Technical note

"Calculation of the effective modulus of a thin-walled cold-formed section under bending according to EN1993-1-3"

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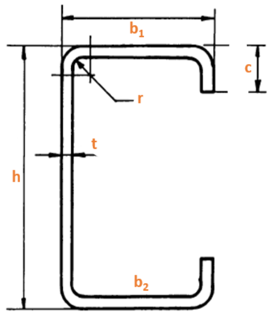
September 2025

This document presents the calculation of the effective modulus $W_{y,eff}$ of a C profile under major axis bending. The geometrical and material properties of the considered section are presented in Table 1. According to prEN 1993-1-3, §7.6.1 (8), the effective section modulus $W_{eff,y}$ should be determined assuming that the cross-section is subject only to subjected only to bending.

Table 1: Geometrical and material properties of the considered section

Properties		Denotations
h [mm]	239,4	
b_1 [mm]	64	
b_2 [mm]	64	
c [mm]	17,67	
r [mm]	1,5	
t [mm]	1,43	
f_{yb} [N/mm^2]	424,44	
E [N/mm^2]	208192	
v [-]	0,3	
ε [-]	0,7441	

A) Checking of geometric proportions according to prEN1993-1-3

The design method of EN1993-1-3 can be applied if the conditions of prEN 1993-1-3, §7.4 (1) are satisfied:

- $h/t \leq 500$ → $239,4/1,43 = 167,4 \leq 500$ → OK
- $b/t \leq 60$ → $64/1,43 = 44,76 \leq 60$ → OK
- $c/t \leq 50$ → $17,67/1,43 = 12,36 \leq 50$ → OK

In order to provide sufficient stiffness and to avoid the primary buckle of the stiffener itself, the following conditions given in prEN 1993-1-3, §7.4 (2) should be satisfied:

- $0,2 \leq c/b \leq 0,6$ → $17,67/64 = 0,28$ → OK

B) Calculation of the centre line dimensions

The influence of the rounded corners can be neglected according to prEN 1993-1-3, §7.3.1 (3), if:

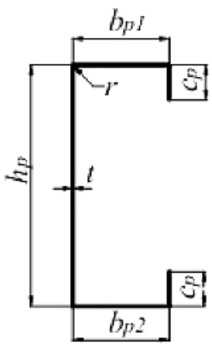
- $r/t \leq 5$ → $1,5/1,43 = 1,049 \leq 5$ → OK
- $r/b_p \leq 0,10$ → $1,5/62,57 = 0,02 \leq 0,10$ → OK

Therefore:

h_p = h-t = 239,4 – 1,43 = 237,97 mm

$b_{p1} = b_{p2} = b_p$ = b-t = 64 – 1,43 = 62,57 mm

c_p = c-t/2 = 17,67-1,43/2 = 16,96 mm



C) Calculation of the effective modulus $W_{eff,y}$ under bending

The section is divided into 3 internal (web and flanges) and 2 external (stiffeners) parts. The upper flange is under pure compression while the lower flange is in tension. Both stiffeners and the web are under linear stress distribution.

C1: Calculation of the effective widths (initial values)

All the notations used in this section are illustrated in Figure 1.

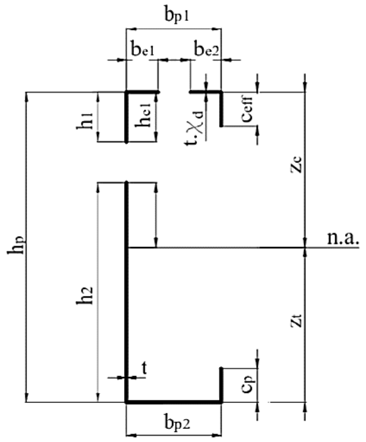


Figure 1: Notations used in this section C

- Effective width of the internal compressed flange (EN 1993-1-5, §4.4)

The stress ratio is $\psi = 1$ (uniform compression), so the buckling factor according to EN 1993-1-5, Table 4.1 is $k_\sigma\ = 4$. The relative slenderness is:

$$\bar{\lambda}_{p,b} = \frac{b_p/t}{28{,}4\varepsilon\sqrt{k_\sigma}} = \frac{62{,}57/1{,}43}{28{,}4 \cdot 0{,}744 \cdot \sqrt{4}} = 1{,}04$$

The reduction factor is:

$$\rho = \frac{\bar{\lambda}_{p,b} - 0{,}055(3+\psi)}{\bar{\lambda}^2_{p,b}} = \frac{1{,}04 - 0{,}055(3+1)}{1{,}04^2} = 0{,}761 < 1$$

The effective width (see in Figure 1) is equal to:

$$b_{eff} = \rho \cdot b_p = 0{,}764 \cdot 62{,}57 = 47{,}59\ mm$$

$$b_{e1} = b_{e2} = 0{,}5 \cdot b_{eff} = 0{,}5 \cdot 47{,}59 = 23{,}80\ mm$$

- Effective width of the edge fold / stiffener (prEN 1993-1-3, §7.6.3.3 (5))

As $c_p/b_p = 16{,}96/62{,}57 = 0{,}271 \leq 0{,}6 \rightarrow k_\sigma = 0{,}50$.

The relative slenderness is:

$$\bar{\lambda}_{p,c} = \frac{c_p/t}{28{,}4\varepsilon\sqrt{k_{\sigma,ext}}} = \frac{16{,}96/1{,}43}{28{,}4 \cdot 0{,}744 \cdot \sqrt{0{,}5}} = 0{,}79$$

The reduction factor is:

$$\rho_c = \frac{\bar{\lambda}_{p,c} - 0{,}188}{\bar{\lambda}^2_{p,c}} = \frac{0{,}793 - 0{,}188}{0{,}793^2} = 0{,}962$$

The effective width (see Figure 1) is equal to $c_{eff} = \rho_c \cdot c_p = 0{,}962 \cdot 16{,}96 = 16{,}31$ mm

C2: Calculation of the distortional reduction factor (prEN 1993-1-3, §7.6.3.2 (1))

The effective area of the stiffener is:

$$A_{st} = \left(b_{e1} + c_{eff}\right)t = (23{,}80 + 16{,}31) \cdot 1{,}43 = 57{,}35\ mm^2$$

The distance from the left face to the centre of the effective area of the stiffener in compression is:

$$b_1 = b_p - \frac{b_{e1}t(0{,}5b_{e1})}{A_{st}} = 62{,}57 \; - \frac{23{,}80 \cdot 1{,}43 \cdot (0{,}5 \cdot 23{,}80)}{57{,}35} = 55{,}51\,mm$$

The spring stiffness according to prEN 1993-1-3, §7.6.3.1 (5) is:

$$K = \frac{Et^3}{4(1-v^2)} \cdot \frac{1}{b_1^2 h_p + b_1^3 + 0{,}5 b_1^2 h_p k_f}$$

where $k_f = 0$ for bending about the y-y axis.

$$K = \frac{208192 \cdot 1{,}43^3}{4(1-0{,}3^2)} \cdot \frac{1}{55{,}51^2 \cdot 237{,}97 + 55{,}51^3 + 0{,}5 \cdot 55{,}51^2 \cdot 237{,}97 \cdot 0} = 0{,}185\,N/mm^2$$

The effective second moment of area of the edge stiffener is:

$$I_{st} = \frac{b_{e1}t^3}{12} + \frac{c_{eff}^3 t}{12} + b_{e1}t\left(\frac{c_{eff}tc_{eff}/2}{A_{st}}\right)^2 + c_{eff}t\left(\frac{c_{eff}}{2} - \frac{c_{eff}tc_{eff}/2}{A_{st}}\right)^2$$

$$I_{st} = 1442{,}02\,mm^4$$

The elastic critical buckling stress (prEN 1993-1-3, §7.6.3.3 (7)) of the edge stiffener is:

$$\sigma_{cr,s} = \frac{2\sqrt{KEI_s}}{A_{st}} = 259{,}88\,N/mm^2$$

The relative slenderness for distortional buckling is:

$$\bar{\lambda}_d = \sqrt{\frac{f_y}{\sigma_{cr,s}}} = \sqrt{\frac{424{,}44}{259{,}88}} = 1{,}278$$

The reduction factor for distortional buckling is $\chi_d = 1{,}47 - 0{,}723\bar{\lambda}_d = 0{,}546$

C3: Calculation of the refined distortional reduction factor

An iteration process is proposed by the Code to refine the value of the reduction factor for distortional buckling. This iteration process performed via an excel spreadsheet and the calculations are summarized in Figure 2 below.

Iteration 1					
Flange			edge fold		
λ_p [-]	0,765		λ_p [-]	0,586	
ρ [-]	0,931	<1	$\lambda_{p,min}$ [-]	0,748	
b_{eff} [mm]	58,27		ρ [-]	1,000	< 1
b_{e2} [mm]	29,13		c_{eff} [mm]	16,96	
A_s [mm^2]	65,91				
b_1 [mm]	53,362				
K [N/mm^2]	0,202				
I_s [mm^4]	1689,41				
$\sigma_{cr,s}$ [N/mm^2]	255,54				
λ_d [-]	1,289				
χ_d [-]	0,538				

Iteration 2					
Flange			edge fold		
λ_p [-]	0,760		λ_p [-]	0,582	
ρ [-]	0,935	<1	$\lambda_{p,min}$ [-]	0,748	
b_{eff} [mm]	58,52		ρ [-]	1,000	< 1
b_{e2} [mm]	29,26		c_{eff} [mm]	16,96	
A_s [mm^2]	66,09				
b_1 [mm]	53,307				
K [N/mm^2]	0,202				
I_s [mm^4]	1691,17				
$\sigma_{cr,s}$ [N/mm^2]	255,26				
λ_d [-]	1,289				
χ_d [-]	0,538				

Iteration 3					
Flange			edge fold		
λ_p [-]	0,759		λ_p [-]	0,582	
ρ [-]	0,936	<1	$\lambda_{p,min}$ [-]	0,748	
b_{eff} [mm]	58,54		ρ [-]	1,000	< 1
b_{e2} [mm]	29,27		c_{eff} [mm]	16,96	
A_s [mm^2]	66,10				
b_1 [mm]	53,304				
K [N/mm^2]	0,202				
I_s [mm^4]	1691,29				
$\sigma_{cr,s}$ [N/mm^2]	255,24				
λ_d [-]	1,290				
χ_d [-]	0,538				

Figure 2: Excerpt from excel spreadsheet

The final values after 3 iterations are:

$$b_{e1} = 23{,}80\,mm \;\; ; \;\; b_{e2} = 29{,}27\,mm \;\; ; \;\; c_{eff} = 16{,}96\text{ mm} \;\; ; \;\; \chi_d = 0{,}538$$

Therefore $t_{red} = \chi_d \cdot t = 0{,}538 \cdot 1{,}43 = 0{,}769\,mm$

C4: Calculation of the effective section properties of the web

The position of the neutral axis in regard to the flange in compression is:

$$h_c = \frac{c_p\left(h_p - \frac{c_p}{2}\right) + b_{p2}h_p + \frac{h_p^2}{2} + \frac{c_{eff}^2\chi_d}{2}}{c_p + b_{p2} + h_p + b_{e1} + \left(b_{e2} + c_{eff}\right)\chi_d} = 128{,}84\, mm$$

The stress ratio is $\psi = \frac{h_c - h_p}{h_c} = -0{,}847$, so the buckling factor according to EN 1993-1-5, Table 4.1 is $k_\sigma = 7{,}81 - 6{,}29\psi + 9{,}78\psi^2 = 20{,}16$. The relative slenderness is:

$$\bar{\lambda}_{p,h} = \frac{h_p/t}{28{,}4\varepsilon\sqrt{k_\sigma}} = \frac{239{,}4/1{,}43}{28{,}4 \cdot 0{,}744 \cdot \sqrt{20{,}16}} = 1{,}754$$

The width reduction factor is:

$$\rho = \frac{\bar{\lambda}_{p,h} - 0{,}055(3+\psi)}{\bar{\lambda}_{p,h}^2} = 0{,}532 < 1$$

The effective width of the zone in compression of the web (see in Figure 1) is equal to:

$$h_{eff} = \rho \cdot h_c = 0{,}532 \cdot 128{,}84 = 68{,}49\, mm$$

Near the flange in compression: $h_{e1} = 0{,}4 \cdot h_{eff} = 27{,}40\, mm$

Near the neutral axis: $h_{e2} = 0{,}6 \cdot h_{eff} = 41{,}10\, mm$

The effective width of the web (see in Figure 1) near the flange in compression is $h_1 = h_{e1} = 27{,}40\, mm$, while near the neutral axis equals $h_2 = h_p - (h_c - h_{e2}) = 150{,}23\, mm$

C: Calculation of the effective section properties

The effective cross-section area is:

$$A_{eff} = t\left[c_p + b_{p2} + h_1 + h_2 + b_{e1} + \left(b_{e2} + c_{eff}\right)\chi_d\right]$$

$$A_{eff} = 437{,}29\, mm^2$$

Position of the neutral axis in regard to the compressed flange:

$$z_c = \frac{t\left[c_p\left(h_p - \frac{c_p}{2}\right) + b_{p2}h_p + h_2\left(h_p - \frac{h_2}{2}\right) + \frac{h_1^2}{2} + \frac{c_{eff}^2\chi_d}{2}\right]}{A_{eff}} = 142{,}90\, mm$$

And in regard to the flange in tension is $z_t = h_p - z_c = 95{,}07\, mm$.

The effective second moment of area of the cross-section is:

$$I_{eff,y} = \frac{h_1^3 t}{12} + \frac{h_2^3 t}{12} + \frac{b_{p2}t^3}{12} + \frac{c_p^3 t}{12} + \frac{b_{e1}t^3}{12} + \frac{b_{e2}(\chi_d t)^3}{12} + \frac{c_{eff}^3(\chi_d t)}{12} + c_p t\left(z_t - \frac{c_p}{2}\right)^2 + b_{p2}tz_t^2 + h_2 t\left(z_t - \frac{h_2}{2}\right)^2 + h_1 t\left(z_c - \frac{h_1}{2}\right)^2 + b_{e1}tz_c^2 + b_{e2}(\chi_d t)z_c^2 + c_{eff}(\chi_d t)\left(z_c - \frac{c_{eff}}{2}\right)^2 = 3527426\, mm^4$$

Then, the effective section modulus is:

$$W_{eff,y} = \frac{I_{eff,y}}{\max(z_c\, ;\, z_t)} = \frac{3527426}{142{,}90} = 24.684{,}5\, mm^3$$