Proposed Annex B

The proposed amendments to EN 1993-1-1 include Annex B which deals with semi-compact sections (the contents of the current Annex B have been promoted to the main part of the code). Richard Henderson of the SCI compares the proposals with the treatment of semi-compact sections in BS 5950.

1 Introduction

In BS 5950-1:2000, section 3.5 Classification of cross-sections includes a subsection: 3.5.6 Effective plastic modulus, dealing with semi-compact sections. This subsection allows semi-compact sections to be designed using either the elastic modulus or the effective plastic modulus (denoted Z and S_{eff} respectively in BS 5950). This approach is limited to bisymmetrical sections, circular tubes and I and H sections with unequal flanges subject to bending in the plane of the web. The value of S_{eff} depends on the limiting values of the web slenderness given in the relevant table. These values adjust the class boundaries according to ratios of axial stress and resistance in the webs of the cross section. The magnitude of S_{eff} falls between the elastic and plastic moduli and credits the cross-section with increased resistance.

Despite the presence of the established approach in BS 5950, BS EN 1993-1-1:2005 did not include a basis for using an increased modulus for the design of semi-compact sections but this omission is now to be remedied. The proposed Annex B in prEN 1993-1-1 now includes the determination of $W_{ep,y}$ the elasto-plastic section modulus for semi-compact doubly symmetric cross-sections and circular or elliptical hollow sections. This is illustrated in Figure 1.

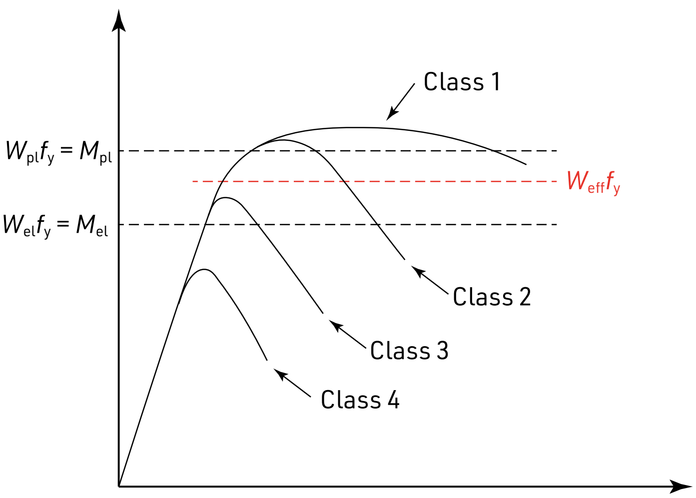

Figure 1: Illustration of effective modulus

The Annex also takes the effect of axial force into account but in this case an adjusted bending resistance is determined by applying a factor to the resistance in the absence of axial force, calculated using the elasto-plastic modulus. The factor depends on the ratio of the design axial force to the plastic axial resistance.

2 Detailed Proposals in Annex B

The proposals have been examined in detail for the case of symmetrical welded I sections. The formulae for the revised proposals are as indicated below.

$$W_{ep,y} = W_{pl,y} - (W_{pl,y} - W_{el,y})\,\beta_{ep,y}$$
$$W_{ep,z} = W_{pl,z} - (W_{pl,z} - W_{el,z})\,\beta_{ep,z}$$

where $W_{ep,y}$ and $W_{ep,z}$ denote the elasto-plastic moduli. The plastic and elastic moduli adopt their usual notation.

The β_{ep} values depend on the parameter ε which varies with the yield strength and the slenderness ratios of the elements of the cross section defined in the classification table.

The class boundaries for certain sections are to be modified. The relevant ones to this article are those relating to webs in compression and combined bending and compression, and the boundary between class 3 and class 4. In general, the slenderness ratios at the boundaries have reduced: for example, for internal compression parts, the slenderness at the class 1/class 2 boundary has reduced from $c/t \le 33\varepsilon$ to $c/t \le 28\varepsilon$.

The expressions for rolled or welded I or H sections are as follows:

$$\beta_{ep,y} = \mathrm{Max}\left\{\frac{\frac{c}{t_f} - 10\varepsilon}{4\varepsilon};\ \frac{\frac{c}{t_w} - 83\varepsilon}{38\varepsilon};\ 0\right\} \text{ but } \beta_{ep,y} \le 1.0$$

$$\beta_{ep,z} = \mathrm{Max}\left\{\frac{\frac{c}{t_f} - 10\varepsilon}{6\varepsilon};\ 0\right\} \text{ but } \beta_{ep,z} \le 1.0$$

In the first expression, 10ε is the limiting slenderness for class 2 for outstand flanges subject to bending; 83ε is the limiting slenderness for class 2 for internal compression parts subject to bending and 38ε is the limiting slenderness for class 3 for internal compression parts subject to compression.

2.1 Resistance of cross-sections

The resistance of cross-sections that are required to sustain combined bending and axial compression is established by determining the design elasto-plastic bending resistance reduced in the presence of axial force. The section classification is established first, followed by the elasto-plastic modulus. The bending resistance is then found and reduced according to the ratio of the design compression force to the plastic compression resistance of the section.

The process is illustrated below in an example and the results compared with the equivalent outcome determined using the BS 5950:2000 procedure.

3 Example

3.1 prEN 1993-1-1 procedure

Design a fully restrained plate girder subject to a bending moment $M_{y,Ed}$ = 615 kNm and an axial compression N_{Ed} = 100 kN. Material grade: S355.

Using the Blue Book resistances for an equivalent rolled section as a starting point, try a beam 530 deep by 230 wide with 12.5 mm thick flanges and a 6 mm thick web. Assume a 6 mm leg web to flange weld.

Section properties are presented in Table 3.1.

Table 3.1 Section Properties

Property	Value	Units
Area	8780	cm³
Plastic modulus $W_{pl,y}$	1870	cm³
Plastic modulus $W_{pl,z}$	335	cm³
Elastic modulus $W_{el,y}$	1696	cm³
Elastic modulus $W_{el,z}$	221	cm³

▸26

▸24

Classify the section

Selected class limits are presented in Table 3.2. In the table, c is the flange outstand beyond the weld toe, d_w is the web depth between weld toes.

Table 3.2 Classification

Flange		Web	
Slenderness	c/t_f = 8.48	Slenderness	d_w/t_w = 82.2
Class 1 limit, bending	9ε = 7.29	Class 1 limit, bending and axial	d_w/t_w = 50.7
		Class 2 limit, bending	d_w/t_w = 67.2
Class 2 limit, bending	10ε = 8.1	Class 2 limit, bending and axial	d_w/t_w = 59.1
		Class 3 limit, compression	d_w/t_w = 30.8
Class 3 limit, bending	14ε = 11.3	Class 3 limit, bending and axial	d_w/t_w = 93.3

The section therefore has class 3 flanges and a class 3 web under this loading. The semi-compact section classification means that the proposed Annex B may be used to determine an elasto-plastic section modulus W_{ep}. Substituting in the equation for $\beta_{ep,y}$,

$$\beta_{ep,y} = \text{Max}\left\{\frac{8.48 - 8.1}{3.24}\ ;\ \frac{82.2 - 67.2}{30.8}\ ;\ 0\right\} \text{ but } \beta_{ep,y} \leq 1.0$$

Precise calculation gives a value of $\beta_{ep,y}$ = 0.485 which differs slightly from the results of the above expression due to rounding. The reduction relative to the plastic modulus is therefore just under half the difference between the plastic and elastic moduli, giving a value for the elasto-plastic modulus of 1785 cm³.

The reduction factor for axial load in the major axis bending resistance for sections of class less slender than 4 is:

$$1 - n = 1 - \frac{N_{Ed}}{N_{pl,Rd}}\ ;\ N_{pl,Rd} = \frac{Af_y}{\gamma_{M0}}$$

For the section being considered, $N_{pl,Rd}$ = 3117 kN so n = 0.0321 and $(1 - n)$ = 0.968. The major axis bending resistance in the presence of axial load is given by:

$$M_{N,ep,y,Rd} = M_{ep,y,Rd}\,(1 - n) = \frac{W_{ep,y} f_y}{\gamma_{M0}}\,(1 - n)$$

Substituting values gives a bending resistance of 614 kNm and a utilization of 1.00 to two significant figures.

3.2 BS 5950 Procedure

The corresponding procedure in BS 5950 involves determining the stress ratios r_1 and r_2 in the section. These are respectively the ratio of the applied axial compression to the web compression resistance, and the ratio of the applied axial compression to the compression resistance of the gross section, both based on the design strength of the web. In this case the web depth d is taken as the depth between flanges. The flange and web thicknesses are denoted T and t respectively. The stress ratios are:

$$r_1 = \frac{100000}{505 \times 6 \times 355} = 0.0930$$

Similarly, the value of r_2 is 0.0321. The value of ε in BS 5950 is 0.88 as it is based on p_y = 275 MPa. The class limits are given in Table 3.3. Some entries in the table are given only for comparison with the prEN values. The flange outstand b is taken from the face of the web.

Table 3.3 Classification

Flange		Web	
Slenderness	b/T = 8.96	Slenderness	d/t = 84.2
Class 1 limit, bending	8ε = 7.04	Class 1 limit, bending	d/t = 70.4
		Class 1 limit, bending and axial	d/t = 64.4
Class 2 limit, bending	9ε = 7.92	Class 2 limit, bending	d/t = 88.0
		Class 2 limit, bending and axial	d/t = 77.2
Class 3 limit, bending	13ε = 11.4	Class 3 limit, bending	d/t = 105.6
		Class 3 limit, bending and axial	d/t = 99.2

The section is therefore class 3.

The effective section modulus is given in BS 5950 cl. 3.5.6.2 for semi-compact sections as:

$$S_{x,eff} = Z_x + (S_x - Z_x)\left[\frac{\left(\frac{\beta_{3w}}{d/t}\right)^2 - 1}{\left(\frac{\beta_{3w}}{\beta_{2w}}\right)^2 - 1}\right] \text{ but } S_{x,eff} \le Z_x + (S_x - Z_x)\left[\frac{\frac{\beta_{3f}}{b/T} - 1}{\frac{\beta_{3f}}{\beta_{2f}} - 1}\right]$$

The suffices of the β values refer to the limiting values of the classifications of the web and flange. For example, β_{3w} refers to the limiting value of d/t for a class three web. The elastic and plastic moduli are denoted Z and S and the suffix x refers to the major axis in BS 5950 notation.

Substituting values:

$$S_{x,eff} = Z_x + (S_x - Z_x)\left[\frac{0.388}{0.651}\right] \text{ but } S_{x,eff} \le Z_x + (S_x - Z_x)\left[\frac{0.277}{0.439}\right]$$

The quotients in square brackets are 0.599 and 0.622 respectively so the effective modulus depends on the web classification. In this case, the effective modulus takes a value about 60% of the way between the elastic and plastic moduli – i.e. 1801 cm³. This is about 1% greater than the elasto-plastic modulus calculated using the prEN. The bending resistance of the section is 639 kNm.

Using cl. 4.8.3.2 to carry out a cross-section check, the utilization is given by:

$$\frac{F_c}{A_g P_y} + \frac{M_x}{M_{cx}} + \frac{M_y}{M_{cy}} \le 1$$

In the example, M_y (the minor axis moment) is zero. The utilization is therefore:

$$\frac{100}{3117} + \frac{615}{639} = 0.994$$

4 Conclusion

The procedure set out in Annex B of prEN 1993-1-1:2020 for determining an elasto-plastic modulus for class 3 sections has a similar result to that adopted in BS 5950. The approaches are different in that the approach to classification in EC3 uses factors that are related to the effect of axial force on the position of the plastic or elastic neutral axis, whereas the BS 5950 approach uses the ratios of applied axial load to the resistance of the web and gross section.

In the prEN, a reduced value of bending resistance in the presence of axial load is calculated, whereas in BS 5950 a cross-section check involves the determination of a utilization factor.

It is interesting that the BS 5950 approach uses the elastic modulus of a class 3 section as a starting point and determines what proportion of the difference between plastic and elastic moduli can be added to suit the classification. The prEN approach uses the plastic modulus as a starting point and determines what proportion of the difference must be deducted.

For the example given, the outcomes are very similar: the prEN approach indicates the section is 0.4% over-utilised, whereas the BS 5950 approach shows the section is 0.6% under-utilized.

The EU funded an RFCS project over 36 months from July 2004: *Plastic member capacity of semi-compact steel sections – a more economic design* to develop and justify the proposed procedure in Annex B. The work involved 60 physical experiments and more than 2600 FE simulations. The total budget was €674k, with an EU contribution of €404k. We can be reassured that structures designed using the procedure in BS 5950 are sound. ■

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