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Optimum design of compression struts of circular and square hollow section made of stainless steel

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ABSTRACT: Optimum design of compression struts of constant cross-section means to determine the profile sizes, which fulfil the constraints on overall and local buckling simultaneously. Formulae are given for this minimum-cross-section-area-design of circular and square hollow section rods made of stainless steel. The design procedure is based on data given by the Eurocode 3 and research results of Rasmussen and Rondal. The optimum sizes can be calculated for given compression force, effective bar length and type of material.

1 INTRODUCTION

The optimum design of tubular trusses needs an efficient suboptimization method for the design of compression members. The optimization method for compression tubular members made of normal steels, described in Farkas & Jármai (1997) can also be used for stainless steel hollow section struts. In their recent research Rasmussen & Rondal (1997, 2000) proposed column curves for stainless steel compression members. In Eurocode 3 (1995) a special part gives design rules for stainless steels. The Steel Construction Institute published design rules as well (Burgan 1992, Baddoo 2002). The corresponding German standards for circular tubes are DIN 17456 and 17457 (1985), as well as the available dimensions are given in DIN 2462 (1981).

The main European manufacturers of stainless steel tubes are as follows: Arcelor Industeel (Belgium – France), ESAB (Sweden), Salzgitter Flachstahl (Germany), Stainless Steel World (The Netherlands).

It is shown in (Farkas & Jármai 1997) that the local buckling slenderness of circular hollow section (CHS) and square hollow section (SHS) $\delta_C = D/t_C$ or $\delta_S = b/t_S$ (Fig.1) determines the economy of a cross-section. Thus, to achieve an economic (minimum cross-sectional area) cross-section, the local buckling factor should be as large as possible.

It is also shown in (Farkas & Jármai 1997) that the minimum cross-sectional-area-solution corresponds to that strut, for which the overall and local buckling constraints are simultaneously active. It should be mentioned that this coupled instability does not decrease the load carrying capacity, since in both constraints the effect of initial imperfections is considered.

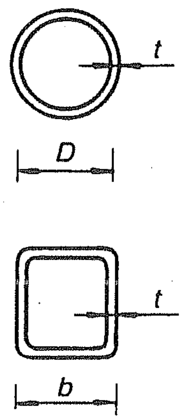

Figure 1. Dimensions of CHS and SHS

2 PROBLEM FORMULATION

A stainless steel type is characterized by the following material and column curve data: $E_0, \sigma_{0.2}, \beta, \lambda_1, \lambda_0, \alpha$ (see Eqs. 1 – 10). In the following we use the subscript C for CHS and S for SHS.

The overall flexural buckling constraint is given by

$$\frac{F}{A} \le \chi \frac{\sigma_{0.2}}{\gamma_{M1}}; \quad (1)$$

$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 - \lambda^2}}; \quad (2)$$

$$\varphi = \frac{1}{2}\left(1 + \eta + \lambda^2\right) \quad (3)$$

$$\lambda = \frac{KL}{r\lambda_E} = \sqrt{\frac{\sigma_{0.2}}{\sigma_{E0}}}; \quad (4)$$

$$\sigma_{E0} = \frac{\pi^2 E_0}{(KL/r)^2}; \quad (5)$$

$$\lambda_E = \pi\sqrt{\frac{E_0}{\sigma_{0.2}}}; \quad (6)$$

$$r = \sqrt{\frac{I_x}{A}} = a\sqrt{A} \quad (7)$$

$$a_C = \sqrt{\delta_C/(8\pi)}; a_S = \sqrt{\delta_S/24} \quad (8)$$

$$A_C = \pi D t_C = \pi D^2/\delta_C; A_S = 4bt_S = 4b^2/\delta_S \quad (9)$$

$$\eta = \alpha[(\lambda - \lambda_1)^\beta - \lambda_0] \quad (10)$$

The local buckling constraints are as follows:

$$D/t_C \le \delta_C \text{ and } b/t_S \le \delta_S \quad (11)$$

The optimum design problem is to compute the profile dimensions for given effective strut length KL, compression force F, steel type and local buckling factor δ.

Using the symbols

$$c_0 = \frac{100K}{\lambda_E}; x = \frac{10^4 F}{L^2}; y = \frac{10^4 A}{L^2}, \quad (12)$$

F in [N], A in [mm^2] and L in [mm].

the overall buckling constraint can be written as

$$\frac{x}{\sigma_{0.2}} \le \frac{y}{\varphi + \sqrt{\varphi^2 - \left(c_0^2/a^2 y\right)}} \quad (13)$$

$$\varphi = \frac{1}{2}\left\{1 + \alpha\left[\left(\frac{c_0}{a\sqrt{y}} - \lambda_1\right)^\beta - \lambda_0\right] + \frac{c_0^2}{a^2 y}\right\} \quad (14)$$

A computer algorithm is used to solve this constraint, i.e. to give y for given x.

The results can be presented in tables or diagrams. Knowing y_C or y_S, the required profile dimensions can be calculated as

$$\frac{100D}{L} = \sqrt{\frac{y_C \delta_C}{\pi}} \text{ or } \frac{100b}{L} = \sqrt{\frac{y_S \delta_S}{4}} \quad (15)$$

and

$$\frac{100t_C}{L} = \frac{100D}{L\delta_C} \text{ or } \frac{100t_S}{L} = \frac{100b}{L\delta_S} \quad (16)$$

Designers can select the available profiles according to these values.

3 LIMITING SLENDERNESSES FOR LOCAL BUCKLING CONSTRAINTS

According to Baddoo (2002) for CHS class 3 $\delta_C = 74\varepsilon_{ST}^2$ and for SHS class 3 $\delta_S = 28\varepsilon$ where

$$\varepsilon_{ST} = \sqrt{\frac{275}{\sigma_{0.2}} \cdot \frac{E}{2.05x10^5}}, \quad (17)$$

the elastic modulus and the yield stress in MPa.

4 CHARACTERISTIC DATA FOR DIFFERENT TYPES OF STAINLESS STEELS

According to Rasmussen & Rondal (2000) the characteristics for S220 and S240 (austenitic alloys) as well as for S480 (duplex alloys) are given in Table 1.

Table 1. Characteristic data for stainless steels

Characteristics	Strength class		
	S220	S240	S480
E_0 (GPa)	200	200	200
$\sigma_{0.2}$ (MPa)	220	240	480
α	1.24	1.14	1.31
β	0.18	0.16	0.18
λ_0	0.55	0.56	0.67
λ_1	0.30	0.30	0.37

According to another article of Rasmussen & Rondal (1997) the characteristics are given for annealed and ½ hardened alloys in Table 2.

Table 2. Characteristics for annealed and ½ hardened ASCE (Specification 1990) 201, 301, 316 alloys

Characteristics	annealed	½ hardened
$E_0 x10^{-5}$ (MPa)	1.931	1.862
$\sigma_{0.2}$ (MPa)	193.1	448.2
α	1.56	1.27
β	0.27	0.16
λ_0	0.55	0.67
λ_1	0.21	0.39

In Table 3 the European and corresponding American stainless steel grades are given.

Table 3. European and American stainless steel grades

European number	European name	American (AISI)
1.4301	X5CrNi 18-10	304
1.4307	X2CrNi 18-9	304L
1.4401	X5CrNiMo 17-12-2	316
1.4404	X2CrNiMo 17-12-2	316L
1.4541	X6CrNiTi 18-10	321
1.44571	X6CrNiMoTi 17-12-2	316Ti
1.4362	X2CrNiN 23-4	-
1.4462	X2CrNiMoN 22-5-3	-

Table 4. Optimization results (y_C) for two stainless steels with characteristics given in Table 2, in the case of CHS

X=$10^4F/L^2$		10	100	1000	2000
			y_C		
Annealed	K=1	0.150	0.740	4.095	12.80
	K=0.9	0.138	0.705	3.742	11.90
	K=0.75	0.121	0.650	3.058	11.00
	K=1	0.132	0.518	2.825	4.819
½ hardened	K=0.9	0.120	0.483	2.696	4.568
	K=0.75	0.103	0.432	2.479	4.117

5 OPTIMIZATION RESULTS FOR TWO STAINLESS STEELS

Tables 4 and 5 give the optimization results for two stainless steel types, the characteristics of which are shown in Table 2, stainless steel number 1.4404 (X2CrNiMo 17-12-2) annealed with a rounded yield stress of 200 and ½ hardened with yield stress of 450 MPa, for CHS and SHS, respectively. Three effective length factors (K) are considered.

Table 5. Optimization results (y_S) for two stainless steels with characteristics given in Table 2, in the case of SHS

x=$10^4F/L^2$		10	100	1000	2000
			y_S		
	K=1	0.240	1.001	5.708	9.546
Annealed	K=0.9	0.219	0.941	5.429	8.957
	K=0.75	0.187	0.851	4.937	7.785
	K=1	0.188	0.679	3.336	5.709
½ hardened	K=0.9	0.168	0.627	3.178	5.448
	K=0.75	0.142	0.549	2.929	5.013

6 NUMERICAL EXAMPLE

Data: F = 250 kN, L = 5 m, K = 0.75, material: annealed 1.4404 (AISI 316L) Table 2 and 3, E_0 = 1.931 x 10^5 MPa, $\sigma_{0.2} = 200$ MPa (rounded), $\alpha, \beta, \lambda_0, \lambda_1$ from Table 2, CHS.

Equation 12: x = 100, from Table 4 $y_C = 0.650$. $A = y_C L^2/10^4 = 1625$ mm^2, Equation 17: $\varepsilon_{ST}^2 = 1.2952, \delta_C = 74\varepsilon^2 = 95.84$, from Equation 15 we obtain D = 222.65 mm and from Equation 16 t_C = 2.32 mm. Using a table of Baddoo (2002) we select the CHS 273x2.6 with A = 2210 mm^2 and the radius of gyration r = 95.6 mm.

Check of the strut: Equation 6: $\lambda_E = 97.62$, Equation 4: $\lambda = 0.4018$, Equation 10: $\eta = 0.04514$, Equation 3: $\varphi = 0.6033$, Equation 2: $\chi = 0.9494$, Equation 1: 113.1<172.6 MPa, OK.

7 CONCLUSIONS

Design method is given for CHS and SHS compression members. The dimensions of a compression strut can be calculated for given compression force, effective strut length and steel type. The characteristics of column curves are given according to Rasmussen and Rondal (1997, 2000). The limiting slendernesses of local buckling are determined according to Baddoo (2002). The optimum design determines the minimum mass solution, since the constraints on overall and local buckling are fulfilled simultaneously. In the numerical example optimum solutions are given for two steel types and for three effective length factors.

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