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WEB GIRDER RESISTANCE TO TRANSVERSE FORCES

Y. Koleková*, I. Baláž**

Abstract: *Transverse force denotes the load which is applied perpendicular to the flange in the plane of the web. The loading is usually free and transient, as for crane runway girders or bridge girders during launching, so that in this case transverse stiffeners are not appropriate. A concentrated transverse loading is often referred to as patch loading. The collapse behaviour of girders subjected to transverse loading is characterized by web yielding, buckling or crippling. A separation of these three phenomena accepted in the former standards is not reasonable. The paper describes the design procedure used in the current Eurocodes, shows its application in numerical example and informs about new improvements.*

Keywords: ***Patch loading, design resistance, Eurocodes, numerical example.***

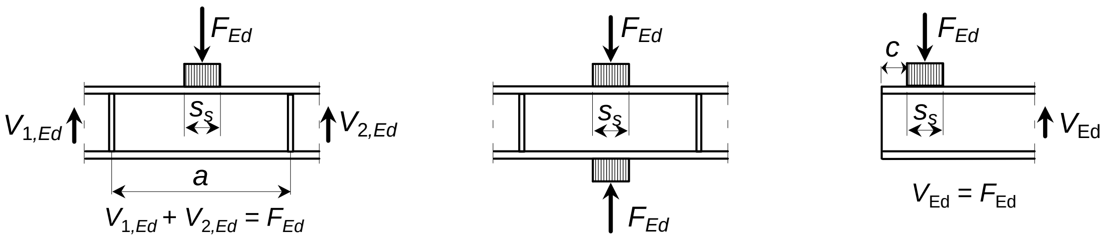
1. Introduction

The design resistance of the webs of rolled beams and welded girders may be determined according to EN 1993-1-5 (2006) in accordance with the clause 6.2 (or cl. 6.7.5 in EN 1999-1-1 (2007)), provided that the compression flange is adequately restrained in the lateral direction.

The load is applied as follows:

a) through the flange and resisted by shear forces in the web, see *Fig. 1(a)*;
b) through one flange and transferred through the web directly to the other flange, see *Fig. 1(b)*;
c) through one flange adjacent to an unstiffened end, see *Fig. 1(c)*.

The interaction of the transverse force F_{Ed}, bending moment M_{Ed} and axial force N_{Ed} may be verified according to sections (3). The interaction of the bending moment M_{Ed}, shear force V_{Ed} and axial force N_{Ed} may be verified using the cl. 7.1 of EN 1993-1-5 (2006) or cl. 6.7.6 in EN 1999-1-1 (2007)). The formulae enabling of the verification of the interaction F_{Ed} and V_{Ed} are investigated in the Evolution Group EG EN 1993-1-5 and they will be available in the next generation of EN 1993-1-5.
The design rules concerning the resistance to transverse force in the standards for steel structures EN 1993-1-5 (2006) and for aluminium alloys structures EN 1999-1-1 (2007) are practically identical.



$$k_F = 6 + 2\left(\frac{b_w}{a}\right)^2 \qquad k_F = 3{,}5 + 2\left(\frac{b_w}{a}\right)^2 \qquad k_F = 2 + 6\,\frac{s_s + c}{b_w} \le 6$$

Type (a) Type (b) Type (c)

Fig. 1: Buckling coefficients k_F for different types of load application

* Assoc. Prof. Ing. Yvona Koleková, PhD.: Department of Structural Mechanics, Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11; 813 68, Bratislava; SK, e-mail: yvona.kolekova@stuba.sk

** Prof. Ing. Ivan Baláž, PhD.: Department of Metal and Timber Structures, Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11; 813 68, Bratislava; SK, e-mail: ivan.baláž@stuba.sk

2. Verification of resistance F_{Rd} to transverse force F_{Ed}

2.1. Design resistence F_{Rd}

For unstiffened or stiffened webs the design resistance to local buckling under transverse forces should be taken as

$$F_{Rd} = L_{eff}\ t_w \frac{f_{yw}}{\gamma_{M1}} \tag{1}$$

where

t_w is the thickness of the web;
f_{yw} the yield strength of the web;
L_{eff} the effective length for resistance to transverse forces, which should be determined from

$$L_{eff} = \chi_F\ \ell_y \tag{2}$$

where

ℓ_y is the effective loaded length, see section (2.4), appropriate to the length of stiff bearing s_s, see section (2.2);
χ_F the reduction factor due to local buckling, see section (2.3).

Partial factors γ_{M0} and γ_{M1} used in EN 1993-1-5 (2006) are defined for different applications in the National Annexes of EN 1993-1 to EN 1993-6. For example the recommended values in EN 1993-1-1 (2005) for buildings are γ_{M0} = 1,0 and γ_{M1} =1,0 and in EN 1993-2 (2007) for bridges are γ_{M0} = 1,0 and γ_{M1} =1,1. In EN 1999-1-1 (2007) there is only partial factor γ_{M1} and its recommended value is γ_{M1} =1,1. All these recommended values were accepted in Slovak and Czech National Annexes. Note that according to the newest opinion of Ad hoc committee at EG EN 1993-1-1 the values of partial factors, which equal to 1,0 should be increased.

2.2. Length of stiff bearing s_s

The length of stiff bearing s_s on the flange should be taken as the distance over which the applied load is effectively distributed at a slope of 1:1, see *Fig. 2* and the numerical example in section (4). However, s_s should not be taken as larger than h_w.

If several concentrated forces are closely spaced, the resistance should be checked for each individual force as well as for the total load with s_s as the centre-to-centre distance between the outer loads.

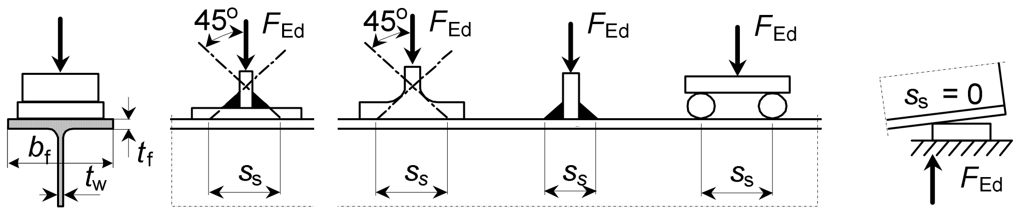


Fig. 2: Length of stiff bearing s_s

If the bearing surface of the applied load rests at an angle to the flange surface, see the right picture in *Fig. 2*, s_s should be taken as zero.

2.3. Reduction factor χ_F for effective length for resistance

The reduction factor χ_F should be obtained from:

$$\chi_F = \frac{0{,}5}{\overline{\lambda}_F} \leq 1{,}0 \tag{3}$$

where

$$\overline{\lambda}_F = \sqrt{\frac{\ell_y t_w f_{yw}}{F_{cr}}} \tag{4}$$

$$F_{cr} = \sigma_{cr} h_w t_w = k_F \sigma_E h_w t_w = k_F \frac{\pi^2 E}{12(1-\nu^2)} h_w t_w = 0.904 k_F E \frac{t_w^3}{h_w} \approx 0{,}9\, k_F E \frac{t_w^3}{h_w} \qquad (5)$$

For webs without longitudinal stiffeners k_F should be obtained from *Fig. 1*.
For webs with longitudinal stiffeners k_F may be taken as

$$k_F = 6 + 2\left[\frac{h_w}{a}\right]^2 + \left[5{,}44\frac{b_1}{a} - 0{,}21\right]\sqrt{\gamma_s} \qquad (6)$$

where
b_1 is the depth of the loaded subpanel taken as the clear distance between the loaded flange and the stiffener

$$\gamma_s = 10{,}9\frac{I_{s\ell,1}}{h_w t_w^3} \leq 13\left[\frac{a}{h_w}\right]^3 + 210\left[0{,}3 - \frac{b_1}{a}\right] \qquad (7)$$

where
$I_{s\ell,1}$ is the second moment of area of the stiffener closest to the loaded flange including contributing parts of the web according to *Fig. 9.1* in EN 1993-1-5 (2006).

Equation (6) is valid for $0{,}05 \leqslant \frac{b_1}{a} \leqslant 0{,}3$ and $\frac{b_1}{h_w} \leqslant 0{,}3$ and loading type a) in *Fig. 1*.

The effective loaded length ℓ_y should be obtained from section (2.4).

2.4. Effective loaded length ℓ_y

The effective loaded length ℓ_y should be calculated as follows:

$$m_1 = \frac{f_{yf} b_f}{f_{yw} t_w} \qquad (8)$$

$$m_2 = 0{,}02\left(\frac{h_w}{t_f}\right)^2 \quad if\ \bar{\lambda}_F > 0{,}5$$
$$m_2 = 0 \quad if\ \bar{\lambda}_F \leq 0{,}5 \qquad (9)$$

For box girders, b_f in equation (8) should be limited to $15\varepsilon\, t_f$ on each side of the web. For box girders with inclined webs the resistance of both the web and flange should be checked. The internal forces to be taken into account are the components of the external load in the plane of the web and flange respectively.

For types a) and b) in *Fig. 1*, ℓ_y should be obtained using:

$$\ell_y = s_s + 2\, t_f \left(1 + \sqrt{m_1 + m_2}\right) \text{, but } \ell_y \leq \text{ distance between adjacent transverse stiffeners} \qquad (10)$$

For type c) ℓ_y should be taken as the smallest value obtained from the equations (10), (11) and (12).

Note that in EN 1993-1-5 (2006) it is written by mistake: „ℓ_y should be taken as the smallest value obtained from the equations (11) and (12)“. However, s_s in (13) should be taken as zero if the structure that introduces the force does not follow the slope of the girder, *see Fig. 2*.

$$\ell_y = \ell_e + t_f\sqrt{\frac{m_1}{2} + \left(\frac{\ell_e}{t_f}\right)^2 + m_2} \qquad (11)$$

$$\ell_y = \ell_e + t_f\sqrt{m_1 + m_2} \qquad (12)$$

where
$$\ell_e = \frac{k_F E\, t_w^2}{2\, f_{yw} h_w} \leq s_s + c \qquad (13)$$

2.5. Verification of the resistance to transverse force

The verification should be performed as follows:

$$\eta_2 = \frac{F_{Ed}}{L_{eff}\ t_w \frac{f_{yw}}{\gamma_{M1}}} \leq 1{,}0 \tag{14}$$

where

F_{Ed} is the design transverse force.

3. Verification of resistance to interaction of transverse force F_{Ed}, bending moment M_{Ed} and axial force N_{Ed}

If the girder is subjected to a concentrated transverse force F_{Ed} acting on the compression flange in conjunction with bending moment M_{Ed} and axial force N_{Ed}, the resistance should be verified using sections (2.5), (3.1), (3.2) and the interaction expression in section (3.3).

3.1. Member verification for uniaxial bending

$$\eta_1 = \frac{N_{Ed}}{A_{eff} \frac{f_y}{\gamma_{M0}}} + \frac{M_{Ed} + N_{Ed}\ e_N}{W_{eff} \frac{f_y}{\gamma_{M0}}} \leq 1{,}0 \tag{15}$$

where

A_{eff} is the effective cross-section area in accordance with 4.3(3) in EN 1993-1-5 (2006);

e_N the shift in the position of neutral axis, see 4.3(3) in EN 1993-1-5 (2006);

M_{Ed} the design bending moment;

N_{Ed} the design axial force;

W_{eff} the effective elastic section modulus, see 4.3(4) in EN 1993-1-5 (2006);

γ_{M0} the partial factor, see application parts EN 1993-2 to 6.

3.2. Members subject to compression and biaxial bending

For members subject to compression and biaxial bending the above equation (15) (15) may be modified as follows:

$$\eta_1 = \frac{N_{Ed}}{A_{eff} \frac{f_y}{\gamma_{M0}}} + \frac{M_{y,Ed} + N_{Ed}\ e_{y,N}}{W_{y,eff} \frac{f_y}{\gamma_{M0}}} + \frac{M_{z,Ed} + N_{Ed}\ e_{z,N}}{W_{z,eff} \frac{f_y}{\gamma_{M0}}} \leq 1{,}0 \tag{16}$$

$M_{y,Ed}$, $M_{z,Ed}$ are the design bending moments with respect to y–y and z–z axes respectively;

e_{yN}, e_{zN} the eccentricities with respect to the neutral axis.

Action effects M_{Ed} and N_{Ed} should include global second order effects where relevant.

The plate buckling verification of the panel should be carried out for the stress resultants at a distance 0,4*a* or 0,5*b*, whichever is the smallest, from the panel end where the stresses are the greater. In this case the gross sectional resistance needs to be checked at the end of the panel.

3.3. Verification of resistance to interaction of F_{Ed}, M_{Ed} and N_{Ed}

$$\eta_2 + 0{,}8\,\eta_1 \leq 1{,}4 \tag{17}$$

If the concentrated load is acting on the tension flange the resistance should be verified according to section (2). Additionally cl. 6.2.1(5) in EN 1993-1-1 (2005) or cl. 6.2.1(5) in EN 1999-1-1 (2007) should be met.

4. Numerical example

Calculate the value of resistance F_{Rd} to transverse force for given structural detail.
Material properties of the purlin and of its supporting beam made of aluminium alloy are as follows:

Alloy: EN AW-7020 T6 EP $t \le 15$ mm $\quad f_o := 290 \cdot MPa \quad f_{of} := f_o \quad f_{ow} := f_o$

$E := 70000 \cdot MPa \quad \nu := 0.3 \quad \gamma_{M1} := 1.10$

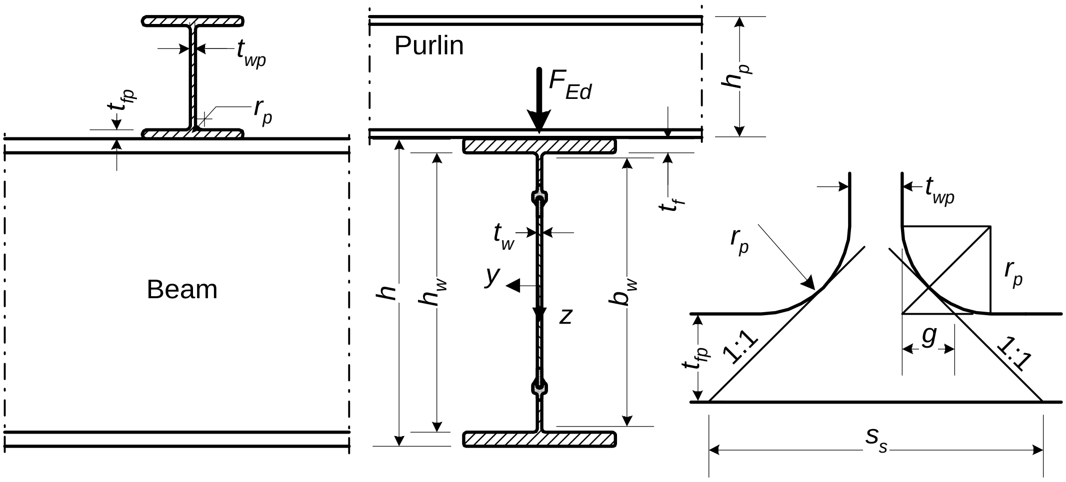


Fig. 3: Verified structural detail

Dimensions

Beam:		Purlin (p):	
Profile height:	$h := 570 \cdot mm$	Profile height:	$h_p := 180 \cdot mm$
Flange width:	$b_f := 160 \cdot mm$	Flange width:	$b_{fp} := 120 \cdot mm$
Flange thickness:	$t_f := 15 \cdot mm$	Flange thickness:	$t_{fp} := 12 \cdot mm$
Web thickness:	$t_w := 5 \cdot mm$	Web thickness:	$t_{wp} := 4 \cdot mm$
Fillet radius:	$r := 5 \cdot mm$	Fillet radius:	$r_p := 4 \cdot mm$
Span:	$L := 10 \cdot m$	Span:	$L_p := 1.2 \cdot m$

Design resistance to transverse force of beam

$a := L \quad h_w := h - 2 \cdot t_f \quad h_w = 540 \cdot mm \quad g := \left(r \cdot \sqrt{2} - r\right) \cdot \sqrt{2} \quad g = 2.9 \cdot mm$

Length of stiff bearing $\quad s_s := t_w + 2 \cdot g + 2 \cdot t_f \quad s_s = 40.9 \cdot mm$

$$\alpha := \frac{a}{h_w} = 18.519 \quad \beta := \frac{s_s}{a} = 0.004 \quad \alpha \cdot \beta = 0.076 \quad \delta := \frac{b_f \cdot t_f}{h_w \cdot t_w} = 0.889$$

Buckling factors for simply supported plate,see formula (7) and Tab. 3 in Baláž & Koleková (2013)

$$k_{FL} := 2 + \frac{1.2}{\alpha^2} + \alpha^2 \cdot \beta^2 \cdot \left(0.5 + \frac{2}{\alpha^2}\right) = 2.006 \quad k_{\sigma b} := 2.5$$

EN buckling factor $\quad k_F := 6 + 2 \cdot \left(\frac{h_w}{a}\right)^2 \quad k_F = 6.01$

Parameter m_1 $\quad m_1 := \frac{f_{of} \cdot b_f}{f_{ow} \cdot t_w} \quad m_1 = 32$

Parameter m_2 $m_2 := 0.02 \cdot \left(\frac{h_w}{t_f}\right)^2 = 25.92$ $l_y := s_s + 2 \cdot t_f \cdot \left(1 + \sqrt{m_1 + m_2}\right) = 0.299\,m$

$m_2 := 0$

Effective loaded length l_y $l_y := s_s + 2 \cdot t_f \cdot \left(1 + \sqrt{m_1 + m_2}\right) = 0.241\,m$

Critical stress $\sigma_E := \dfrac{\pi^2 \cdot E}{12 \cdot \left(1 - \nu^2\right) \cdot \left(\frac{h_w}{t_w}\right)^2} = 5.424\,MPa$ $\dfrac{\pi^2}{12 \cdot \left(1 - \nu^2\right)} = 0.904$

Critical force $F_{cr} := k_F \cdot \sigma_E \cdot h_w \cdot t_w = 87.956 \cdot kN$

$$F_{cr} := 0.9 \cdot k_F \cdot E \cdot \frac{t_w^3}{h_w} = 87.585\,kN$$

Slenderness $\lambda_{p.F} := \sqrt{\dfrac{l_y \cdot t_w \cdot f_{ow}}{F_{cr}}} = 1.996$

Reduction factor $\chi_F := \dfrac{0.5}{\lambda_{p.F}} = 0.251$

Design resistance $F_{Rd.b} := \chi_F \cdot \dfrac{l_y \cdot t_w \cdot f_{ow}}{\gamma_{M1}} = 79.45 \cdot kN$

Beam flange induced buckling

Elastic moment resistance utilised $k := 0.55$

$LS = \dfrac{h_w}{t_w} = 108$ $RS = \dfrac{k \cdot E}{f_{of}} \cdot \sqrt{\dfrac{h_w \cdot t_w}{b_f \cdot t_f}} = 140.8$ $LS < RS$ OK!

Design resistance of purlin to transverse force

$a_p := 2 \cdot L_p$ $h_{wp} := h_p - 2 \cdot t_{fp}$ $h_{wp} = 156 \cdot mm$ $g_p := \left(r_p \cdot \sqrt{2} - r_p\right) \cdot \sqrt{2}$ $g_p = 2.3 \cdot mm$

Length of stiff bearing $s_{sp} := t_{wp} + 2 \cdot g_p + 2 \cdot t_{fp}$ $s_{sp} = 32.7 \cdot mm$

$\alpha_p := \dfrac{a_p}{h_{wp}} = 15.385$ $\beta_p := \dfrac{s_{sp}}{a_p} = 0.014$ $\alpha_p \cdot \beta_p = 0.21$ $\delta_p := \dfrac{b_{fp} \cdot t_{fp}}{h_{wp} \cdot t_{wp}} = 2.308$

Buckling factors for simply supported plate,see formula (7) and Tab. 3 in Baláž & Koleková (2013) $k_{FLp} := 2 + \dfrac{1.2}{\alpha_p^2} + \alpha_p^2 \cdot \beta_p^2 \cdot \left(0.5 + \dfrac{2}{\alpha_p^2}\right) = 2.027$ $k_{\sigma p} := 2.7$

EN buckling factor $k_{Fp} := 6 + 2 \cdot \left(\dfrac{h_{wp}}{a_p}\right)^2$ $k_{Fp} = 6.01$

Parameter m_1 $m_{1p} := \dfrac{f_{of} \cdot b_{fp}}{f_{ow} \cdot t_{wp}}$ $m_{1p} = 30$

Parameter m_2 $m_{2p} := 0.02 \cdot \left(\dfrac{h_{wp}}{t_{fp}}\right)^2 = 3.38$ $l_{yp} := s_{sp} + 2 \cdot t_{fp} \cdot \left(1 + \sqrt{m_{1p} + m_{2p}}\right) = 0.195\,m$

$$m_{2p} := 0$$

Effective loaded length l_y $$l_{yp} := s_{sp} + 2 \cdot t_{fp} \cdot \left(1 + \sqrt{m_{1p} + m_{2p}}\right) = 0.188\, m$$

Critical stress $$\sigma_{Ep} := \frac{\pi^2 \cdot E}{12 \cdot \left(1 - \nu^2\right) \cdot \left(\frac{h_{wp}}{t_{wp}}\right)^2} = 41.595 \cdot MPa$$

Critical force $$F_{crp} := k_{Fp} \cdot \sigma_{Ep} \cdot h_{wp} \cdot t_{wp} = 155.953 \cdot kN$$

$$F_{crp} := 0.9 \cdot k_{Fp} \cdot E \cdot \frac{t_{wp}^{\ 3}}{h_{wp}} = 155.295 \cdot kN$$

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Slenderness $$\lambda_{p.Fp} := \sqrt{\frac{l_{yp} \cdot t_{wp} \cdot f_{ow}}{F_{crp}}} = 1.185$$

Reduction factor $$\chi_{Fp} := \frac{0.5}{\lambda_{p.Fp}} = 0.422$$

Design resistance $$F_{Rd.p} := \chi_{Fp} \cdot \frac{l_{yp} \cdot t_{wp} \cdot f_{ow}}{\gamma_{M1}} = 83.681 \cdot kN$$

Purlin flange induced buckling

Elastic moment resistance utilised $k := 0.55$

$LS = \frac{h_{wp}}{t_{wp}} = 39$ $RS = \frac{k \cdot E}{f_{of}} \cdot \sqrt{\frac{h_{wp} \cdot t_{wp}}{b_{fp} \cdot t_{fp}}} = 87.4$ $LS < RS$ OK!

Design resistance to transverse force of detail, where purlin is supported by beam is the smaller value of the beam and the purlin resistance

$F_{Rd.b} = 79.45\, kN$ $F_{Rd.p} = 83.681\, kN$

In EN 1999-1-1 (2007) the symbol f_o is used for the characteristic value of 0,2 % proof strength. In EN 1993-1-1 (2005) the symbol f_y is used for the characteristic value of the yield strength.

In the above numerical example the term "factor" recommended by ISO standard is used instead of the term "coefficient". Eurocodes use the term "buckling coefficient".

5. Conclusions

Transverse force denotes the load which is applied perpendicular to the flange in the plane of the web. The loading is usually free and transient, as for crane runway girders or bridge girders during launching, so that in this case transverse stiffeners are not appropriate. A concentrated transverse loading is often referred to as patch loading.

The collapse behaviour of girders subjected to transverse loading is characterized by three failure modes: yielding, buckling or crippling of the web. In reality, however, no accurate separation of these phenomena is possible so that an individual treatment of each of them as it was done in ENV 1993-1-5 (1997) and consequently in national standards Czech ČSN 73 1401 (1998) and Slovak STN 73 1401 (1998), is not reasonable.

The design procedure used in Eurocodes EN 1993-1-5 (2006) and EN 1999-1-1 (2007) is based on Lagerquist (1995). Some improvements to Eurocodes were proposed by Davaine and they may be found in the manual (Beg, Kuhlmann, Davaine, Braun 2010). Some missing solutions in Eurocodes are solved in Evolution Groups. In EG EN 1993-1-5 there are for example proposals concerning: a) Resistance to transverse forces of girders with corrugated webs (Kövesdi, Braun, Kuhlmann, Dunai 2012), b) interaction between transverse force and shear force (Kuhlmann, Braun 2012).

The second author of submitted paper is responsible for implementation and application of Eurocodes in Slovak Republic. During period longer than 12 years he translated many parts of Eurocodes, created many National Annexes and many scientific backgrounds, which were used in the official CEN Corrigenda and CEN Amendments of Eurocodes. This is true for example for European prestandards ENVs and standards ENs of the most important parts for the design of steel and aluminium structures: EN 1993-1-1, -1-3, -1-5 and EN 1999-1-1, respectively. *Tab. 1* shows terminology used in translation of EN 1993-1-5 (2006) in Slovak language.

Tab. 1: Terminology used in English, Slovak, German, French and Czech EN 1993-1-5 editions

Č.	ENGLISH	SLOVENSKY	DEUTSCH	FRANÇAIS	ČESKY
1	effective cross-section	efektívny, [účinný] prierez	effektiver Querschnitt	section transversale efficace	účinný průřez
2	effective^{p} width	účinná šírka (súvisí s vydúvaním tlačených stien)	wirksame Breite	largeur efficace	účinná^{p} šířka
3	effective^{s} width	spolupôsobica šírka (súvisí s ochabnutím šmykom)	mittragende Breite	largeur efficace	účinná^{s} šířka
4	effective width	efektívna šírka (všeobecne, alebo interakcia vydúvania tlačených stien a ochabnutia šmykom)	effektive Breite	largeur efficace	účinná šířka
5	gross cross-section	neredukovaný prierez	Bruttoquerschnitt	section transversale brute	plný průřez
6	plated structural elements	nosné stenové prvky	Plattenbeulen	plaques planes	boulení stěn
7	plate	stena, plech	Blech	plaque	stěna, plech
8	panel	pole steny	Blechfeld, Gesamtfeld, ausgesteiftes Beulfeld	panneau	panel
9	subpanel	čiastkové pole steny	Einzelfeld	panneau secondaire	subpanel
10	shear force	šmyková sila (užší význam, derivácia momentu na prúte), priečna sila (širší význam)	Querkraft [Schubkraft]	effort tranchant	smyková síla
11	shear lag	ochabnutie šmykom	Schubverzerrungen	traînage de cisaillement	smykové ochabnutí

6. Summary

The paper (Baláž, Koleková 2013) is devoted to the comparison of the buckling factors k_σ of the critical stress of the plate subjected to transverse force F_{Ed} , valid for simply supported plate calculated by various authors. The buckling factor k_σ differs from the buckling factor k_F , which was proposed by Lagerquist (1995) for Eurocodes EN 1993-1-5 (2006) and EN 1999-1-1 (2007). The buckling factor k_σ cannot be used in design rules of Eurocodes. The buckling factor k_F takes into account the more realistic boundary conditions and relevant Eurocode design procedure is based on numerous experiments (Lagerquist 1995).

In this paper design procedures of EN 1993-1-5 (2006) and EN 1999-1-1 (2007) are described and explained. It is also shown, where are the mistakes in Eurocode EN 1993-1-5 (2006). The design rules of EN 1999-1-1 (2007), which are practically identical with the design rules of EN 1993-1-5 (2006), are applied for the type a) (see *Fig. 1*) in detailed numerical example. In the example a purlin is supported by a beam. Both members are without longitudinal stiffeners having extruded profiles (EP) made of aluminium alloy EN AW-7002-T6.

Acknowledgements

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