Research Programme of the Research Fund for Coal and Steel

STROnger Steels in the Built Environment (STROBE)

Amendments to Eurocode 3 and National Annexes

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Work package 6: Exploitation of Results

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Contents

1 INTRODUCTION

The STROBE research project has studied the performance of HSS members, aiming to fill gaps where knowledge was missing, and develop more competitive design rules where the existing rules were unnecessarily conservative. This document summarises the contributions and potential amendments to design rules in Eurocode 3 arising from STROBE as a result of the work carried out in WP1, 2 and 3.

2 AMENDMENTS TO EUROCODE 3

2.1 Ductility and toughness

Existing text in EN 1993-1-1:2005

3.2.2 Ductility requirements

(1) For steels a minimum ductility is required that should be expressed in terms of limits for:

– the ratio f_u / f_y of the specified minimum ultimate tensile strength f_u to the specified minimum yiel strength f_y;

– the elongation at failure on a gauge length of $5{,}65\sqrt{A_o}$ (where A_0 is the original cross-sectional area);

– the ultimate strain ε_u, where ε_u corresponds to the ultimate strength f_u .

NOTE The limiting values of the ratio f_u / f_y , the elongation at failure and the ultimate strain ε_u ma be defined in the National Annex. The following values are recommended:

– $f_u / f_y \geq 1{,}10$;

– elongation at failure not less than 15%;

– $\varepsilon_u \geq 15\varepsilon_y$, where ε_y is the yield strain ($\varepsilon_y = f_y / E$).

Existing text in EN 1993-1-12:2006

NOTE The limiting values of the ratio f_u/f_y, the elongation at failure and the ultimate strain ε_u for steel greater than S460 up to S700 may be defined in the National Annex. The following values are recommended

- $f_u/f_y \geq 1{,}05$;

- elongation at failure not less than 10 %;

- $\varepsilon_u \geq 15 f_y/E$.

STROBE Amendment in prEN 1993-1-1

5.2.2 Ductility requirements

(1) A minimum ductility shall be provided and shall be expressed in terms of limiting values for

- The ratio f_u/f_y
- The elongation at failure on a gauge length of $5{,}65\sqrt{A_0}$ (where A_0 is the original cross-sectional area)

NOTE The limiting values are given below unless the National Annex gives different limiting values:

a) For plastic global analysis

— $f_u/f_y \geq 1{,}10$;

— elongation at failure not less than 15 %.

b) For elastic global analysis

— $f_u/f_y \geq 1{,}05$;

— elongation at failure not less than 12 %.

Note that the requirement: $\varepsilon_u \geq 15\ \varepsilon_y$ is removed

2.2 Plastic design

Existing text in EN 1993-1-1:2005

5.4 Methods of analysis considering material non-linearities

5.4.1 General

(1) The internal forces and moments may be determined using either

a) elastic global analysis

b) plastic global analysis.

NOTE For finite element model (FEM) analysis see EN 1993-1-5.

(2) Elastic global analysis may be used in all cases.

(3) Plastic global analysis may be used only where the structure has sufficient rotation capacity at th actual locations of the plastic hinges, whether this is in the members or in the joints. Where a plastic hing occurs in a member, the member cross sections should be double symmetric or single symmetric with a plan of symmetry in the same plane as the rotation of the plastic hinge and it should satisfy the requirement specified in 5.6. Where a plastic hinge occurs in a joint the joint should either have sufficient strength t ensure the hinge remains in the member or should be able to sustain the plastic resistance for a sufficien rotation, see EN 1993-1-8.

(4)B As a simplified method for a limited plastic redistribution of moments in continuous beams wher following an elastic analysis some peak moments exceed the plastic bending resistance of 15 % maximum the parts in excess of these peak moments may be redistributed in any member, provided, that:

a) the internal forces and moments in the frame remain in equilibrium with the applied loads, and

b) all the members in which the moments are reduced have Class 1 or Class 2 cross-sections (see 5.5), and

c) lateral torsional buckling of the members is prevented.

5.4.3 Plastic global analysis

(1) Plastic global analysis allows for the effects of material non-linearity in calculating the action effect of a structural system. The behaviour should be modelled by one of the following methods:

– by elastic-plastic analysis with plastified sections and/or joints as plastic hinges,

– by non-linear plastic analysis considering the partial plastification of members in plastic zones,

– by rigid plastic analysis neglecting the elastic behaviour between hinges.

Table 5.2 Maximum width-to-thickness ratios for compression parts

Class 1 limits (to permit plastic design) are:

Outstand Flange in compression: $\frac{c}{t} \leq 9\varepsilon$

Web in bending: $\frac{c}{t} \leq 72\varepsilon$

Existing text in EN 1993-1-12:2006

EN 1993-1-1 Clause 5.4.1 (3) and (4) are not applicable to steels with grades greater than S460 up to S700.

EN 1993-1-1 Clause 5.4.3(1): For steels of grades greater than S460 up to S700, the global analysis using non-linear plastic analysis considering partial plastification of members in plastic zones only, applies.

STROBE Amendment (submitted to prEN 1993-1-1):

The plastic design methods for steels up to S460 are suitable for members and frames made of steel grades up to and including S690 steel, provided the following stricter Class 1 slenderness limits are adopted:

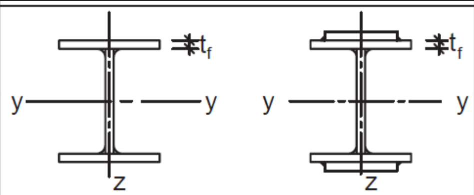
Outstand Flange in compression: $\frac{c}{t} \leq 8\varepsilon$

Web in bending: $\frac{c}{t} \leq 60\varepsilon$

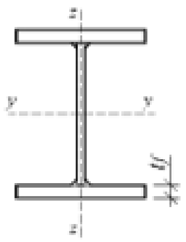
2.3 Flexural buckling curves

Existing text in EN 1993-1-1:2005, EN 1993-1-12 and prEN 1993-1-1

Table 5.3/8.3 Selection of buckling curve for flexural buckling

Cross section		Limits	Buckling about axis	Buckling curve S 235 S 275 S 355 S 420	Buckling curve S460 to S700
Welded I-sections		$t_f \leq 40$ mm	y – y z – z	b c	b c
		$t_f > 40$ mm	y – y z – z	c d	c d

STROBE Amendment (submitted to prEN 1993-1-1)

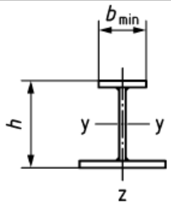
	Fabrication	Limits	Axis	S235 to S420	S460 to S700
Welded profiles		$t_f \leq 40$ mm	y-y z-z	b c	a b
		$t_f > 40$ mm	y-y z-z	c d	b c

2.4 Lateral torsional buckling curves

Existing text in EN 1993-1-1:2005, EN 193-1-12 and prEN 1993-1-1 (all steel strengths)

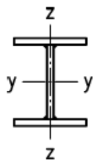
In general cases of prismatic members with arbitrary boundary conditions, , α_{LT} is given by Table 8.4.

Table 8.4 — Selection of buckling curves for general cases

Cross-section		Limits	Buckling curve
Welded I-sections[a]		$h/b_{\min} \leq 2{,}0$	c
		$h/b_{\min} > 2{,}0$	d

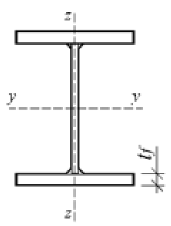
For doubly symmetric I- and H- sections and fork boundary conditions at both ends, α_{LT} is given by Table 8.5**.**

Table 8.5 — Imperfection factor α_{LT} for lateral torsional buckling of doubly symmetric I- and H-sections

Welded I-sections		$t_{\mathrm{f}} \leq 40$ mm	$0{,}21\sqrt{\frac{W_{\mathrm{el,y}}}{W_{\mathrm{el,z}}}}$ but: $\alpha_{LT} \leq 0{,}64$
		$t_{\mathrm{f}} > 40$ mm	$0{,}25\sqrt{\frac{W_{\mathrm{el,y}}}{W_{\mathrm{el,z}}}}$ but: $\alpha_{LT} \leq 0{,}76$

STROBE Amendment (submitted to prEN 1993-1-1)

Cross-section	Limits	S235 S275 S355 S420	S460 to S700
Welded I-section	h/b≤2 h/b>2	c d	b c

Cross-section		Limits	α_{LT}	
			S235 to S420	S460 to S700
Welded profiles		$t_f \leq 40$ mm	$0.21\sqrt{\frac{W_{el,y}}{W_{el,z}}} \leq 0.64$	$0.16\sqrt{\frac{W_{el,y}}{W_{el,z}}} \leq 0.49$
		$t_f > 40$ mm	$0.25\sqrt{\frac{W_{el,y}}{W_{el,z}}} \leq 0.76$	$0.21\sqrt{\frac{W_{el,y}}{W_{el,z}}} \leq 0.64$

2.5 Residual stresses in welded sections

Existing text in prEN 1993-1-14 (all steel strengths)

(3) For welded structures, the peak value of the tensile residual stress may be taken as equal to the yield strength of the material for steel grades between S235 and S700. The peak value of the compressive residual stress depends on the manufacturing process and the geometry of the cross-section.

(4) Residual stress patterns for hot-rolled and welded carbon steel I-sections and for welded box sections may be taken from Figures 4.4-4.6.

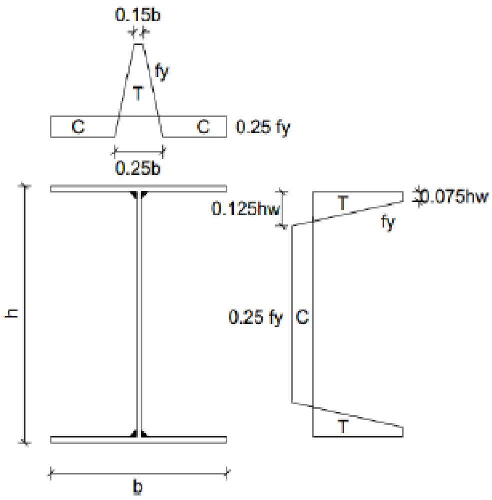


Figure 4.5: Residual stresses for welded I-sections.

STROBE Amendment (submitted to prEN 1993-1-14)

Replace f_y with 235 MPa. This was the original ECCS recommendation[1], and work on STROBE has shown this figure remains valid even for S690 steel sections. Somehow over time f_y in the ECCS recommendation started to replace 235 MPa.

3 OTHER CONTRIBUTIONS RELATING TO EUROCODE 3

3.1 Test results

The work carried out on STROBE has resulted in a useful set of test results on HSS materials, cross-sections, members and frames. Historically, test results on HSS members, particularly welded I section members, has been sparse. This data will therefore be useful in the future to validate FE models and assess the reliability of design rules in accordance with EN 1990 [1[2]].

The applicability of the Class 2 and 3 slenderness limits in accordance with Section 5.5 of EN 1993-1-1: *Classification limits for HSS Class 2 and 3* were confirmed for S690 welded I sections in bending.

3.2 Limits on maximum strains for finite elements

EN 1993-1-5, Annex C.8 contains a requirement that when modelling structures using FE, the limiting principal strain should be taken as 5%. In the revision of Eurocode 3, the contents of this annex have now been moved to prEN 1993-1-14, which still recommends a value for the maximum acceptable plastic strain of 5%. STROBE has confirmed that this limit of 5% is acceptable.

In addition, STROBE has confirmed that design techniques based on geometrically and materially nonlinear analysis with imperfections (GMNIA) with strain limits can be applied to HSS. This will be included in prEN 1993-1-14, Annex C *Limits on maximum strains for beam finite elements analyses*, and a current draft is shown in Figure 3.1. In this Annex, the parameter Ω should be limited to 10 for HSS to recognise the lower ductility and increased likelihood of fracture.

Annex C [normative] – Limits on maximum strains for beam finite elements

C.1 Use of this Annex

(1) This Normative Annex contains additional provisions to 5.1.2 and 8.1.5(2) for defining cross-section failure in beam finite element models through the application of strain limits.

C.2 Scope and field of application

(1) This Normative Annex applies to beam finite element models and replaces the need for cross-section classification and cross-section resistance checks.

(2) This Normative Annex applies to doubly-symmetric I- and H-sections and square and rectangular hollow sections.

(3) This Normative Annex does not apply to shell finite element models.

C.3 Strain limits

(1) Strain limits, from the Continuous Strength Method (CSM), may be used to simulate cross-section failure due to local buckling in beam finite element analyses. The design value of the maximum longitudinal compressive strain ε_{Ed} at each cross-section shall satisfy

$$\frac{\varepsilon_{\mathrm{Ed}}}{\varepsilon_{\mathrm{csm}}} \leq 1{,}0 \qquad \text{(C.1)}$$

where:

$\varepsilon_{\mathrm{Ed}}$ is the design value of the maximum longitudinal compressive strain, see C(2),

$\varepsilon_{\mathrm{csm}}$ is the CSM strain limit given by Formula (C.2) when a material model with a sharply-defined yield point (e.g. for hot-rolled steel) is used (see 5.3.2(1)c) and Formula (C.3) when a rounded material model (e.g. the two-stage Ramberg-Osgood model for cold-formed steel and stainless steel) is used (see section 5.3.3).

$$\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_y} = \begin{cases} \dfrac{0{,}25}{\bar{\lambda}_{\mathrm{p,cs}}^{\;3{,}6}} \leq \Omega & \text{for } \bar{\lambda}_{\mathrm{p,cs}} \leq 0{,}68 \\ \left(1 - \dfrac{0{,}222}{\bar{\lambda}_{\mathrm{p,cs}}^{\;1{,}050}}\right)\dfrac{1}{\bar{\lambda}_{\mathrm{p,cs}}^{\;1{,}050}} & \text{for } 0{,}68 < \bar{\lambda}_{\mathrm{p,cs}} \leq 1{,}00 \end{cases} \qquad \text{(C.2)}$$

$$\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_y} = \begin{cases} \dfrac{0{,}25}{\bar{\lambda}_{\mathrm{p,cs}}^{\;3{,}6}} + \dfrac{0.002}{\varepsilon_y} \leq \Omega & \text{for } \bar{\lambda}_{\mathrm{p,cs}} \leq 0{,}68 \\ \left(1 - \dfrac{0{,}222}{\bar{\lambda}_{\mathrm{p,cs}}^{\;1{,}050}}\right)\dfrac{1}{\bar{\lambda}_{\mathrm{p,cs}}^{\;1{,}050}} + \dfrac{0.002(\sigma/f_y)^n}{\varepsilon_y} & \text{for } 0{,}68 < \bar{\lambda}_{\mathrm{p,cs}} < 1{,}00 \end{cases} \qquad \text{(C.3)}$$

where:

$\varepsilon_y = f_y/E$ is the yield strain,

$\bar{\lambda}_{\mathrm{p,cs}} = \sqrt{f_y/\sigma_{\mathrm{cr,cs}}}$ is local slenderness of the full cross-section,

$\sigma_{\mathrm{cr,cs}}$ is elastic local buckling stress of the full cross-section,

Ω is a project specific parameter that defines the maximum permissible level of plastic strain in the structure.

NOTE: A value of Ω = 15 is recommended.

prEN 1993-1-14: 2020 (E)

(2) The design value of the maximum compressive strain at each cross-section ε_{Ed} may be taken as the maximum value averaged over a length of member equal to the elastic local buckling half-wavelength $L_{b,cs}$. A maximum element length equal to the elastic local buckling half-wavelength $L_{b,cs}$ should be used. Strains should be averaged over the number of elements that lie wholly within $L_{b,cs}$.

(3) In beam elements, the interaction between bending and shear should be accounted for through a reduction factor ρ_{csm} applied to the strain limit ε_{csm}, given by:

$$\frac{\varepsilon_{Ed}}{\rho_{csm}\varepsilon_{csm}} \leq 1 \qquad \text{for} \qquad V_{Ed} > 0.5V_{pl,Rd} \tag{C.4}$$

where:

$$\rho_{csm} = \begin{cases} 1 & \text{for} \quad V_{Ed} \leq 0.5V_{pl,Rd} \\ \frac{0.5}{0.5+\rho} & \text{for} \quad V_{Ed} > 0.5V_{pl,Rd} \end{cases} \tag{C.5}$$

$$\rho = \left(\frac{2V_{Ed}}{V_{pl,Rd}} - 1\right)^2 \tag{C.6}$$

V_{Ed} is the design shear force,

$V_{pl,Rd}$ is the plastic shear resistance of the cross-section.

Figure 3.1 Extract from prEN 1993-1-14, Annex C

4 REFERENCES

1 ECCS. Ultimate limit state calculation of sway frames with rigid joints. 1st ed. P033. ECCS technical committee 8 – structural stability. Brussels: European Convention of Constructional Steel Work, 1984.

2 EN 1990 Eurocode: Basis of Structural design. European Committee for Standardization (CEN), 2002.