CLASSIFICATION OF CROSS SECTIONS FOR STEEL BEAMS IN DIFFERENT DESIGN CODES

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ABSTRACT

In the paper comparison of classification for I-sections of steel beams in different design codes - Eurocode 3, DIN 18 800 (Germany), B7 (Finland), BSK and Bygg K18 (Sweden) and SNiP II-23-81* (the former Soviet Union) - is presented. It is shown, that the limits of classification, especially between Class 3 and Class 4 webs, differ quite remarkably. The aim is to "position" Eurocode 3 among the other codes in respect of the considered point.

INTRODUCTION

In different codes the cross sections are handled quite differently. In Eurocode 3, DIN 18 800 and B7 cross sections are divided into 4 classes, while in Swedish codes only 3 classes are considered. In SNiP the concept of cross section class as such is lacking at all, but still 3 classes can be specified in context of the presented principles. In the present paper the definitions of the classes, as given in Eurocode 3 (EC 3) Part 1.1 5.3.2 (1), are used:

> **Class 1 cross sections** are those which can form a plastic hinge with the rotation capacity for plastic analysis.
>
> **Class 2 cross sections** are those which can develop their plastic moment resistance, but have limited rotation capacity.

Class 3 cross sections are those in which the calculated stress in the extreme compression fibre of the steel member can reach its yield strength, but local buckling is liable to prevent development of the plastic moment resistance.

Class 4 cross sections are those in which it is necessary to make explicit allowances for the effects of local buckling when determining their moment resistance or compression resistance.

To make the different codes better comparable, similar initial data and assumptions are to be applied. For the same purpose, in the following as much as possible, the EC 3 symbols and way of expression presentation is applied for all the considered codes, consequently some formal differences may occur as to the original documents. Also several differences in starting points have to be kept in mind: the elasticity ratio of steel according to SNiP is $2.06 \cdot 10^5$ N/mm^2 ($2.10 \cdot 10^5$ N/mm^2 in EC 3), in DIN the "basic" strength of steel, used to express cross section classification ratios, is 240 N/mm^2 (235 N/mm^2 in EC 3), some of the codes include the thickness of fillet weld in the depth of the web and in the width of the flange outstand, some do not. etc.

Only the basic design situations are considered, so the following assumptions are applied:

- the cross section is symmetrical about both axis and constant in the whole span of the beam;
- the web is not subject to local transverse loading, causing crushing, crippling or buckling failure;
- shear stress in the considered cross sections does not exceed 0.5 τ_{cr};
- the beam is not subjected to axial force;
- the possibility of shear buckling is excluded.

It should be pointed out that in all the codes the limit between cross section element classes 3 and 4 (i.e. the limit of buckling resistance of cross section elements) is based on the same well-known expression of critical stresses in a plate:

$$\sigma_{cr} = k_\sigma \pi^2 E (t/b)^2 / [12(1-\nu^2)]; \qquad (1)$$

or inserting elasticity ratio $E = 2.10 \cdot 10^5$ N/mm^2 and Poisson coefficient $\nu = 0.3$:

$$\sigma_{cr} = 189800 k_\sigma (t/b)^2; \qquad (1a)$$

The value of k_σ is determined by the boundary conditions of the cross section element. For example in EC 3, B7 and DIN 18 800 the connection between the web and flanges is presumed to be moment-free and consequently $k_\sigma = 23.9$ (in Finnish B7 the rounded value 24.0 is used). Alternatively in SNiP the connection of web to the flanges is considered as semi-rigid due to the presence of obligatory transverse stiffeners and so k_σ obtains values between 33.0 and 39.0 depending on the proportions of the web and flanges. In Swedish codes the type of connection depends on the proportions of the cross section as well and can be moment-free or semi-rigid, respectively the value of k_σ changes.

Most of the codes use $k_\sigma = 0.43$ for compression flanges.

Quite remarkable differences occur between codes in specifying how close the actual stresses may reach to the critical value. At the same time in some of the codes considered the answer to this question can be interpreted in two different ways.

CLASSIFICATION OF CROSS-SECTIONS IN EUROCODE 3

Limits of cross section classes in EC 3 are expressed in terms of proportions of the cross section elements in table 5.3.1 as follows:

Class 1: web: $d/t_w \leq 72\varepsilon$; (2)

compression flange: $c/t_f \leq 9\varepsilon$ (for welded sections); (3)

where d - web depth, see fig. 1.;

t_w - web thickness;

c - flange outstand width, see fig 1.;

t_f - flange thickness;

$\varepsilon = (235/f_y)^{0.5}$ - factor, depending on the strength of steel;

f_y - nominal value of the yield strength for steel.

Class 2: web: $d/t_w \leq 83\varepsilon$; (4)

compression flange: $c/t_f \leq 10\varepsilon$; (5)

Class 3: web: $d/t_w \leq 124\varepsilon$; (6)

compression flange: $c/t_f \leq 14\varepsilon$; (7)

Cross-sections that fail to satisfy those criteria, belong to class 4.

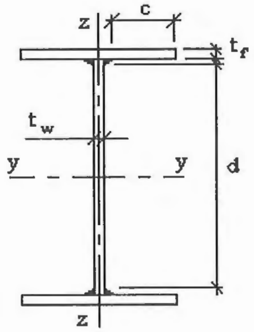

Fig 1. Gross cross-section of a beam

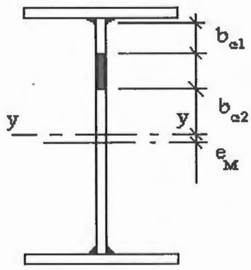

Fig. 2. Effective cross-section of a beam

The design of a class 4 section is based on the effective cross-section concept, i.e. due to local buckling parts of the cross-section are excluded from the cross-section area and section modulus (see fig. 2). This is gained by reduction factor ρ, defined in EC 3, 5.3.5 (3) as:

$$\rho = 1, \quad \text{if } \overline{\lambda}_p \leq 0.673;$$
$$\rho = (\lambda_p - 0.22)/\overline{\lambda}_p^2, \quad \text{if } \overline{\lambda}_p > 0.673; \tag{8}$$

where: $\overline{\lambda}_p = (f_y/\sigma_{cr})^{0.5} = (b/t)/(28.4\varepsilon\, k_\sigma^{0.5})$ - plate slenderness; (9)

$b = d$ for web;

$b = c$ for compression flange (see fig. 1);

t - relevant plate thickness (web or compression flange)

Equation (8) gives us the limit between class 3 and class 4 cross-section as $\overline{\lambda}_p = 0.673$, the corresponding proportions of the cross-section elements are as follows:

web: $d/t_w = 93.4\varepsilon$; (10)

compression flange: $c/t_f = 12.5\varepsilon$; (11)

which is essentially different from eq. (6) and eq. (7) respectively. Although table 5.3.1 and 5.3.5 (3) belong to *Application Rules*, which are not obligatory in design and may have alternatives, still presence of this kind of difference in a code document may be confusing.

The reduction factor is applied to the part of the web subjected to compression as follows (see fig. 2):

$$b_{eff} = \rho b_c; \qquad b_{e1} = 0.4 b_{eff}; \qquad b_{e2} = 0.6 b_{eff}; \tag{12}$$

where b_c - depth of the compression zone for the gross cross section (i.e. for a symmetrical I-section b_c= 0.5d for a symmetrical I-section with compression flange of class 1,2 or 3; for sections with class 4 compression flange, the shift of neutral axis due to reduction of compression flange area should be taken into account.

CLASSIFICATION OF CROSS-SECTIONS IN DIN 18 800

The classification of cross-sections is presented mainly in DIN 18 800 part 1, 7.5.2 - 7.5.4. The limit proportions for class 1 and 2 are quite close to the respective values in EC 3:

Class 1: web: $d/t_w = 64(240/f_y)^{0.5} = 64.7\varepsilon$; (13)
compression flange: $c/t_f = 9(240/f_y)^{0.5} = 9.1\varepsilon$; (14)

Class 2: web: $d/t_w = 74.8\varepsilon$; (15)
compression flange: $c/t_f = 11.1\varepsilon$; (16)

Class 3: Unlike in EC 3 the slenderness is not based on the nominal value of the yield strength but actual maximum stress:

web: $d/t_w = 133[240/(\sigma_1\gamma_M)]^{0.5} = 134.4\varepsilon_\sigma$; (17)
compression flange: $c/t_f = 12.9[240/(\sigma_1\gamma_M)]^{0.5} = 13.0\varepsilon_\sigma$; (18)

where σ_1 - maximum value of the design compression stress in the section element;

γ_M - partial safety factor for steel strength;

$\varepsilon_\sigma = [235/(\sigma_1\gamma_M)]^{0.5}$; at the limit, i.e. if $\sigma_1 = f_y/\gamma_M$ => $\varepsilon_\sigma = \varepsilon$;

The reduction factor ρ for class 4 effective cross section is determined in DIN, part 2, 7.4, table 27 as follows:

$$\rho = (1/\bar{\lambda}_{p\sigma})[(0.97 + 0.03\psi) - (0.16 + 0{,}06\psi)/\bar{\lambda}_{p\sigma}]; \tag{19}$$

where ψ - ratio of stresses on the opposite edges of the section element (e.g. $\psi = 1$ for uniform compression over the element, $\psi = -1$ for the web of a symmetrical I-section beam);

$$\bar{\lambda}_{p\sigma} = [(\sigma\gamma_M)/(189800k_\sigma)]^{0.5}(b/t) = (b/t)/[28.1\varepsilon_\sigma(k_\sigma)^{0.5}]; \tag{20}$$

For webs of symmetrical I-section beams $k_\sigma = 23.9$ and $\psi = -1$.
At the limit between classes 3 and 4 we obtain:

$$\rho = (1/\bar{\lambda}_{p\sigma})(0.94 - 0.10/\bar{\lambda}_{p\sigma}) = 1; \qquad \Rightarrow \qquad \bar{\lambda}_{p\sigma} = 0.818;$$

Inserting those values into eq. (20) and expressing the limit proportions we gain the limit proportion for webs between classes 3 and 4 as:

$$d/t_w = 113.6\varepsilon_\sigma; \tag{21}$$

which differs quite remarkably from the value, obtained in eq. (17).

For compression flanges of symmetrical I-section beams $k_\sigma = 0.43$ and $\psi = 1$.
At the limit between classes 3 and 4 we obtain:

$$\rho = (1/\bar{\lambda}_{p\sigma})(1 - 0{,}22/\bar{\lambda}_{p\sigma}) = 1; \qquad \Rightarrow \qquad \bar{\lambda}_{p\sigma} = 0.673;$$

which coincides with the relevant value of EC 3.

Inserting the obtained values into eq. (20), we can express the limit proportion for flanges between class 3 and 4 as follows:

$$c/t_f = 13.0\varepsilon_\sigma; \qquad (22)$$

which is exactly the same as eq. (18).

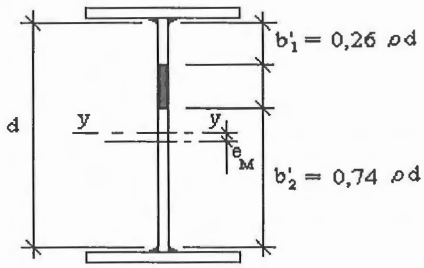

Fig. 3. The effective cross-section of a beam according to DIN 18 800.

To determine the effective area of the cross-section, the full depth of the web must be reduced by the factor ρ. In case $\psi = -1$ the depths of the effective zones in the web are determined as follows, see also fig. 3:

$$b'_1 = 0.26\rho d; \qquad b'_2 = 0.74\rho d; \qquad (23)$$

The effective zone of the flange is determined analogously to EC 3.

CLASSIFICATION OF CROSS SECTIONS IN THE FINNISH CODE B7

The classification principles are presented in B7 fig. 3.3 and section 4.6.2 for limits between classes 3 and 4 as follows:

Class 1:	web:	$d/t_w = 2.4(E/f_y)^{0.5} = 71.7\varepsilon;$	(24)
	compression flange:	$c/t_f = 0.30(E/f_y)^{0.5} = 9.0\varepsilon;$	(25)

Class 2: web: $d/t_w = 3.0(E/f_y)^{0.5} = 89.7\varepsilon$; (26)

compression flange: $c/t_f = 0.36(E/f_y)^{0.5} = 10.8\varepsilon$; (27)

Class 3: compression flange: $c/t_f = 0.44(E/f_y)^{0.5} = 13.1\varepsilon$; (28)

The limit proportion for webs between classes 3 and 4 is not directly defined, it comes out of the criterion that for class 3 sections the slenderness $\bar{\lambda}_p \leq 0.72$ (see 4.6.2, table 4.8 in B7).

The slenderness is in principle the same as in EC 3:

$$\bar{\lambda}_p = (f_y/\sigma_{el})^{0.5} = (1/\varepsilon)(235/\sigma_{el})^{0.5}; \tag{29}$$

where $\sigma_{el} = \{k_\sigma \pi^2 E/[12(1-\nu^2)]\}(t/b)^2 = 455200(t/b)^2$, (30)

whereby for beam web $k_\sigma = 24.0$ is applied (a rounded value of 23.9, used in EC 3 and DIN). Now provided that at the limit between classes 3 and 4 $\bar{\lambda}_p = 0.72$, the limit proportion for web appears to be as:

$$d/t_w = 100.2\varepsilon; \tag{31}$$

Analogously we can obtain the limit proportion between classes 3 and 4 for compression flange outstand from table 4.8, inserting $\bar{\lambda}_p = 0.71$ and $k_\sigma = 0.43$ into eq. (29):

$$c/t_f = 13.1\varepsilon; \tag{32}$$

As a result we can see that the limit conditions coincide both for webs and flanges and no problem of interpretation arises in section classification according to B7.

The reduction factor for web is obtained as follows:

$$\begin{aligned} \rho &= 1, && \text{if } \bar{\lambda}_p \leq 0.72; \\ \rho &= (1/\bar{\lambda}_p)[1.00 - 1/(5\bar{\lambda}_p)], && \text{if } 0.72 < \bar{\lambda}_p \leq 5; \end{aligned} \tag{33}$$

The reduction factor is applied to the compression zone of the web. The depths of the effective zones to the both sides of the noneffective zone are equal.

The reduction factor for compression flange is determined as follows:

$$\rho = 1, \qquad \text{if } \bar{\lambda}_p \leq 0.71;$$
$$\rho = 1.5 - \bar{\lambda}_p/2^{0.5}, \qquad \text{if } 0.71 < \bar{\lambda}_p \leq 1.06; \qquad (34)$$

Unlike the other codes, here the flange thickness is reduced by the factor ρ (see fig. 4).

CLASSIFICATION OF CROSS-SECTIONS IN SWEDISH CODES BSK AND BYGG K18

3 cross-section classes are defined in the Swedish codes:

Class 1 cross sections are those, which can form a plastic hinge with sufficient rotation capacity, i.e. in principle the same as in EC 3.

Class 2 cross sections are those in which stresses in the extreme compression fibre can reach the yield strength, but further plastic deformation is not allowed, i.e. corresponding to class 3 in EC 3.

Class 3 cross sections are those in which any of the compression elements is subject to local buckling before the stresses in extreme compression fibre can reach the yield strength, i.e. corresponding to class 4 in EC 3.

The limit proportions are given as follows:

Class 1: web: $d/t_w = 2.4(E/f_y)^{0.5} = 71.7\varepsilon;$ (35)

compression flange: $c/t_f = 0.3(E/f_y)^{0.5} = 9.0\varepsilon;$ (36)

Class 2 (EC 3 class 3):

web: $d/t_w = 3.2\kappa_f(E/f_y)^{0.5} = 95.6\kappa_f\varepsilon,$ (37)

where $\kappa_f = 2.5 - 1.5[(c/t_f)/(13.15\varepsilon)]$, $1.0 \leq \kappa_f \leq 1.5$; (38)

i.e. in case the compression flange belongs to class 1, then $\kappa_f = 1.5$ and the limit proportions between classes 2 and 3 (EC 3 classes 3 and 4) are as follows:

web $d/t_w = 143.5\varepsilon$; (37a)

compression flange: $c/t_f = 0.44(E/f_y)^{0.5} = 13.15\varepsilon$; (39)

Class 3 (EC 3 class 4) effective cross-section area (and section modulus) are calculated by reducing the thickness of the relevant compression elements of the section. The reduction factors are determined as follows:

web: if $\lambda \leq 0.6$ => $\rho = 1$;

if $\lambda > 0.6$ => $\rho = 0.07 + 0.63/\lambda + 0.043/\lambda^2$; (40)

where $\lambda = [0.375 b_c/(\kappa_f t_w)](f_y/E)^{0.5}$; (41)

b_c - depth of the compression zone of the web (0.5d for symmetrical section).

The reduction factor ρ is applied to the web thickness in compression zone.

Provided that $\lambda = 0.6$ we can express the limit proportions for the web between classes 2 and 3 (EC 3 classes 3 and 4) as follows:

$$d/t_w = 2b_c/t_w = 2\times0.6\kappa_f(E/f_y)^{0.5}/0.375 = 95.6\kappa_f\varepsilon; \quad (42)$$

compression flange: if $\lambda \leq 0.67$ => $\rho = 1$;

if $\lambda > 0.67$ => $\rho = 1/\lambda - 0.22/\lambda^2$; (43)

where $\lambda = 1.52(c/t_f)(f_y/E)$; (44)

The reduction factor ρ is applied to the thickness of the compression flange.

The limit proportion of the compression flange outstand, provided that $\lambda = 0.67$ at the limit, is as follows:

$$c/t_f = 0.67(E/f_y)^{0.5}/1.52 = 13.17\varepsilon \tag{45}$$

So the limit proportions in eq. (42) and eq. (45) coincide with those eq. (37) and eq. (39) respectively (BSK table 6:21) and no problem of interpretation arises as with EC 3 and DIN.

CONDITIONAL CLASSIFICATION OF CROSS-SECTIONS IN SNIP II-23-81*

The concept of cross-section classes is not directly included in the former Soviet Union code SNiP-II-23-81*. But still there are rules given, which regulate the limits of plastic moment resistance application and plastic hinge formation, and also the limit proportions of compression elements to prevent local buckling.

Classes 1 and 2

Without additional prescriptions plastic moment resistance can be applied if the slenderness of the web (in terms of SNiP) and the proportions of the compression flange outstand satisfy the following conditions:

web (see SNiP sec. 7.5): $\bar{\lambda}_w = \bar{\lambda}_{w,SNiP} = (d/t_w)(R_y/E)^{0.5} \leq 2.2;$ (46)

where R_y - design yield strength of steel, ($R_y = f_y/\gamma_{M1}$ in terms of EC 3);
$E = 2.06 \cdot 10^5$ N/mm^2.

Provided that the partial safety factor $\gamma_{M1} = 1{,}1$, the limit proportions for section between classes 1 and 2 can be obtained as follows:

web: $d/t_w \leq 68.3\varepsilon;$ (47)
compression flange (see SNiP, sec. 7.24): $c/t_f \leq 0.3(E/R_y)^{0.5} = 9.3\varepsilon;$ (48)
$c/t_f \leq 0.11(d/t_w);$ (49)

In case the web dimension ratio exceeds the limit given in eq. (47), plastic deformations are allowed, but only partially, not in the whole depth of the section. Further details are not included in the present paper. It should only be mentioned, that those sections with limited plastic moment resistance belong in principle still to the class 1 as redistribution of moments is allowed. At the same time the rotation capacity analysis is not required.

Class 3

The compression flanges are not susceptible to buckling if the proportion of the flange outstand satisfies the criterion:

$$c/t_f \leq 0.5(E/R_y)^{0.5} = 15.5\varepsilon; \tag{50}$$

SNiP does not allow local buckling of the compression flange, i.e. flanges cannot belong to class 4.

For webs the situation is a little bit more complicated. SNiP requires transverse stiffeners with spacing not exceeding 2d on the web, if the web slenderness $\bar{\lambda}_{w,SNiP} > 3.2$ (i.e. if $d/t_w > 99.4$). Provided that this requirement is satisfied, the buckling resistance of the web is satisfied if:

$$\bar{\lambda}_{w,SNiP} \leq 3.5; \tag{51}$$

or expressing the limit proportion:

$$d/t_w \leq 108.7\varepsilon. \tag{52}$$

If the criterion in eq. (52) is not satisfied, the buckling resistance must be checked according to SNiP, 7.4 as follows:

$$[(\sigma/\sigma_{cr})^2 + (\tau/\tau_{cr})^2]^{0.5} \leq \gamma_c; \tag{53}$$

where: σ - compression stress at the edge of the web from the bending moment which is averaged across the section limited by the transverse stiffeners (but not wider than d);

$\tau = V/(dt_w)$ - shear stress from the shear force which is averaged across the same section as the moment for σ;

γ_c - factor of work conditions ($\gamma_c = 1$ in most cases);

Critical bending stresses are determined as:

$$\sigma_{cr} = c_{cr}R_y/\bar{\lambda}_{w,SNiP}^2 = c_{cr}E_{SNiP}(t_w/d)^2; \qquad (54)$$

The factor c_{cr} depends on the stiffness of the compression flange and connection type of the flange to other elements, c_{cr} = 30.0...35.5 (see SNiP II-23-81*, table 21). As $E_{SNiP} = 2.06 \cdot 10^5$ N/mm² and for most cases in practice $c_{cr} = 30.0$, the critical stress is expressed as:

$$\sigma_{cr} = 6180000(t_w/d)^2; \qquad (55)$$

Comparing this value to eq. (1a), $k_\sigma = 32.56$ can be obtained.

Provided that shear stresses are not present in the considered beam section ($\tau = 0$), compression stress at the edge of the web $\sigma \approx R_y$, the partial safety factor $\gamma_M = 1.1$ and factor of work conditions $\gamma_c = 1$, the web limit proportion of buckling resistance (i.e. limit between classes 3 and 4) can be obtained as:

$$d/t_w \leq 170.0\varepsilon; \qquad (56)$$

In the same situation, but with $\tau = 0.5\tau_{cr}$ the limit proportion is:

$$d/t_w \leq 158.3\varepsilon; \qquad (56a)$$

As it has been shown, SNiP II-23-81* dares to apply less reserve than the other codes as to web buckling. It is due to the fact that the rigidity of connection between the web and flanges, which are supported by transverse stiffeners, is taken into account more precisely. At the same time, web buckling and post-critical work is allowed by SNiP only if $\bar{\lambda}_w \geq 6$, i.e. if $d/t_w \geq 186.3$!

NUMERICAL EXAMPLE

In the following the effective modulus for the welded symmetrical I-section are calculated according to different codes. The beam is made of Fe 510 ($f_y = 355$ N/mm²).

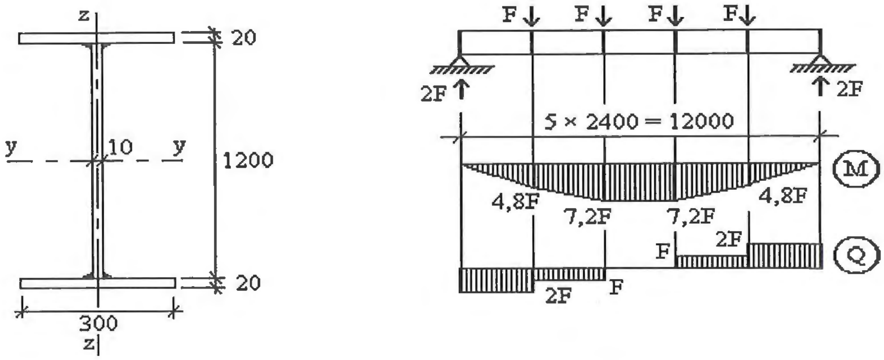

Fig. 4. Cross-section, load scheme and inner forces of the beam.

For steel Fe 510: $\varepsilon = (235/f_y) = 0.81$;
web cross-section area: $A_w = 10 \cdot 1200 = 12000$ mm²;
flange cross-section area: $A_f = 20 \cdot 300 = 6000$ mm² ($= 0.5\ A_w$);
gross cross-section area of the beam: $A = 24000$ mm²;
second moment of gross area: $I_y = 590560 \cdot 10^4$ mm⁴;
gross section modulus: $W_{el.y} = 9525 \cdot 10^3$ mm³.

For compression flange (not including the depth of welds):

$$c/t_f = 145/20 = 7.25 = 8.95\varepsilon;$$

Consequently the compression flange does not belong to class 4 by any of the codes.
For web (not including the depth of the welds):

$$d/t_w = 1200/10 = 120 = 148.1\varepsilon;$$

In all the codes but SNiP II-23-81* the web clearly belongs to class 4 (in terms of EC 3 classification).
The effective section modulus are as follows:

- EC 3:	$W_{eff} = 8869 \cdot 10^3$ mm³	(93.1% of $W_{el.y}$);
- DIN 18 800:	$W_{eff} = 8912 \cdot 10^3$ mm³	(93.6% of $W_{el.y}$);
- B7:	$W_{eff} = 9034 \cdot 10^3$ mm³	(94.8% of $W_{el.y}$);

- BSK / Bygg K 18: $W_{eff} = 9451 \cdot 10^3$ mm³ (99.2% of $W_{el.y}$);

(here for relatively narrow and thick flange $\kappa_f = 1.479$)

-SNiP II-23-81* $W_{eff} = W_{el.y} = 9525 \cdot 10^3$ mm³ .

CONCLUSION

It is shown that the classification limits of I-sections are quite different in considered codes. Especially clearly the difference in limit between class 3 and 4 webs, which determines the criterion of web buckling, is expressed. Some confusion is caused by the possibility to apply two interpretations to the limit between classes 3 and 4 in EC 3, DIN 18 800 and B7. Also the ways of reduction of the cross-section in class 4 to obtain the effective cross-section are different. Despite of that at least in the presented example the effective section modulus values by EC 3, DIN and B7 are very close. In the same design situation according to the SNiP methology considerably greater load can be applied to the beam as to web buckling, because the web-flange connection is taken as semi-rigid. For the same reason in the presented example the effective section modulus by the Swedish codes is nearly the same as the elastic section modulus. With thinner and wider flange the results by the Swedish codes approach to those by EC 3, B7 and DIN 18 800.

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