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SELECTION OF STRUCTURAL STEEL TOUGHNESS ACCORDING TO SR EN 1993-1-10: 2005

BY

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Abstract. Some aspects concerning the selection of the structural steel toughness according to SR EN 1993-1-10: 2005 are presented. Some comments and a worked example are also presented.

Key words: structural steel; brittle fracture; toughness; steel grade.

1. Introduction

The proper selection of the structural steel grade has to take into account the following aspects:

a) the structural steel grade, by choosing the nominal value of the yield strength, f_y;

b) the steel sub-grade by, choosing the fracture toughness in order to avoid the brittle fracture of tension elements at the lowest service temperature expected to occur within the intended design life of the structure;

c) the choice of a quality class in which steel with improved through-thickness properties is necessary.

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The structural steel is symbolized by letters *S*; *P*; *L*,… followed by a series of other symbols as presented in Fig. 1.

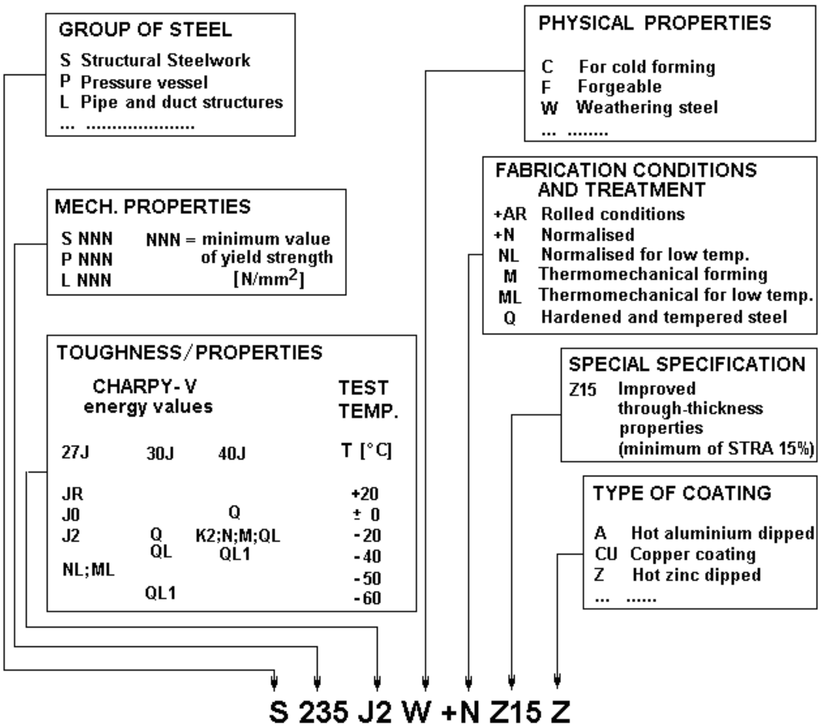

Fig. 1 – Structural steel.

Table 2.1 of EN 1993-1-10: 2003, or of the Romanian norm SR EN1993-1-10: 2005 specifies the maximum permissible values of element thickness to avoid brittle fracture in terms of three stress levels, expressed as proportions of the nominal yield strength:

$$\sigma_{Ed} = 0.75 f_y\,(t)\text{, [N/mm}^2\text{];} \tag{1a}$$

$$\sigma_{Ed} = 0.50 f_y\,(t)\text{, [N/mm}^2\text{];} \tag{1b}$$

$$\sigma_{Ed} = 0.25 f_y\,(t)\text{, [N/mm}^2\text{];} \tag{1c}$$

where:

$$\sigma_{Ed} = \sigma_p + \sigma_s = \sigma_{Ed}^* + \sigma_s = \chi f_y(t)\text{, [N/mm}^2\text{];} \tag{2}$$

is the relevant design stress; σ_p – the tension stress from external "frequent load" – permanent load, G_k, and variable frequent load, $\psi_1 Q_k$; σ_s – the global residual stress from remote restrains; in bridge design equal to the value of 100 N/mm^2 for all steel grades;

$$f_y(t) = f_{y,\text{nom}} - 0.25\frac{t}{t_0}\ [\text{N/mm}^2]; \quad (3)$$

t – plate thickness, [mm]; t_0 = 1 mm.

2. Selection of Structural Steel Sub-Grade

2.1. Algorithm for the Selection of the Steel Sub-Grade

The selection of the allowable plate thickness from Table 2.1 of EN 1993-1-10 can be carried out in accordance with the flow given in Joint Report (2008), Fig. 2.

If the conditions $\varepsilon' \leq 4 \times 10^{-4}$ and $\varepsilon_{cf} \leq 2\%$ are not fulfilled, the correction terms ΔT_ε and $\Delta T_{\varepsilon_{cf}}$ are taken into account to evaluate T_{Ed}.

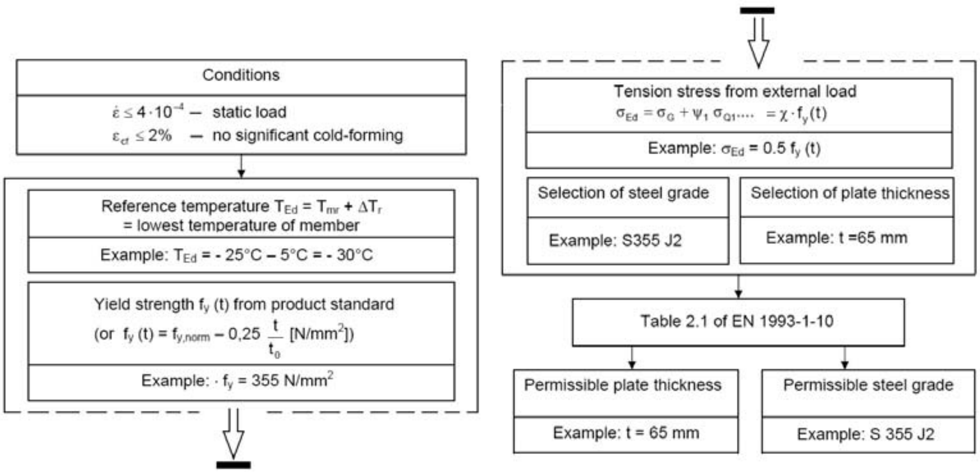

Fig. 2 – Algorithm for steel-subgrade selection.

2.2. Relevant Design Stress

The maximum active stress, σ_{Ed}, is the nominal stress at the potential fracture location. This value corresponds to the maximum possible "frequent stress", where, for the ultimate limit state verification, yielding of the extreme fiber of the elastic cross-section has been assumed.

In most cases the nominal stress, σ_{Ed}, is between the limits σ_{Ed} = = $0.75f_y(t)$ and $\sigma_{Ed} = 0.50f_y(t)$.

The load-combination to determine the stress level is given by:

$$E_d = E\left\{A[T_{Ed}]"+"\sum G_K"+"\psi_1 Q_{K_1}"+"\psi_{2,i} Q_{K_i}\right\}, \tag{4}$$

where: A is the leading action at the reference temperature T_{Ed} that influences the toughness of material of the member considered and which might also lead to stress from restraint of movements; $\sum G_K$ – the permanent actions; $\psi_1 Q_K$ – the frequent value of the variable load and $\psi_{2,i} Q_{K_i}$ – the quasi-permanent values of the accompanying variable loads (the combinations factors ψ_1 and ψ_2 will be considered in accordance with EN 1990).

Two procedures can be used to determine the stress level:

a) A procedure based on the global estimation of stress level.

b) A procedure based on the effective tension stress.

a) *Procedure based on the global estimation of stress level*

The following steps are carried out in this case:

a) the actions, combination and safety factors are established:

$$\gamma_G; \quad \gamma_Q; \quad \psi_1; \quad \gamma_M = [\gamma_{M0}; \gamma_{M1}; \gamma_{M2}]; \tag{5}$$

b) the ratio between the stresses given by characteristic permanent loads and live loads is estimated:

$$\frac{\sigma(G_k)}{\sigma(Q_k)} = \alpha \quad \Rightarrow \quad \sigma(G_k) = \alpha\sigma(Q_k); \tag{6}$$

c) the equations system is solved:

$$\begin{cases} \sigma(G_k) = \sigma(Q_k), \\ \sigma_{ult} = \sigma_{Ed.\mathrm{ULS}} = \gamma_G \sigma(G_k) + \gamma_Q \sigma(Q_k) = \dfrac{f_y(t)}{\gamma_M}, \\ \sigma_{Ed} = \sigma(G_k) + \psi_1 \sigma(Q_k) = \chi f_y(t). \end{cases} \tag{7}$$

It follows:

$$\chi = \frac{\alpha + \psi_1}{\gamma_M (\alpha\gamma_G + \gamma_Q)}. \tag{8}$$

The stress level will be obtained using relation (2).

It is considered that the residual stress, σ_s = 100 N/mm^2, is included in the calculation.

b) *Procedure based on the effective tension stress*

In this procedure the tension stress in the most susceptible location of brittle fracture is evaluated.

The fundamental load combination or the frequent actions combination, without taking into account the action factors, can be used namely

$$\sigma_{Ed}^{*} = \sigma\left[(G_k) + \psi_1(Q_k)\right] = \chi f_y(t)\,, \tag{9a}$$

$$\sigma_{Ed}^{*} = \sigma(G_k) + \psi_1\sigma(Q_{k1}) + \sigma\left[\sum_{i>1}(\psi_{2.i}Q_{ki})\right]. \tag{9b}$$

2.3. The Reference Temperature T_{Ed}

The reference temperature, T_{Ed}, at the potential fracture location should be determined using the following expression

$$T_{Ed} = T_{md} + \Delta T_r + \Delta T_\sigma + \Delta T_R + \Delta T_\varepsilon + \Delta T_{\varepsilon_{cf}}\,, \tag{10}$$

where: T_{md} is the lowest air temperature with a specified return period (see EN 1991-1-5); ΔT_r – an adjustment for radiation loss (see EN 1991-1-5; e.g. - 5 K); ΔT_σ – the adjustment for stress and yield strength of the material, crack imperfection and member shape and dimensions; it can be taken that $\Delta T_\sigma = 0^\circ\text{C}$; ΔT_R – a safety allowance, if required, to reflect different reliability levels for different applications; it is recommended that $\Delta T_R = 0^\circ\text{C}$ (see EN 1990 Annex D); ΔT_ε – the adjustment for a strain rate other than the reference strain rate $\varepsilon'_o \le 4\times10^{-4}\text{s}^{-1}$. For $\varepsilon'_o \le 4\times10^{-4}\text{s}^{-1}$, we obtain $\Delta T_\varepsilon = 0^\circ\text{C}$.

For strain rate $\varepsilon'_o > 4\times10^{-4}\text{s}^{-1}$, ΔT_ε will be determined as follows:

$$\Delta T_\varepsilon = -\frac{1{,}440 - f_y(t)}{550}\left[\ln(\varepsilon'/\varepsilon'_o)\right]^{1.5},\ [^\circ\text{C}] \tag{11}$$

where: $\varepsilon'_o = 4\times10^{-4}\text{s}^{-1}$, $4\times10^{-4} < \varepsilon' < 5\times10^{3}\text{s}^{-1}$; $\Delta T_{\varepsilon_{cf}}$ – the adjustment for the degree of cold forming.

The effect of cold forming is taken into account by the term $\Delta T_{\varepsilon_{cf}}$, which is added to the term T_{Ed}, where:

$$\Delta T_{\varepsilon_{cf}} = -3\varepsilon_{cf} = -3\text{DCF},\ [^\circ\text{C}]. \tag{12}$$

The correction factor, DCF, is the degree of cold forming, in [%], and applies only for DCF ≥ 2%; it is constant for DCF ≥ 15%.

The degree of cold forming can be determined with relation

$$\text{DCF} = \varepsilon_{\max} - \varepsilon_d = \left(\frac{t}{2\,r}100 - 2\right),\ [\%], \tag{13}$$

where r is the deformation radius and t – the plate thickness.

3. Worked Example

In what follows next the choice of the material for the steel main girders in the case of an industrial platform is considered.

The following design data are known:

a) steel grade: S 335;

b) bending moments: $M_{Ed}^{(G)} = 200\ \text{kN}\cdot\text{m}$; $M_{Ed}^{(Q)} = 1{,}100\ \text{kN}\cdot\text{m}$; $\psi_1 = 0.9$ (Category E);

c) minimum air temperature: –35ºC;

d) elevation and cross-section girder, Fig. 3.

3.1. Solution

a) *Relevant stress*

The yield strength taking into account the flange plate thickness is

$$f_y(t) = f_{y.\text{nom}} - 0.25\frac{t}{t_0} = 235 - 0.25\frac{15}{1} = 231\ \text{N/mm}^2.$$

The relevant bending moment is

$$M_{Ed}^{*} = M_{Ed}^{(G)} + \psi_1 M_{Ed}^{(Q)} = 200 + 0.9\times 1{,}100 = 1{,}190\ \text{kN}\cdot\text{m}.$$

The relevant tension stress in the bottom flange evaluated for the elastic cross-section, is

$$\sigma_p = \sigma_{Ed}^{*} = \frac{M_{Ed}^{*}}{W_{y.el}} = \frac{1{,}190\times 10^4}{8{,}174} = 1{,}456\ \text{daN/cm}^2 \approx 146\ \text{N/mm}^2.$$

The relevant stress level will be:

$$\sigma_{Ed} = \sigma_p = \frac{146}{231} f_y(t) = 0.63 f_y(t).$$

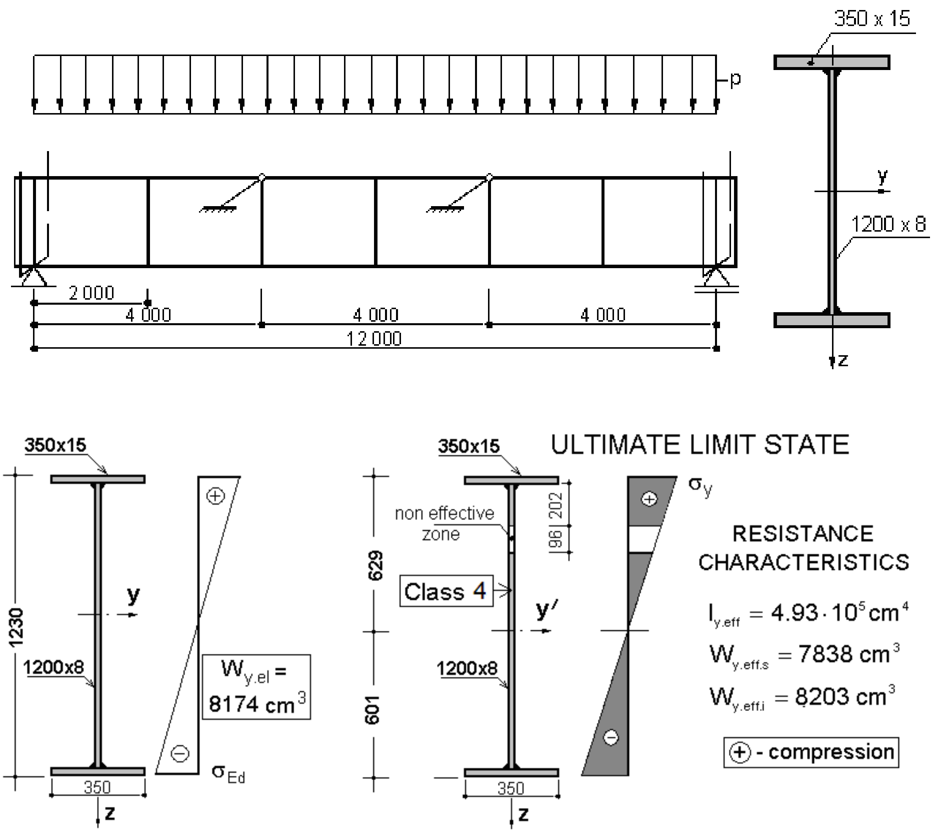

Fig. 3 – Elevation and cross-section.

b) *Reference temperature*

The reference temperature is evaluated in Table 1.

Table 1
Reference Temperature

No.	Effect	Symbol	Value
1	Lowest air temperature	T_{md}	–35ºC
2	Maximal radiation loss	ΔT_r	–5ºC
3	Adjustment for stress and yield strength	ΔT_σ	0ºK
4	Safety allowance	ΔT_R	0ºK
5	Adjustment term from strain rate	ΔT_ε	0ºC
6	Adjustment term from cold forming	$\Delta T_{\varepsilon_{cf}}$	0ºK
	T_{Ed}		–40ºC

c) *Choosing the steel subgrade*

By using Table 2.1 of SR EN 1993-1-10:2005, we obtain the steel sub-grade of the steel S 235, according to Fig. 4 (part of Table 2.1).

For a reference temperature equal to a value $T_{Ed} \approx -40$ºC, a relevant stress $\sigma_{Ed} = 0.60 f_y(t) < 0.75 f_y(t)$, steel S 235 can be used, with a maximum permissible thickness t = 25 mm > t_{eff} =15 mm, sub-grade: JR.

Steel grade	Sub-grade	Charpy energy K_V		Reference temperature T_{Ed} [°C]																				
		T [°C]	J_{min}	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50
				$\sigma_{Ed} = 0{,}75\ f_y(t)$							$\sigma_{Ed} = 0{,}50\ f_y(t)$							$\sigma_{Ed} = 0{,}25\ f_y(t)$						
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	85	75	65	60
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	115	100	85	75
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	155	135	115	100

Fig. 4 – Part of table 2.1, SR EN 1993-1-10:2005.

4. Conclusions

The proper choice of the steel grade and sub-grade is a key factor to ensuring the necessary safety of a steel construction to avoid brittle fracture at low temperature.

The selection method of the steel characteristics presented in the European norm EN 1993-1-10 is based on a complex theory of the fracture-behavior of the steel and it offers a design procedure to determine the quality of the material.

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STABILIREA TENACITĂŢII OŢELULUI PENTRU CONSTRUCŢII METALICE ÎN CONFORMITATE CU SR EN 1993-1-10: 2005

(Rezumat)

Se prezintă unele aspecte privind stabilirea tenacităţii oţelului pentru evitarea producerii fenomenului de fragilizare în elementele de construcţii metalice, în conformitate cu normativul SR EN 1993-1-10: 2005.

Lucrarea include un exemplu de aplicare a metodologiei de stabilire a clasei de calitate a oţelului structural, pentru grinzile principale ale unei platforme industriale.