostim vzdolžnim robom

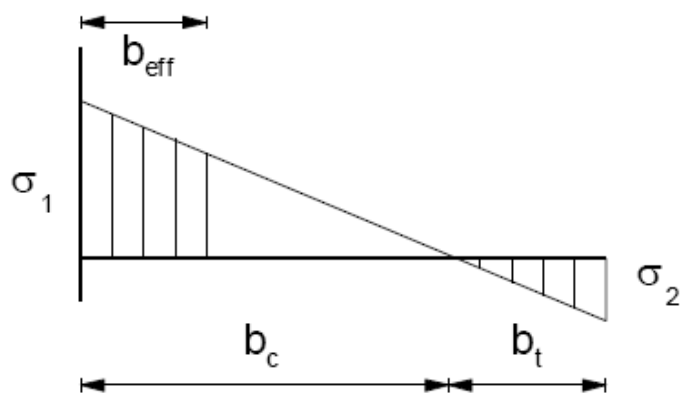
Razporeditev napetosti		Sodelujoča širina b_{eff}		
		$1 > \psi \geq 0:$ $b_{eff} = \rho c$		
		$\psi < 0:$ $b_{eff} = \rho b_c = \rho c / (1 - \psi)$		
$\psi = \sigma_2 / \sigma_1$	1	0	-1	$1 \geq \psi \geq -1$
k_σ	0.43	0.57	0.85	$0.57 - 0.21\psi + 0.07\psi^2$

Sodelujoča širina pri pločevinah z enim prostim vzdolžnim robom



$$1 > \psi \geq 0:$$

$$b_{\text{eff}} = \rho c$$



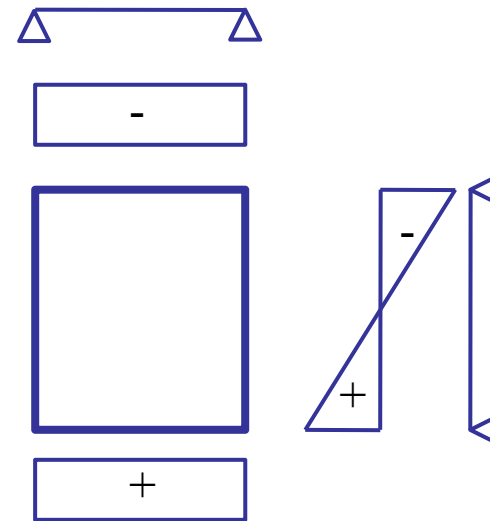
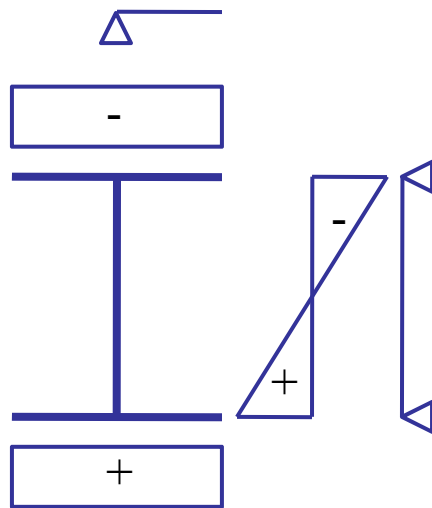
$$\psi < 0:$$

$$b_{\text{eff}} = \rho b_c = \rho c / (1 - \psi)$$

$\psi = \sigma_2 / \sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1
k_σ	0.43	$\frac{0.578}{0.34 + \psi}$	1.70	$1.7 - 5\psi + 17.1\psi^2$	23.8

Sodelujoča širina pri prečnih prerezih

- Pri vitkih prerezih obravnavamo vsako pločevino zase - sodelujočo širino določimo za vsako pločevino posebej.

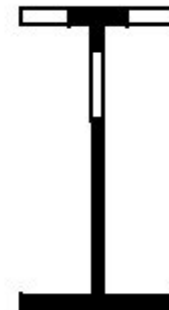


Sodelujoč (efektivni) prerez določen s sodelujočo širino

Sodelujoč prerez – čisti tlak



Sodelujoč prerez – čisti moment



- Račun geometrijskih karakteristik: A_{eff} , W_{eff} , J_{eff}

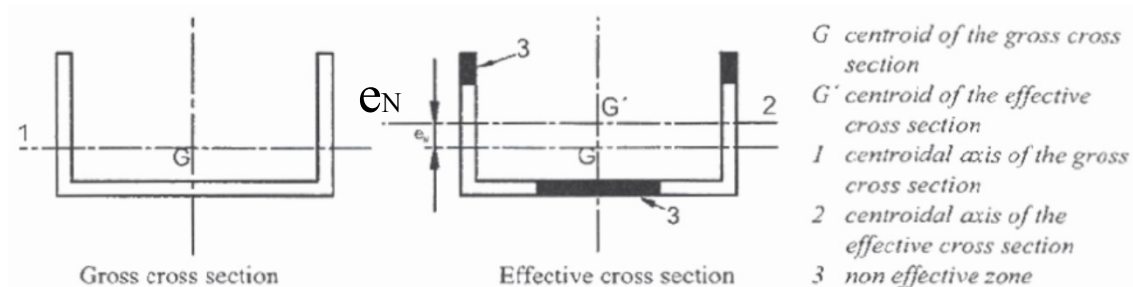
Rezultat je sodelujoč prerez, v katerem izbočenih delov pločevin ne upoštevamo. Obravnavamo ga enako kot prereze 3. razreda kompaktnosti.

□ Zaradi nesimetričnega razporeda sodelujočih širin se lahko sodelujočemu prerezu spremeni lega težišča glede na začetni prerez:

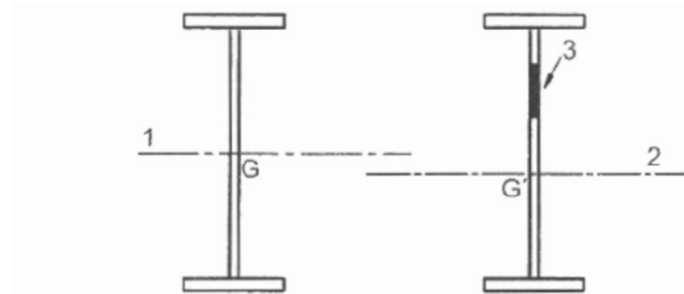
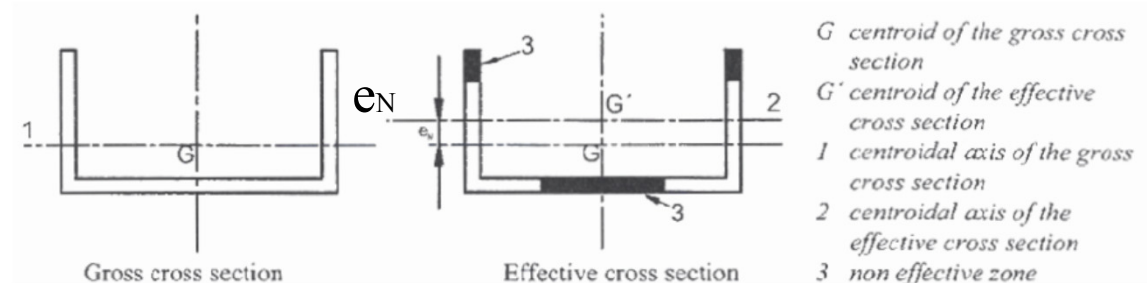
- osna sila – e_N (samo nesimetrični prerezi);
- moment – e_M .

□ Razvije se dodatni moment $\Delta M = N e_N$

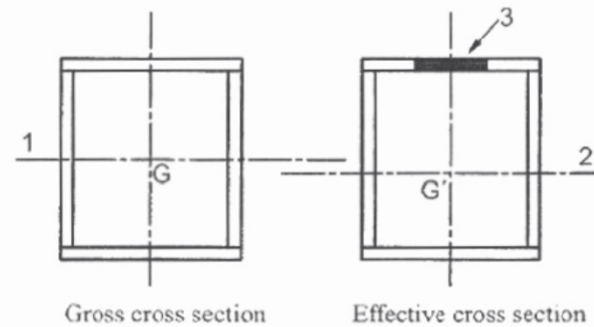
□ Račun geometrijskih karakteristik: A_{eff} , W_{eff} , J_{eff}



Nosilnost vitkih prerezov

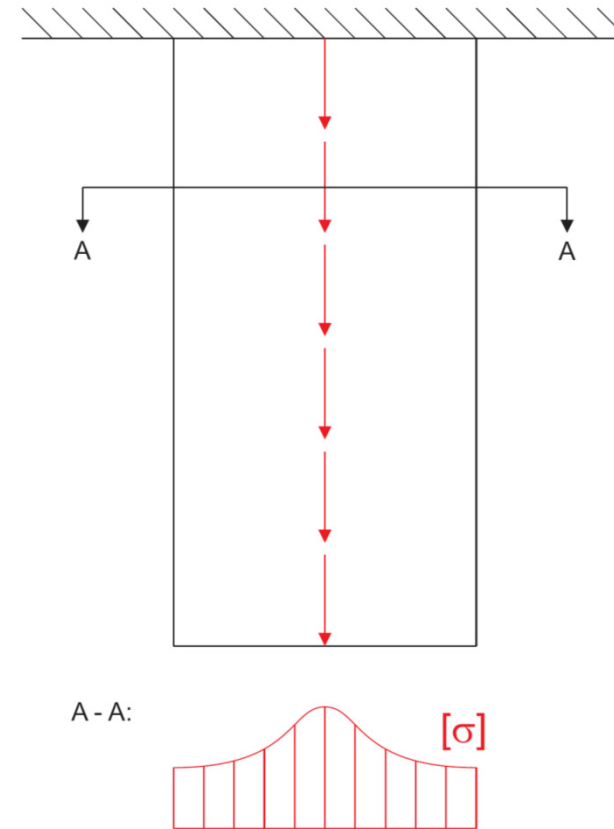
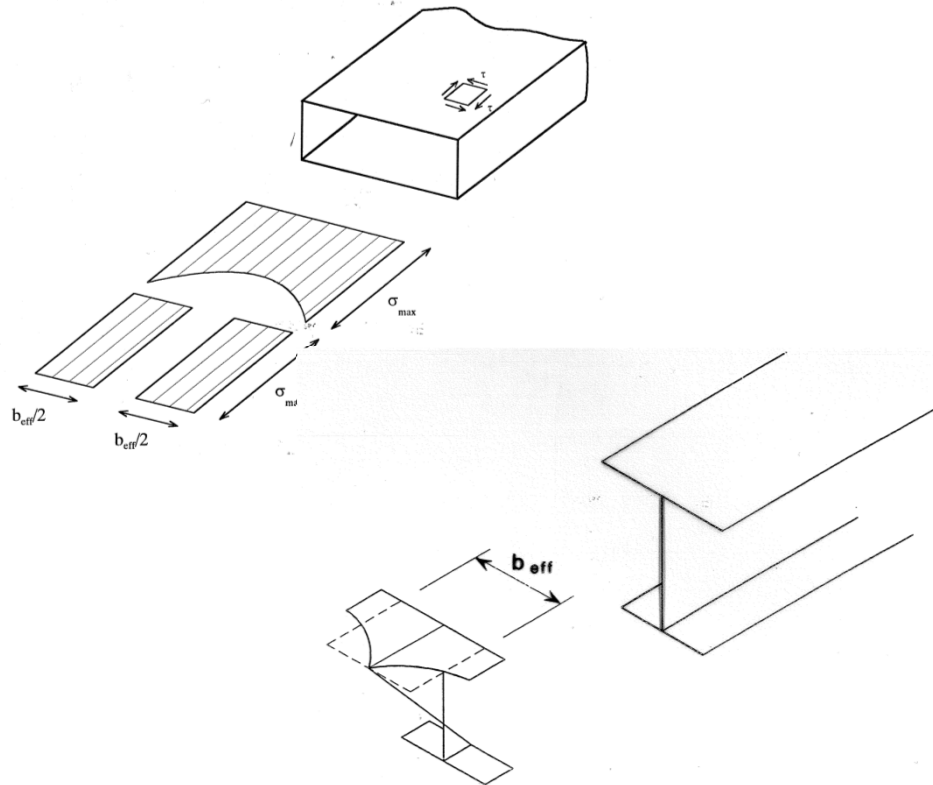


$$\frac{N}{A_{eff}} + \frac{M + Ne_N}{W_{eff}} \leq \frac{f_y}{\gamma_{M0}}$$



4. razred kompaktnosti

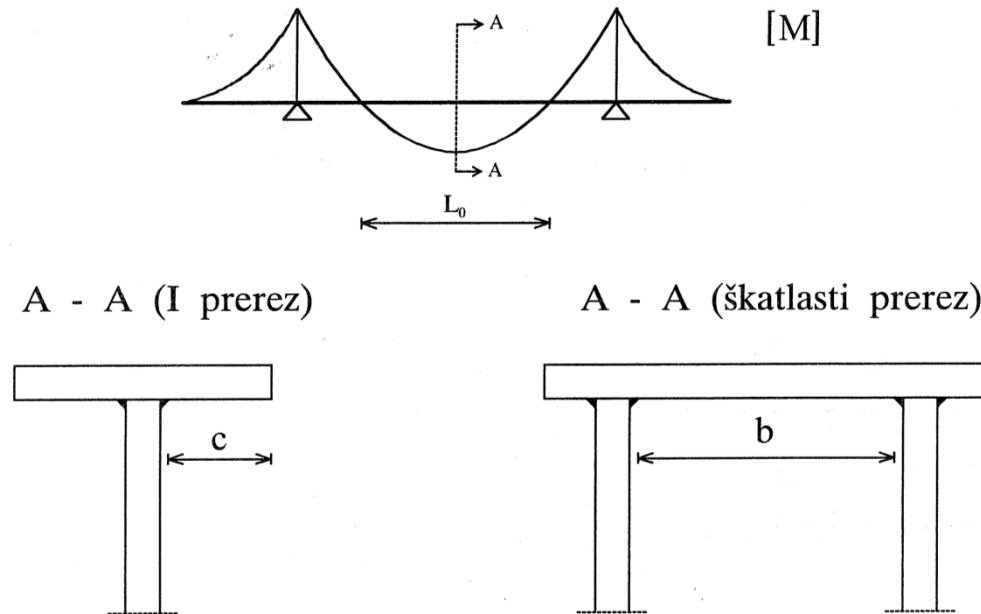
Strižna podajnost pasnic – shear lag



Pri širokih pasnicah se zaradi strižne podajnosti pojavi neenakomeren razpored napetosti (shear lag). Upoštevamo ga lahko z metodo sodelujoče širine – **v tlaku in nategu**.

Strižna podajnost

Strižno podajnost pri stavbah upoštevamo le izjemoma. Pri standardnih vroče valjanih in podobnih varjenih profilih ga zanemarimo, pri ostalih profilih pa, če je izpolnjen pogoj:



previsni elementi $c \leq L_0/20$
notranji element $b \leq L_0/10$

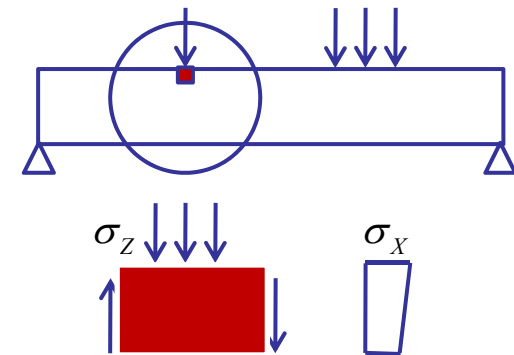
Točnejši izračun – glej SIST EN 1993-1-5

Elastična kontrola pri kombinaciji napetosti

- Misesov pogoj tečenja – začetek plastifikacije (v eni točki)

$$\left(\frac{\sigma_{x,Ed}}{f_y / \gamma_{M0}} \right)^2 + \left(\frac{\sigma_{z,Ed}}{f_y / \gamma_{M0}} \right)^2 - \left(\frac{\sigma_{x,Ed}}{f_y / \gamma_{M0}} \right) \left(\frac{\sigma_{z,Ed}}{f_y / \gamma_{M0}} \right) + 3 \left(\frac{\tau_{Ed}}{f_y / \gamma_{M0}} \right)^2 \leq 1,0$$

- $\sigma_{x,Ed}$ = vzdolžna napetost v opazovani točki
- $\sigma_{z,Ed}$ = prečna napetost v opazovani točki
- τ_{Ed} = strižna napetost v opazovani točki



Ta pogoj je v primerjavi s kriterijem plastične nosilnosti prečnega prereza zelo konservativen (npr. interakcija M-V).

Projektna nosilnost prečnih prerezov

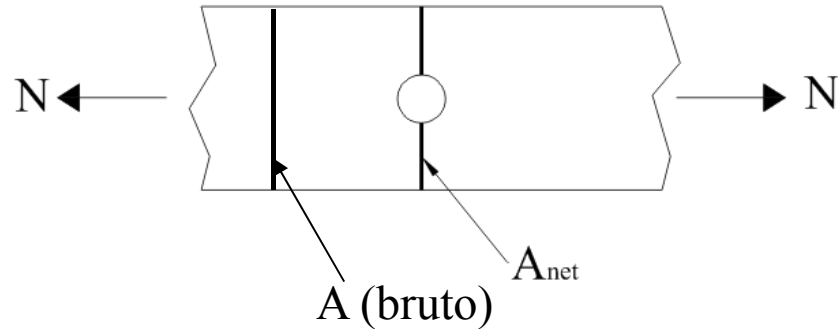
□ Prečni prerezi v nategu (vsi razredi kompaktnosti)

- Projektna nosilnost bruto prereza:

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}, \quad \gamma_{M0} = 1.0$$

- Projektna nosilnost neto prereza:

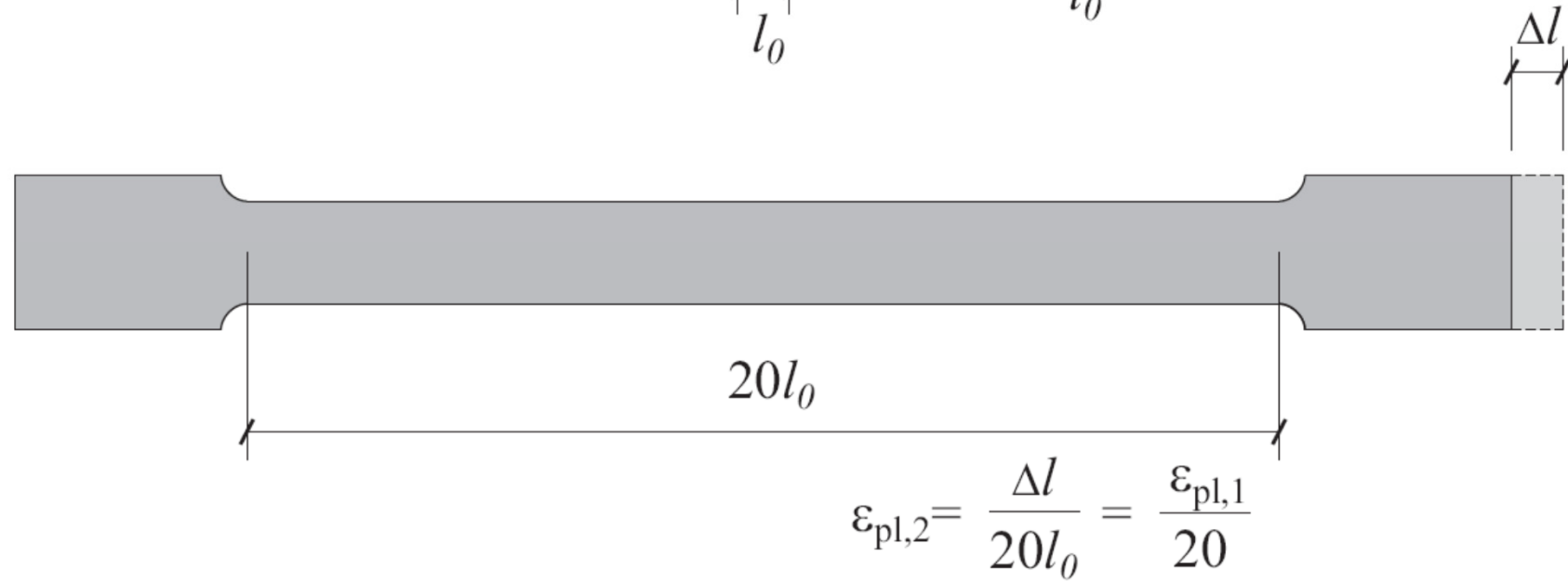
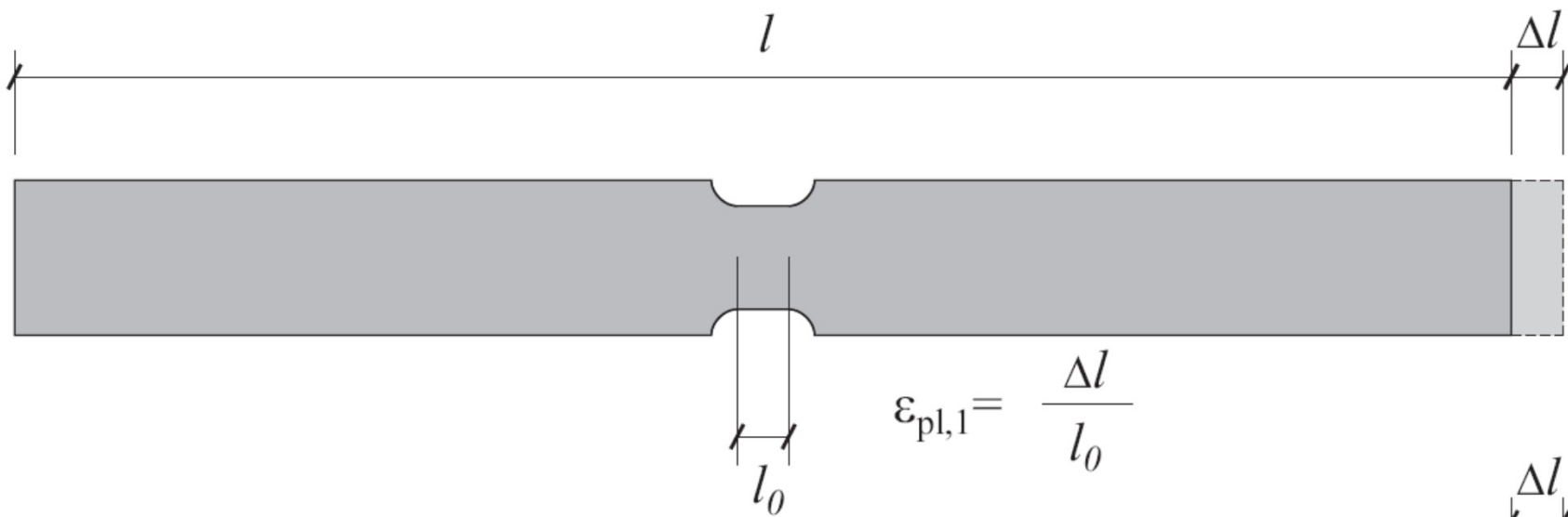
$$N_{u,Rd} = \frac{0.9A_{net}f_u}{\gamma_{M2}}, \quad \gamma_{M2} = 1.25$$



- Pogoj duktilne porušitve:

$$N_{pl,Rd} \leq N_{u,Rd} \quad \frac{A_{net}}{A} \geq \frac{f_y \gamma_{M2}}{0.9 f_u \gamma_{M0}}$$

jeklo	$\gamma_{M0} = 1.00$	$\gamma_{M0} = 1.10$
S235J0	0.907	0.824
S355J0	1.016	0.915
S460M	1.183	1.076



- **Prečni prerezi v tlaku**

1., 2. in 3. razred kompaktnosti

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$$

4. razred kompaktnosti

$$N_{c,Rd} = \frac{A_{eff} f_y}{\gamma_{M0}}$$

- **Prečni prerezi v enoosnem upogibu**

1. in 2. razred kompaktnosti

$$M_{Ed} \leq M_{pl,Rd} = \frac{W_{pl} \cdot f_y}{\gamma_{M0}}$$

3. razred kompaktnosti

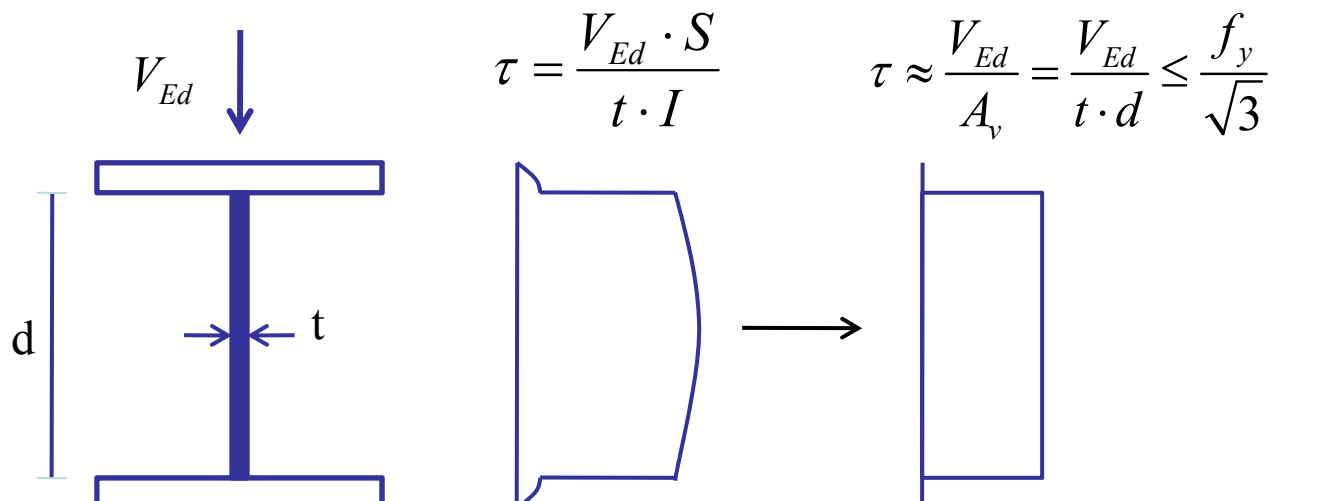
$$M_{Ed} \leq M_{el,Rd} = \frac{W_{el} \cdot f_y}{\gamma_{M0}}$$

4. razred kompaktnosti

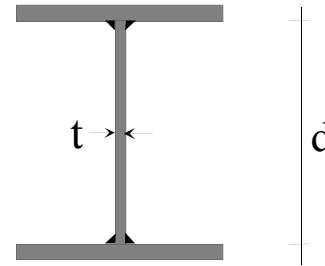
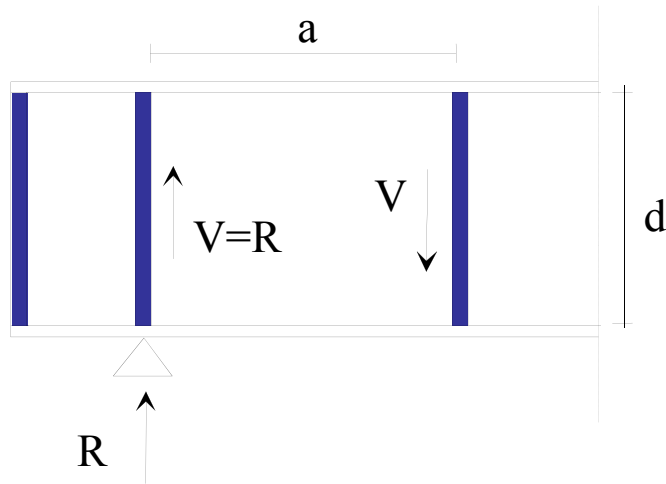
$$M_{Ed} \leq M_{c,Rd} = \frac{W_{eff} \cdot f_y}{\gamma_{M0}}$$

Strižna nosilnost jeklenih prečnih prerezov

Strige prevzemajo predvsem pločevine, vzporedne strižni sili.


$$\tau = \frac{V_{Ed} \cdot S}{t \cdot I}$$
$$\tau \approx \frac{V_{Ed}}{A_v} = \frac{V_{Ed}}{t \cdot d} \leq \frac{f_y}{\sqrt{3}}$$
$$V_{pl,Rd} \left(\tau = \frac{f_y}{\sqrt{3}} \right) = \frac{A_v \cdot f_y}{\sqrt{3} \cdot \gamma_{Mo}}$$

- **Prečni prerezi v strigu**



$$\alpha = \frac{a}{d}$$

$$k_\tau = 5,34 + \frac{4,0}{\alpha^2} \quad \text{pri } \alpha \geq 1,0$$

$$k_\tau = 4,0 + \frac{5,34}{\alpha^2} \quad \text{pri } \alpha < 1,0$$

Kompaktna stojina (SIST EN 1993-1-1)

$$\frac{d}{t} \leq \frac{72}{\eta} \varepsilon \quad \alpha = \infty,$$

ali

$$\frac{d}{t} \leq \frac{31}{\eta} \varepsilon \sqrt{k_\tau}, \quad \alpha = \frac{a}{d}$$

$$V_{pl,Rd} = \frac{\eta \cdot d \cdot t \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}}$$

Vitka stojina (SIST EN 1993-1-5)

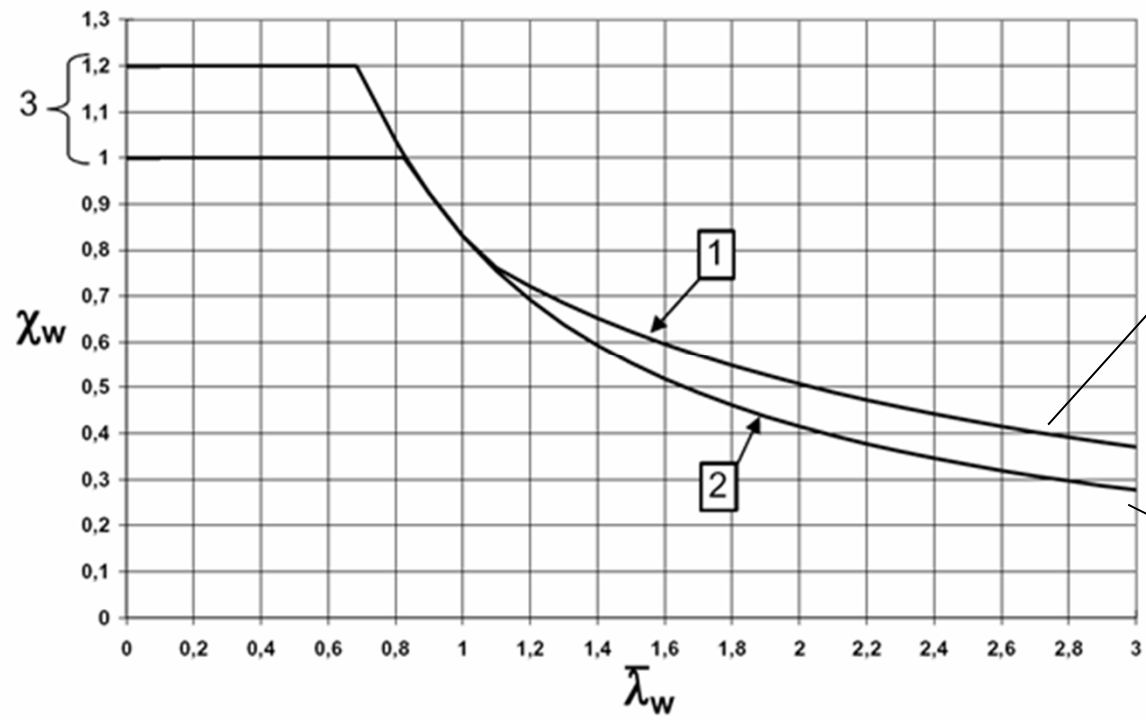
$$\frac{d}{t} > \frac{72}{\eta} \varepsilon \quad \alpha = \infty$$

ali

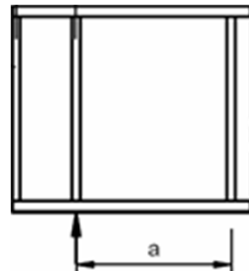
$$\frac{d}{t} > \frac{31}{\eta} \varepsilon \sqrt{k_\tau}, \quad \alpha = \frac{a}{d}$$

$$V_{bw,Rd} = \frac{\chi_w \cdot d \cdot t \cdot f_y}{\sqrt{3} \cdot \gamma_{M1}}, \quad \chi_w = f(\bar{\lambda}_w)$$

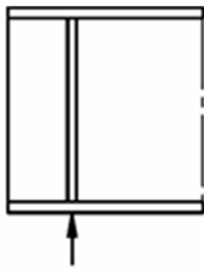
Za jekla S235 do S460 $\eta = 1.2$, za jekla višje trdnosti $\eta = 1.0$



1 ... toga robna podpora



2 ... podajna robna podpora

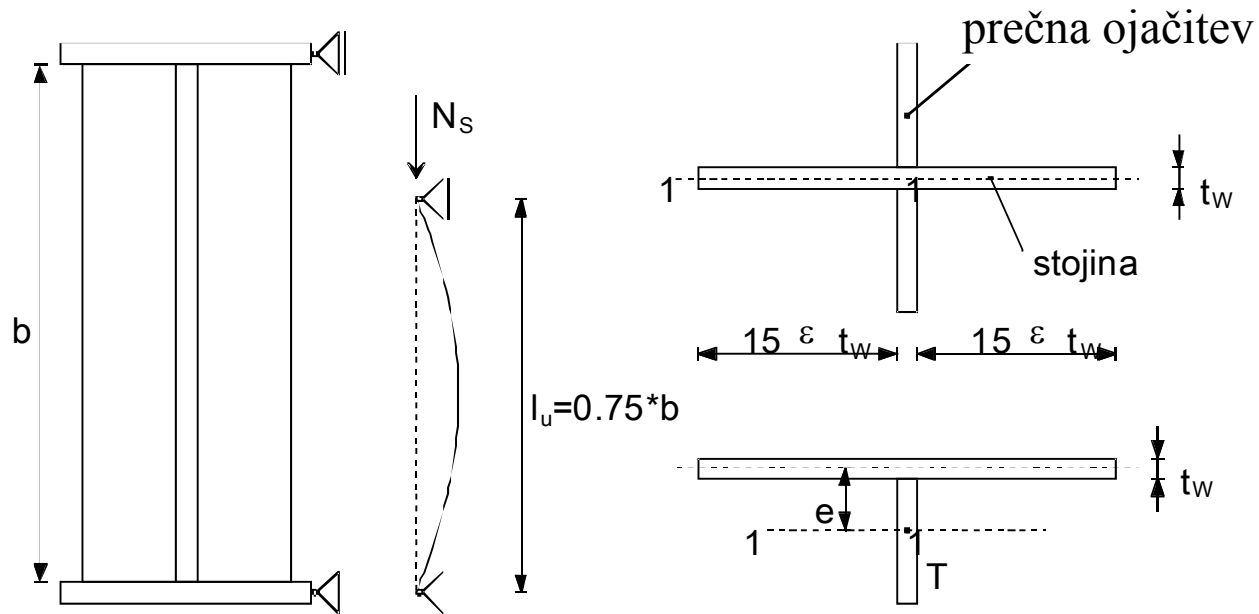


3 ... $\eta = 1.0 - 1.2$

	Toga robna podpora	Podajna robna podpora
$\bar{\lambda}_w < 0,83/\eta$	η	η
$0,83/\eta \leq \bar{\lambda}_w < 1,08$	$0,83/\bar{\lambda}_w$	$0,83/\bar{\lambda}_w$
$\bar{\lambda}_w \geq 1,08$	$1,37/(0,7 + \bar{\lambda}_w)$	$0,83/\bar{\lambda}_w$

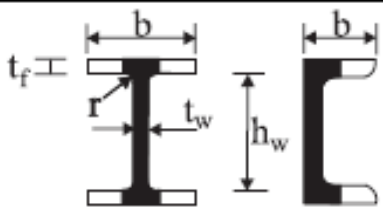
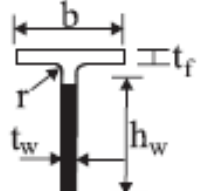
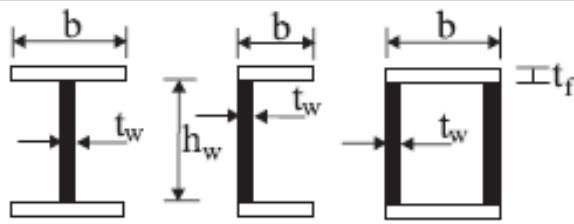
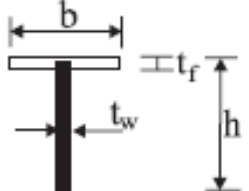
χ_w

Določanje uklonske nosilnosti prečnih ojačitev

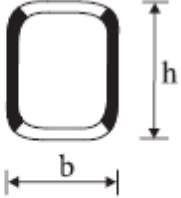
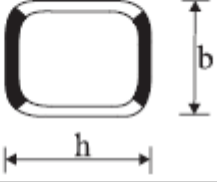




uklonska krivulja c, uklon okoli osi 1-1

Površina strižnega prereza A_v

Vrsta prereza		Smer delovanja strižne sile	A_v	Oblika prereza
vroče valjani profili	I, H, U	vzporedno s stojino	$A - 2bt_f + (t_w + 2r)t_f$ vendar $A_v \geq \eta h_w t_w$ (za I, H)	
	T		$0,9(A - bt_f)$	
varjeni profili	I, H, U, škatlasti	vzporedno s stojino	$\eta \sum (h_w t_w)$	
	T		$t_w \left(h - \frac{t_f}{2} \right)$	

Površina strižnega prereza A_v

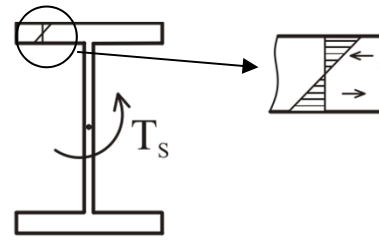
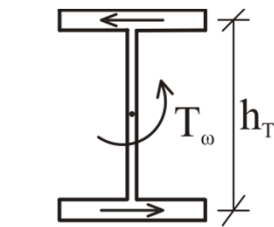
Vrsta prereza	Smer delovanja strižne sile	A_v	Oblika prereza
valjani pravokotni votli profili	vzporedno z višino	$\frac{Ah}{b+h}$	
	vzporedno s širino	$\frac{Ab}{b+h}$	
okrogli votli profili in cevi	ni pomembno	$\frac{2A}{\pi} \approx 0,64A$	
pločevine in polni pravokotni profili	ni pomembno	A	

		$A_v / (\eta h_w t_w)$		
		A_v	$\eta = 1,0$	$\eta = 1,2$
HEA	100	7,52	1,88	1,57
	300	37,75	1,70	1,41
	600	92,75	1,32	1,10
HEB	100	9,00	1,88	1,56
	300	47,35	1,64	1,37
	600	110,85	1,32	1,10
HEM	100	18,00	1,88	1,56
	300	90,45	1,64	1,37
	600	150,00	1,32	1,10
IPE	100	5,06	1,39	1,16
	300	25,67	1,30	1,08
	600	83,80	1,24	1,04
U	60	3,94	1,37	1,14
	160	13,34	1,28	1,07
	300	33,52	1,25	1,04

- **Torzijsko obremenjeni prečni prerezi**

Ovirana torzija

Neovirana torzija



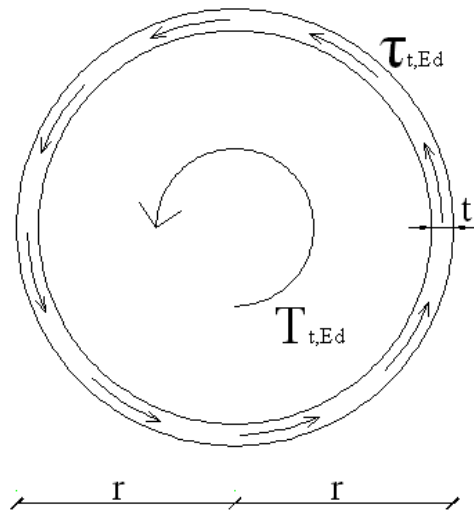
$$\frac{T_{Ed}}{T_{Rd}} \leq 1,0$$

$$T_{Ed} = T_{t,Ed} + T_{w,Ed}$$

$T_{t,Ed}$ prispevek enakomerne (St. Venantove torzije)

$T_{w,Ed}$ prispevek ovirane torzije.

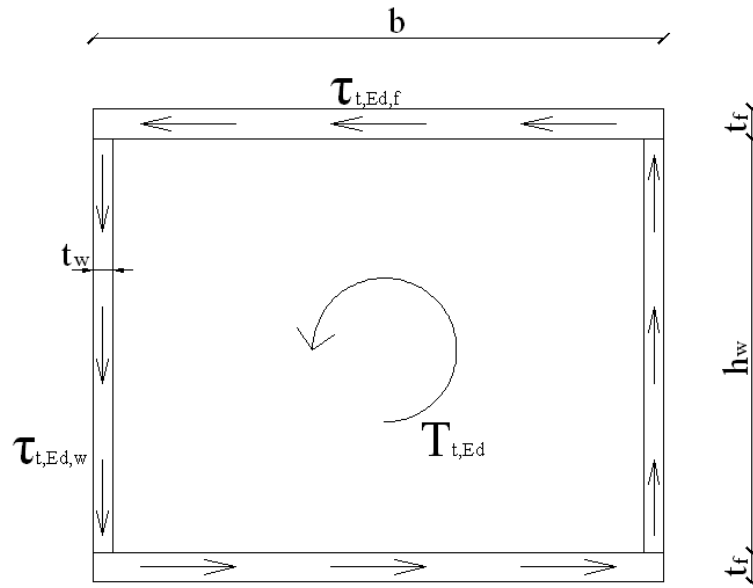
Enakomerna torzija - cevi



$$\tau_{t,Ed} \approx \frac{T_{t,Ed}}{2 \cdot \pi \cdot r^2 \cdot t}$$

$$I_t \approx 2 \cdot \pi \cdot r^3 \cdot t \quad \left(\frac{t}{r} \ll 1 \right)$$

Enakomerna torzija – škatlasti prerezi

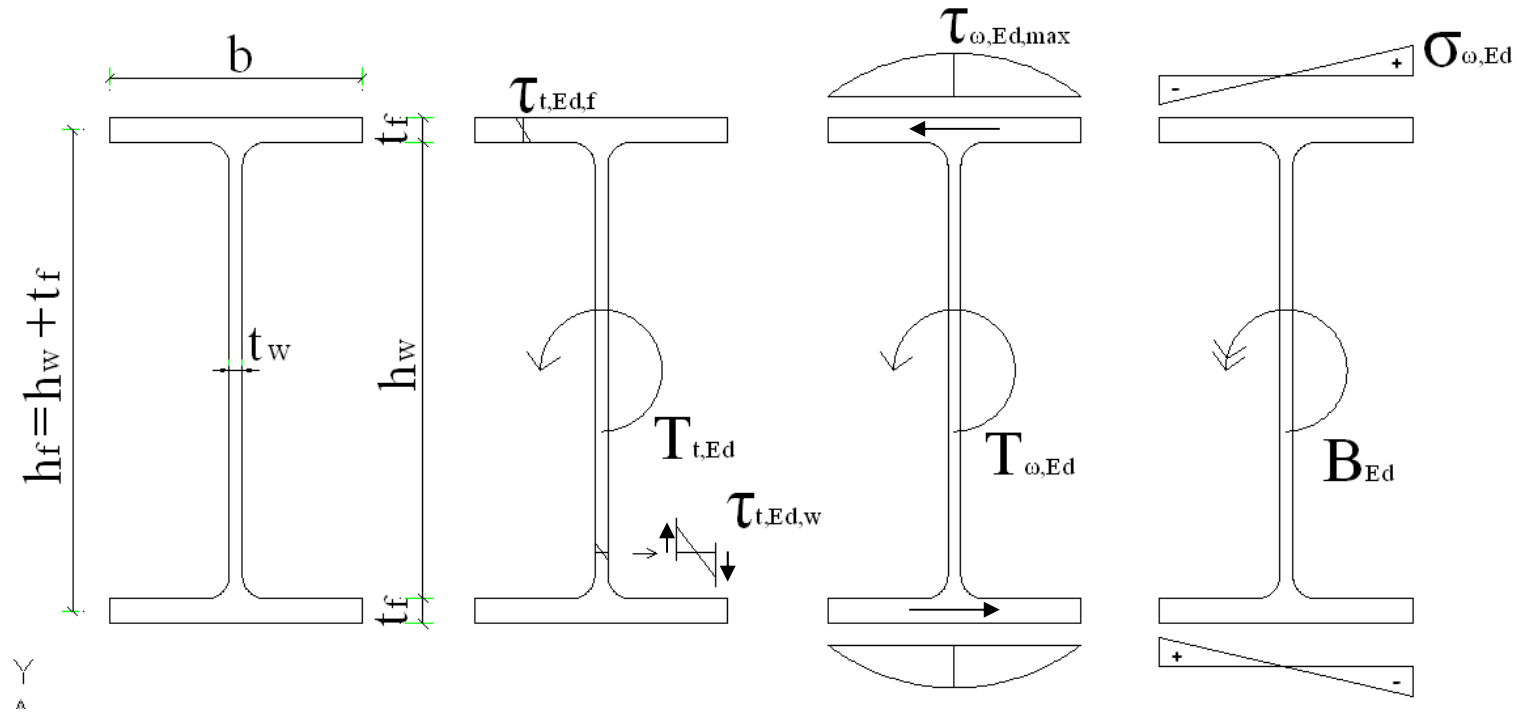


$$I_t = \frac{2 \cdot (h_w + t_f)^2 \cdot (b - t_w)^2}{\frac{h_w + t_f}{t_w} + \frac{b - t_w}{t_f}}$$

$$\tau_{t,Ed,f} \approx \frac{T_{t,Ed}}{2 \cdot (h_w + t_f) \cdot (b - t_w) \cdot t_f}$$

$$\tau_{t,Ed,w} \approx \frac{T_{t,Ed}}{2 \cdot (h_w + t_f) \cdot (b - t_w) \cdot t_w}$$

Torzija pri odprtih prerezih



$$I_t \approx \frac{1}{3} \cdot (h_w \cdot t_w^3 + 2 \cdot b \cdot t_f^3)$$

$$I_\omega = \frac{b^3 \cdot t_f \cdot h_f^2}{24}$$

$$\tau_{t,Ed,f} = \frac{T_{t,Ed} \cdot t_f}{I_t}$$

$$\tau_{t,Ed,w} = \frac{T_{t,Ed} \cdot t_w}{I_t}$$

$$\tau_{\omega,Ed} = 1,5 \cdot \frac{T_{\omega,Ed}}{h_f \cdot b \cdot t_f}$$

$$\sigma_{\omega,Ed} = \frac{B_{Ed}}{b^2 \cdot t_f \cdot h_f / 6}$$

- **Torzijsko obremenjeni prečni prerezi**

$$V_{Ed} \leq V_{pl,T,Rd}$$

$\tau_{t,Ed}$ – strižna napetost
pri enakomerni torziji

- **I in H profili**

$$V_{pl,T,Rd} = \sqrt{1 - \frac{\tau_{t,Ed}}{1,25 f_y / (\sqrt{3} \gamma_{M0})}} V_{pl,Rd}$$

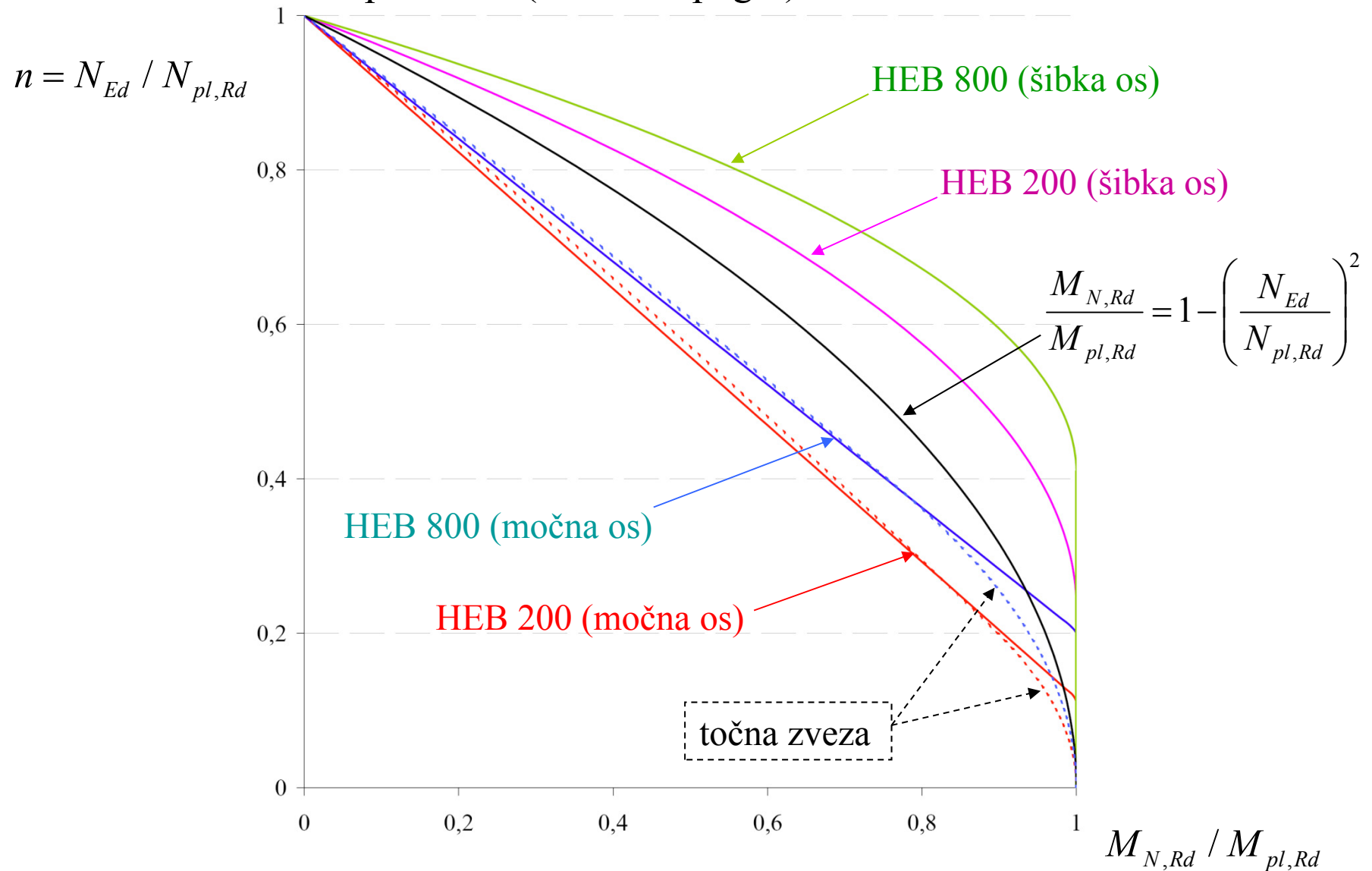
$\tau_{w,Ed}$ – strižna napetost
pri ovirani torziji

- **U profili**

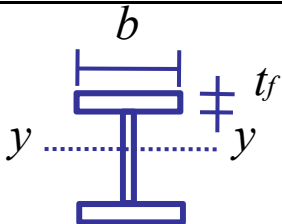
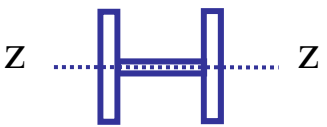
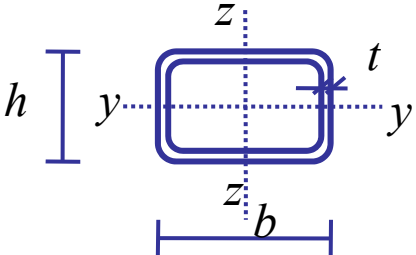
$$V_{pl,T,Rd} = \left[\sqrt{1 - \frac{\tau_{t,Ed}}{1,25 f_y / (\sqrt{3} \gamma_{M0})} - \frac{\tau_{w,Ed}}{f_y / (\sqrt{3} \gamma_{M0})}} \right] V_{pl,Rd}$$

Nosilnost kompaktnih prerezov (M + N)

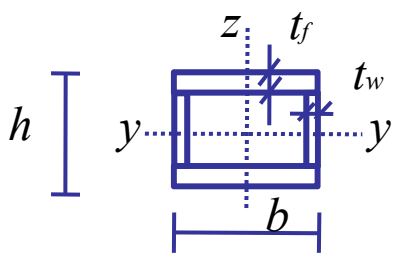
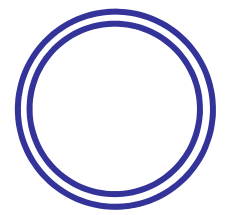
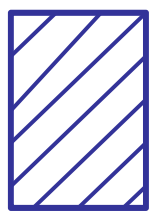
- 1. in 2. razred kompaktnosti (enoosni upogib)



Plastična nosilnost za enoosni upogib z osno silo

Prerez	Nivo osne sile	$M_{N,Rd}$
	$n \leq 0.5a \leq 0.25$	$M_{N,y,Rd} = M_{pl,y,Rd}$
	$n > 0.25$ ali $n > 0.5a$	$M_{N,y,Rd} = M_{pl,y,Rd} \frac{1-n}{(1-0.5a)} \leq M_{pl,y,Rd}$
	$n \leq a \leq 0.5$	$M_{N,z,Rd} = M_{pl,z,Rd}$
	$n > a$ ali $n > 0.5$	$M_{N,z,Rd} = M_{pl,z,Rd} \left[1 - \left(\frac{n-a}{1-a} \right)^2 \right]$
	$n \leq 0.5a_w \leq 0.25$	$M_{N,y,Rd} = M_{pl,y,Rd}$
	$n > 0.25$ ali $n > 0.5a_w$	$M_{N,y,Rd} = M_{pl,y,Rd} \frac{1-n}{(1-0.5a_w)} \leq M_{pl,y,Rd}$
$n = N_{Ed} / N_{pl,Rd}$		
$a = (A - 2bt_f) / A ; a \leq 0.5$ (I, H profili)		
$a_w = (A - 2bt) / A ; a_w \leq 0.5$ (HOP)		
$a_w = (A - 2bt_f) / A ; a_w \leq 0.5$ (varjeni)		

Plastična nosilnost za enoosni upogib z osno silo

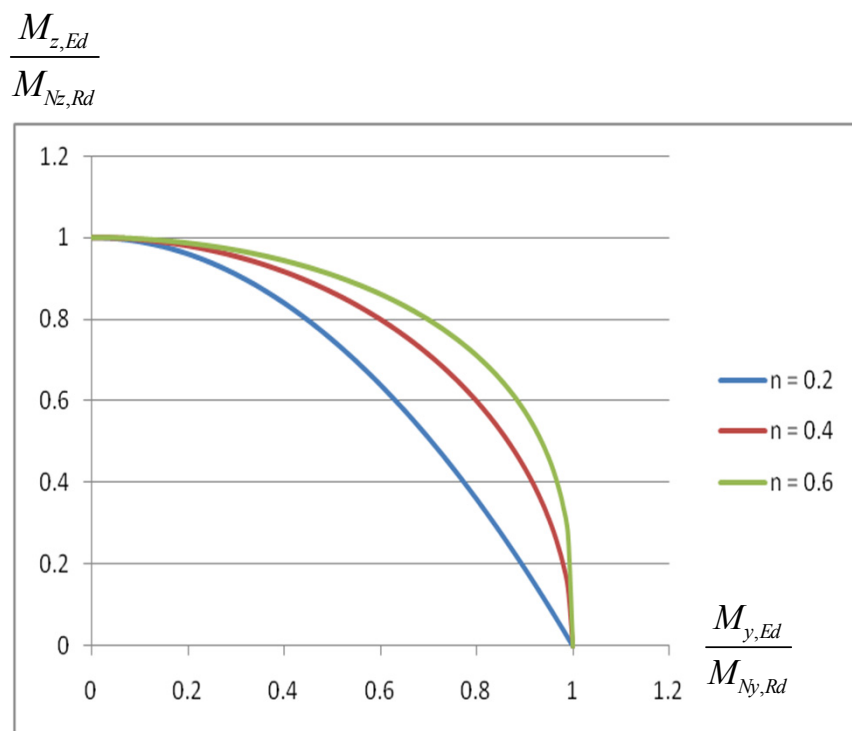
Prerez	Nivo osne sile	$M_{N,Rd}$
	$n \leq 0.5a_f \leq 0.25$	$M_{N,z,Rd} = M_{pl,z,Rd}$
	$n > 0.25$ ali $n > 0.5a_f$	$M_{N,z,Rd} = M_{pl,z,Rd} \frac{1-n}{(1-0.5a_f)} \leq M_{pl,z,Rd}$
	$n \leq 0.15$	$M_{N,Rd} = M_{pl,Rd}$
	$n > 0.15$	$M_{N,Rd} = M_{pl,Rd} \cdot 1,04(1-n^{1,7})$
	za vse vrednosti n	$M_{N,Rd} = M_{pl,Rd} (1-n^2)$
$n = N_{Ed} / N_{pl,Rd}$ $a_f = (A - 2ht) / A ; a \leq 0.5$ (HOP) $a_f = (A - 2ht_w) / A ; a \leq 0.5$ (varjeni)		

Plastična nosilnost za dvoosni upogib z osno silo

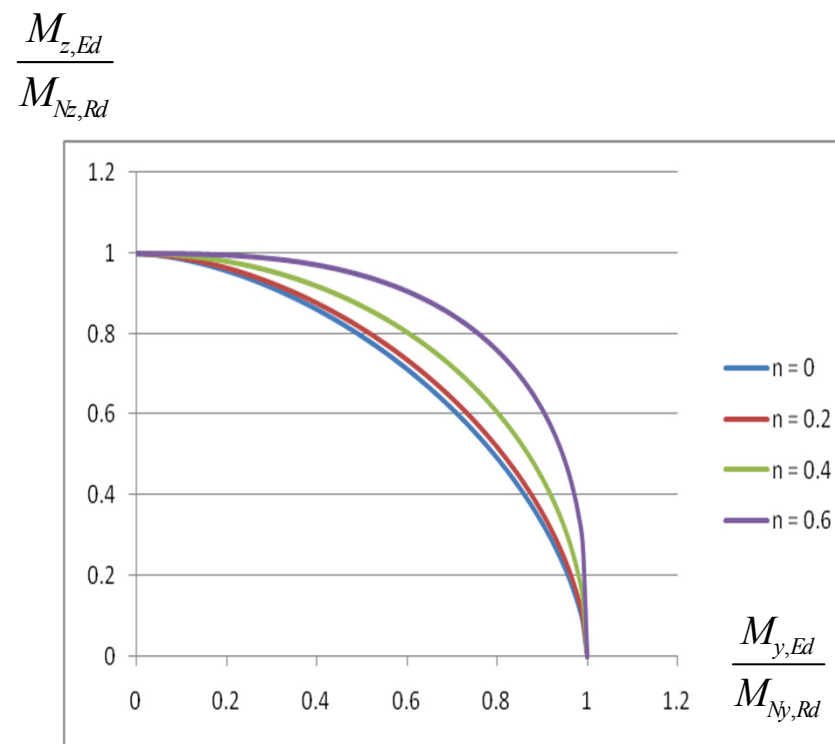
$\left[\frac{M_{y.Ed}}{M_{Ny.Rd}} \right]^\alpha + \left[\frac{M_{z.Ed}}{M_{Nz.Rd}} \right]^\beta \leq 1.0$		
Prerez	α	β
I in H profili	2	$5n, \beta \geq 1.0$
okrogle cevi	2	2
pravokotni votli profili	$\frac{1.66}{1 - 1.13n^2}, \alpha \leq 6$ (1.66)	$\frac{1.66}{1 - 1.13n^2}, \beta \leq 6$
polni pravokotni profili, pločevine	$1.73 + 1.8n^3$	$1.73 + 1.8n^3$
$n = \frac{N_{Ed}}{N_{pl.Rd}}$		
<p>Poenostavljeni izraz, ki je na varni strani:</p> $\frac{N_{Ed}}{N_{pl.Rd}} + \frac{M_{y.Ed}}{M_{pl.y.Rd}} + \frac{M_{z.Ed}}{M_{pl.z.Rd}} \leq 1.0$		

Interakcijski diagram za dvoosni upogib z osno silo

I in H profili

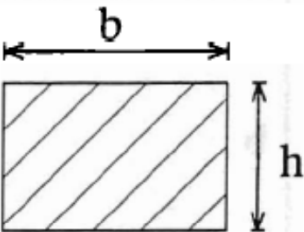
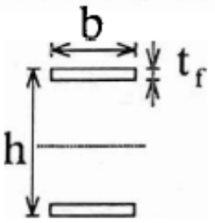
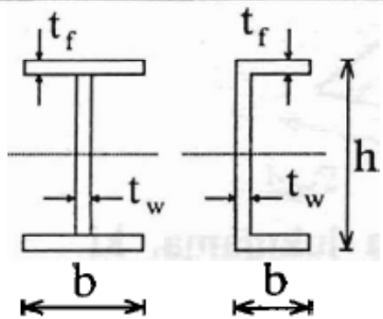


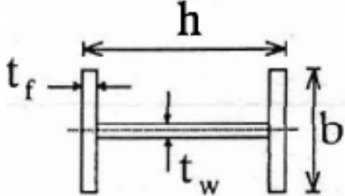
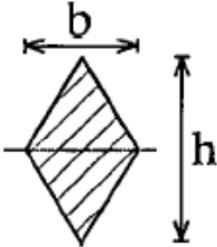
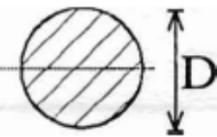

Pravokotni votli profili

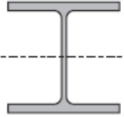
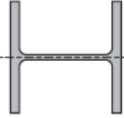
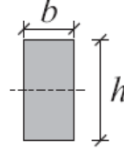
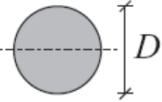
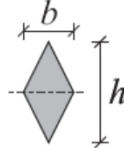
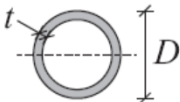


kjer je $n = N_{Ed} / N_{pl,Rd}$

Račun geometrijskih karakteristik značilnih prerezov

Prerez	W_{el}	W_{pl}	$\alpha_{pl} = \frac{W_{pl}}{W_{el}}$
	$\frac{bh^2}{6}$	$\frac{bh^2}{4}$	1.5
	$bt_f (h-t_f)$	$bt_f (h-t_f)$	1.0
	$\frac{[bh^3 - (b-t_w)(h-2t_f)^3]}{6h}$	$\frac{bt_f(h-t_f) + t_w(h-2t_f)^2}{4}$	1.1 do 1.2 (1.15)
* I,H,U prerezi, močna os			

Prerez	W_{el}	W_{pl}	$\alpha_{pl} = \frac{W_{pl}}{W_{el}}$
 <p>I,H prerez, šibka os</p>	$\frac{b^2 t_f}{3} + \frac{t_w^3 (h - 2t_f)}{6b}$	$\frac{b^2 t_f}{2} + \frac{t_w^2 (h - 2t_f)}{4}$	1.5 do 1.7 (1.67)
	$\frac{bh^3}{24}$	$\frac{bh^3}{12}$	2.0
	$\frac{\pi D^3}{32}$	$\frac{d^3}{6}$	1.7
	$\pi [D^4 - (D - 2t)^4] \frac{1}{32D}$ $\pi D^2 t / 4 \quad (\text{pri } t \ll D)$	$D^3 \left[1 - \left[1 - \frac{2t}{D} \right]^3 \right] \frac{1}{6}$ $D^2 t \quad (\text{pri } t \ll D)$	<p>pri $t = D/10$ 1.4 pri $t \ll D$ 1.27</p>

	A [cm ²]	W _{el} [cm ³]	W _{pl} [cm ³]	α _{pl}	W _{pl,norm}	W _{el,norm}
 HEB 400	198	2880	3232	1,12	0,12	0,22
 HEB 400	198	721	1104	1,53	0,04	0,06
 $h/b = 2$	198	656,7	985,0	1,50	0,04	0,05
	198	393,0	667,1	1,70	0,03	0,03
 $h/b = 2$	198	13068,0	26136,0	2,00	1,00	1,00
	198	1898,0	2416,6	1,27	0,09	0,15

$$W_{el,norm} = \frac{W_{el,i}}{W_{el,max}}$$

$$W_{pl,norm} = \frac{W_{pl,i}}{W_{pl,max}}$$

- 3. razred kompaktnosti $\sigma_{\max,Ed} \leq \frac{f_y}{\gamma_{M0}}$

$$\frac{N_{Ed}}{A} + \frac{M_{y,Ed}}{W_{el,y}} + \frac{M_{z,Ed}}{M_{el,z}} \leq \frac{f_y}{\gamma_{M0}}$$

ali

$$\frac{N_{Ed}}{N_{pl,Rd}} + \frac{M_{y,Ed}}{M_{y,el,Rd}} + \frac{M_{z,Ed}}{M_{z,el,Rd}} \leq 1,0$$

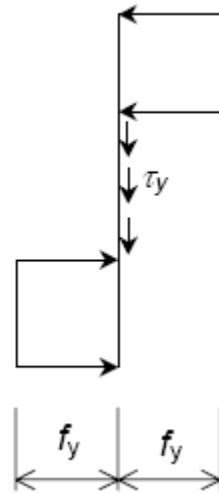
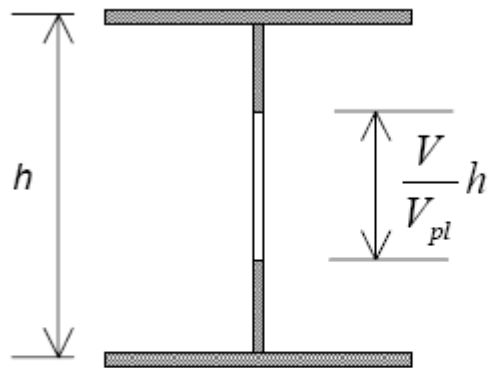
- 4. razred kompaktnosti $\sigma_{\max,Ed} \leq \frac{f_y}{\gamma_{M0}}$

$$\frac{N_{Ed}}{A_{eff}} + \frac{M_{y,Ed} + N_{Ed} e_{Ny}}{W_{eff,y,min}} + \frac{M_{z,Ed} + N_{Ed} e_{Nz}}{W_{eff,z,min}} \leq \frac{f_y}{\gamma_{M0}}$$

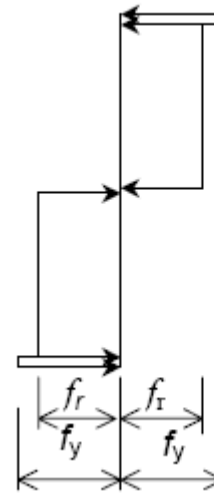
ali

$$\frac{N_{Ed}}{A_{eff} f_y / \gamma_{M0}} + \frac{M_{y,Ed} + N_{Ed} e_{Ny}}{W_{eff,y,min} f_y / \gamma_{M0}} + \frac{M_{z,Ed} + N_{Ed} e_{Nz}}{W_{eff,z,min} f_y / \gamma_{M0}} \leq 1.0$$

Interakcija strig, upogib in osna sila



a)



b)

$$V_{pl} = \tau_y h t_w$$

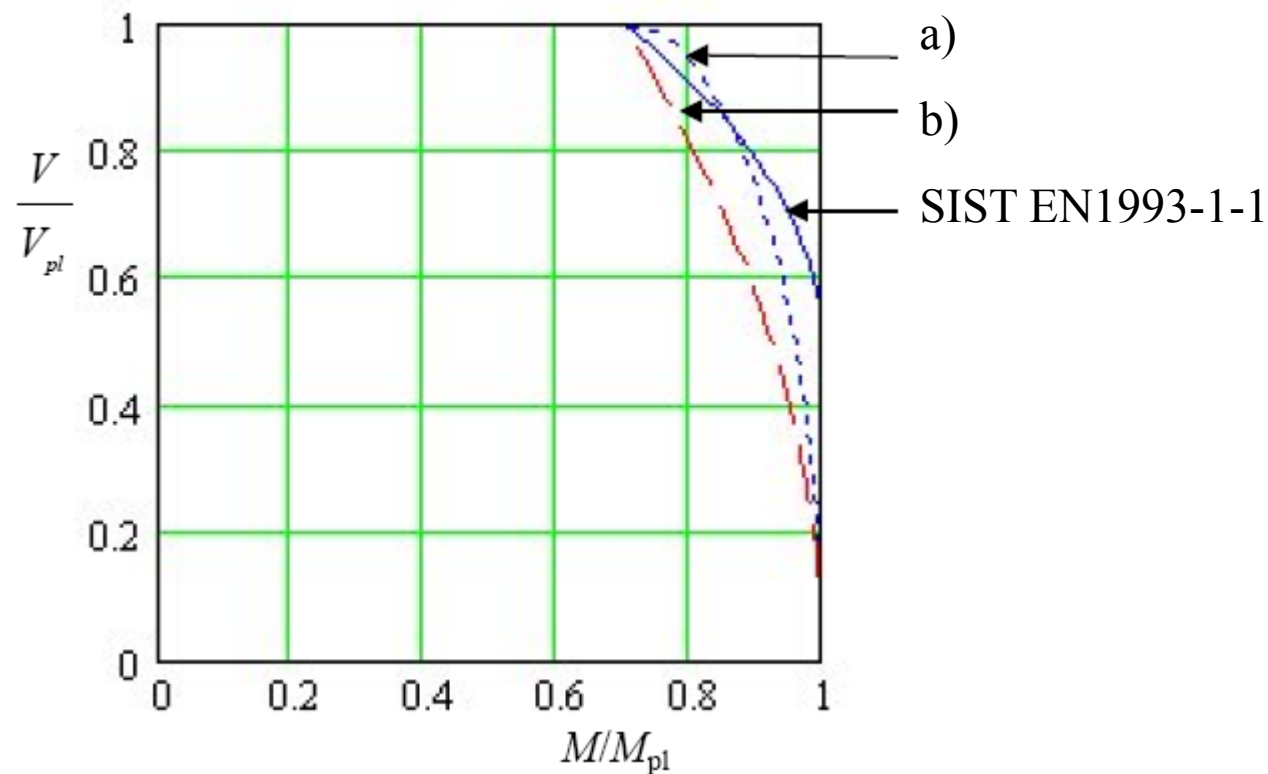
$$\tau_y = f_y / \sqrt{3}$$

$$f_r = \sqrt{f_y^2 - 3\tau^2}$$

$$f_r = \sqrt{f_y^2 - 3\left(\frac{V}{h \cdot t_w}\right)^2}$$

Interakcija strig + upogib

Plastična nosilnost



a)
$$\frac{M}{M_{pl}} + \left(1 - \frac{M_f}{M_{pl}}\right) \left(\frac{V}{V_{pl}}\right) = 1 \quad \text{if } M > M_f$$

b)
$$\frac{M}{M_{pl}} + \left(1 - \frac{M_f}{M_{pl}}\right) \left(1 - \sqrt{1 - \left(\frac{V}{V_{pl}}\right)^2}\right) = 1 \quad \text{if } M > M_f$$

SIST EN1993-1-1

$$\frac{M}{M_{pl}} + \left(1 - \frac{M_f}{M_{pl}}\right) \left(\frac{2V}{V_{pl}} - 1\right)^2 = 1 \quad \text{if } V > 0,5V_{pl}$$

Interakcija striga in upogiba (vsi razredi kompaktnosti)

- Vpliv interakcije pri $V_{Ed} \geq 0,5V_{pl,Rd}$

$$\rho = \left(\frac{2V_{Ed}}{V_{pl,Rd}} - 1 \right)^2$$

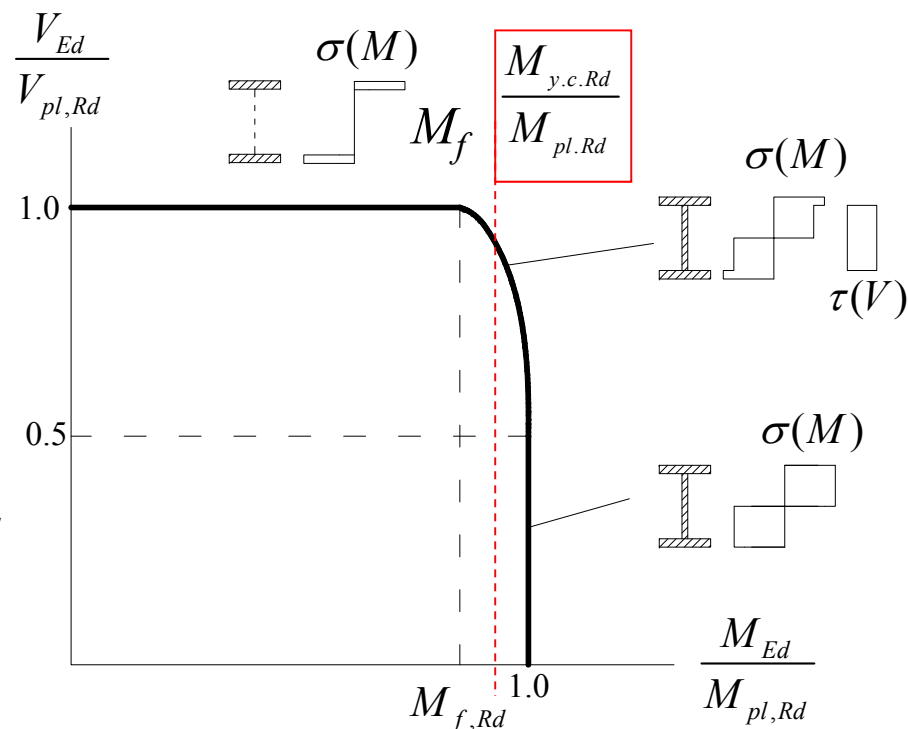
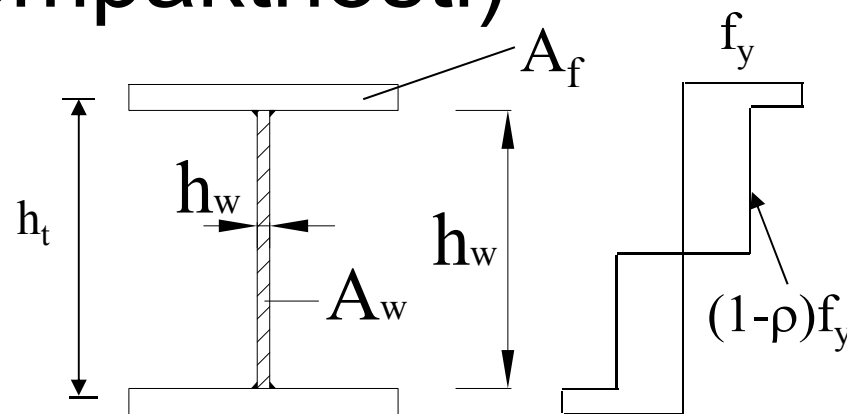
- Zaradi striga reducirana upogibna nosilnost:

$$M_{y,V,Rd} = \frac{\left[W_{pl,y} - \frac{\rho A_w^2}{4t_w} \right] f_y}{\gamma_{M0}} \leq M_{y,c,Rd}$$

ali

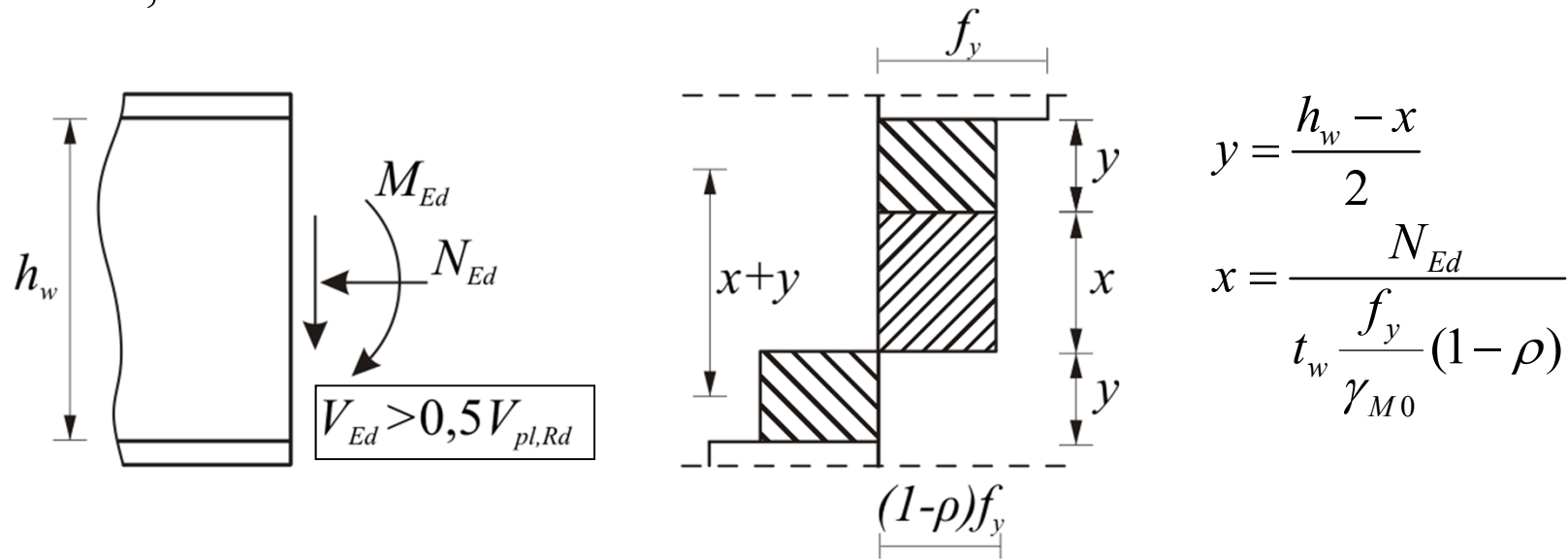
$$M_{y,V,Rd} = M_f + (M_{pl,Rd} - M_f)(1 - \rho) \leq M_{y,c,Rd}$$

$$M_f = A_f h_t$$



Projektna nosilnost prečnih prerezov – M, N, V

□ 1. ,2. RAZRED KOMPAKTNOSTI



$$y = \frac{h_w - x}{2}$$

$$x = \frac{N_{Ed}}{t_w \frac{f_y}{\gamma_{M0}} (1 - \rho)}$$

$$M_{pl,w,Red,Rd} = \frac{y \cdot t_w (1 - \rho) f_y \cdot (x + y)}{\gamma_{M0}}$$

$$\rho = \left(\frac{2V_{Ed}}{V_{pl,Rd}} - 1 \right)^2$$

$$M_{Ed} \leq M_{pl,N,Rd} = M_{f,Rd} + M_{pl,w,Red,Rd}$$

$$V_{pl,Rd} = \frac{A_v (f_y / \sqrt{3})}{\gamma_{M0}}$$

□ 3. RAZRED KOMPAKTNOSTI

$$\frac{N_{Ed}}{N_{pl,Rd}} + \frac{M_{y,Ed}}{M_{el,y,Rd}} \leq 1,0 - \rho \frac{M_{w,Rd}}{M_{pl,Rd}}$$

$$\rho = \left(\frac{2V_{Ed}}{V_{pl,Rd}} - 1 \right)^2$$

ali poenostavljeno

$$\frac{N_{Ed}}{N_{pl,Rd}} + \frac{M_{y,Ed}}{M_{el,y,Rd}} \leq 1,0 - \rho$$

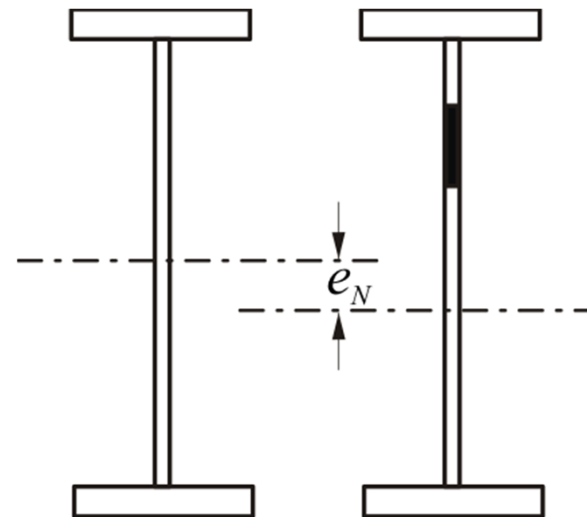
$$V_{pl,Rd} = \frac{A_v (f_y / \sqrt{3})}{\gamma_{M0}}$$

□ 4. RAZRED KOMPAKTNOSTI

$$\frac{N_{Ed}}{A_{eff} \cdot f_y / \gamma_{M0}} + \frac{M_{y,Ed} + N_{Ed} e_{Ny}}{W_{eff} \cdot f_y / \gamma_{M0}} \leq 1,0 - \rho$$

$$\rho = \left(\frac{2V_{Ed}}{V_{b,Rd}} - 1 \right)^2$$

$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd}$$



Projektna nosilnost prečnih prerezov 3. razreda kompaktnosti

