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OPTIMUM DESIGN OF STEEL ELEMENTS FOR FIRE SAFETY

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INTRODUCTION

Safety in general and fire safety in particular, after several major disasters, has become a subject of increasing importance in recent years. A general definition for the fire resistance of construction elements can be the following: the time after which an element, when submitted to the action of a fire, ceases to fulfil the functions for which it has been designed.

In this paper simple column parts which are subject to compression have been investigated, so stress and stability constraints have been formulated for beam and column profiles according to Eurocode 3. We have calculated both welded and rolled I-section profiles. For the column parts we have used rolled universal column (UC) profile. In case of welded profile we have four unknowns, in case of rolled profiles the number of unknowns is smaller, only one, if we consider a family of I-sections like Universal Columns (UC).

The problem is to find suitable column profiles, which fulfil the design constraints, include fire safety ones and minimize the objective function. The objective function can contain not only the material, but the different fabrication costs, like cutting, welding, edge grinding, surface preparation and painting. We compared the elements with different length. We also optimise for fire protection, using different protective materials. The steel can be protected by materials such as mineral fibres, gypsum boards, concrete, intumescent paints and water-filled structures. Their efficiencies and costs are greatly different. Gypsum boards are relatively cheap, but not too aesthetic, intumescent paints are attractive but more expensive. In this case we concentrated to intumescent paints with different thickness and protection time.

1 OPTIMIZATION OF COMPRESSED COLUMNS FOR FIRE SAFETY

In the optimum design procedure the safety and fitness for production are guaranteed by fulfilling of design and fabrication constraints, and the economy is achieved by minimization of a cost function. The most suitable version can be selected by cost comparison of the different solutions. For the purpose of economic design of welded steel structures a relatively simple cost calculation method is developed [1,2,3].

At the optimization we considered mass and cost as objective function to be minimised. Cost contains material, welding (if any) and painting cost. Investigating intumescent paints we can get an interesting picture comparing the fire resistance of protected and unprotected steel profiles.

1.1 Overall buckling constraint for ambient temperature

The overall buckling of a column can be calculated by Eurocode 3 [4]

$$N \le N_0 . \tag{1}$$

The compression force limit is as follows

$$N_0 = \chi f_y A , \tag{2}$$

the buckling factor

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}, \phi = \frac{1}{2}\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right], \tag{3}$$

where

$$\bar{\lambda} = \frac{\lambda}{\lambda_E}, \lambda = \frac{L}{r}, r = \sqrt{\frac{I}{A}}, \lambda_E = \pi\sqrt{\frac{E}{f_y}} ; \qquad \alpha = 0.49. \tag{4}$$

1.2 Overall buckling constraint in fire

In case of fire the constraint looks similar [5]

$$N_{fi,d} \le N_{b,fi,Rd} \,. \tag{5}$$

The compression force limit can be calculated on high temperature as follows:

$$N_{b,fi,t,Rd} = \chi_{fi} \cdot A_a \cdot k_{y,\theta,\max} \cdot \frac{f_y}{\gamma_{M,fi}} \tag{6}$$

The dimensionless slenderness parameter is:

$$\bar{\lambda}_y = \frac{K_y L}{r_y \lambda_E}; \text{ the buckling parameter } K_y = 0.5, \tag{7}$$

$$r_y = \left(\frac{I_y}{A}\right)^{0.5}; \lambda_E = \pi\left(\frac{E}{f_y}\right)^{0.5}; \; E \text{ is the Young modulus,} \tag{8}$$

$$\bar{\lambda}_{fi} = \frac{\bar{\lambda}_y}{k_{y,\theta} / k_{E,\theta}} \,. \tag{9}$$

The buckling coefficient can be calculated with the dimensionless reduced slenderness $\chi_{fi,\theta}$

$$\chi_{fi} = \frac{1}{\phi_{fi} + \left(\phi_{fi}^{\,2} - \bar{\lambda}_{fi}^{\,2}\right)^{0.5}}; \;\; \phi_{fi} = 0.5\left[1 + 0.34\left(\bar{\lambda}_{fi} - 0.2\right) + \bar{\lambda}_{fi}^2\right]. \tag{10}$$

The designed resistance value is $N_{\mathrm{b,fi,Rd}}$

$$\frac{N_{fi,d}}{N_{b,fi,Rd}} \le 1 \,. \tag{11}$$

For ambient temperature we use limit slendernesses for the welded I-beam.

$$h/t_w \le 42\varepsilon; \;\; b/t_f \le 28\varepsilon; \;\; \varepsilon = \sqrt{\frac{235}{f_y}} \,. \tag{12}$$

For fire Eurocode 3 proposed a decreased value of

$$b/t \le 0.8x42\varepsilon = 33.6\varepsilon \,. \tag{13}$$

According to the experiments of Knobloch and calculations of Heidarpour & Bradford

$$b/t \le 0.6x42\varepsilon = 25.2\varepsilon \tag{15}$$

$$\alpha = 0.65\sqrt{\frac{235}{f_y}}, \bar{\lambda}_\Theta = \bar{\lambda}\sqrt{\frac{k_{y\Theta i}}{k_{E\Theta i}}} \,. \tag{16}$$

Factors of $k_{y\Theta i}$ and $k_{E\Theta i}$ can be approximated by linear intervals of

$$k_{y\Theta 0} = 1 \qquad \text{if } 20^0\mathrm{C} < \Theta_a < 400^0\mathrm{C}, \tag{17}$$

$$k_{y\Theta 1} = \frac{500 - \Theta_a}{100} 0.22 + 0.78 \;\; \text{if } 400^0\mathrm{C} < \Theta_a < 500^0\mathrm{C}, \tag{18}$$

$$k_{y\Theta 2} = \frac{600 - \Theta_a}{100} 0.31 + 0.47 \;\; \text{if } 500^0\mathrm{C} < \Theta_a < 600^0\mathrm{C}, \tag{19}$$

and

$$k_{E\Theta 0} = 1 \qquad \text{if } 20^0\mathrm{C} < \Theta_a < 100^0\mathrm{C}, \tag{20}$$

$$k_{E\Theta 1} = \frac{500 - \Theta_a}{400} 0.4 + 0.6 \quad \text{if } 100^0\mathrm{C} < \Theta_a < 500^0\mathrm{C}, \tag{21}$$

$$k_{E\Theta 2} = \frac{600 - \Theta_a}{100} 0.29 + 0.31 \quad \text{if } 500^0\mathrm{C} < \Theta_a < 600^0\mathrm{C}. \tag{22}$$

1.3 Calculation of temperature

For unprotected structure the calculation of temperature is as follows [5]:

The time at the beginning of the fire is $t_i = 0$, and every time period: $\Delta t_i = 10$ we calculate it $t_i = t_i + \Delta t_i$ [sec].

Chancing the time from $0 \le t_i \le t_{\max}$[sec], where t_{max} can be ½, 1, 1 ½, 2 , 4 hours, means 1800, 3600, 5400, 7200, 14400 [sec].

The temperature of the steel can be between 20 [˚C] ≤ Θ_a ≤ 1200 [˚C]

Starting values for temperature and density are as follows:

$$\Theta_a = 20\,[^\circ\mathrm{C}],\ \Delta\Theta_a = 0\,[^\circ\mathrm{C}],\ \rho_m = 7850\,,\ \rho = 7.85x10^{-6}\,. \tag{23}$$

The specific heat of steel can be calculated as a function of different temperature according to Eurocode [5].

The gas temperature in the vicinity of the fire exposed member (standard temperature-time curve) [7]

$$\Theta_g = 20 + 345\, log\left(8\frac{t_i}{60} + 1\right)\ [^\circ\mathrm{C}]. \tag{24}$$

The net *convection* heat flux

$$\dot{h}_{netc} = \alpha_c\left(\Theta_g - \Theta_a\right). \tag{25}$$

Where the coefficient of heat transfer by convection $\alpha_c = 25$ [W/m^{2}K].

The net *radiative* heat flux

$$\dot{h}_{netr} = \Phi\varepsilon_m\varepsilon_f\sigma\left[\left(\Theta_g + 273\right)^4 - \left(\Theta_a + 273\right)^4\right]\ [\mathrm{W/m^2}], \tag{26}$$

where the configuration factor $\Phi = 1$, the surface emissivity of the member $\varepsilon_{\mathrm{m}} = 0.8$, the emissivity of the fire $\varepsilon_{\mathrm{f}} = 1.0$, the Stephan Boltzmann constant $\sigma = 5.67x10^{-8}$ [W/m^{2}K^4].

The total net heat flux can be calculated as the sum of convection and radiative heat fluxes

$$\dot{h}_{netd} = \dot{h}_{netc} + \dot{h}_{netr}\,;\quad A_m V_m = \frac{1}{10^{-3} t_2}\,. \tag{27}$$

The temperature changing

$$\Delta\Theta_a = k_{sh}\frac{A_m V_m h_{netd}\Delta t_i}{c_a \rho_m}\,, \tag{28}$$

where k_{sh} = 1, the specific heat c_a is also depending on the temperature as given in Eurocode 3 [5].

The surface temperature of the steel member

$$\Theta_a = \Theta_a + \Delta\Theta_a\,. \tag{29}$$

The iteration process calculates the temperature in the function of time.

1.4 Calculation of material properties

The calculation of the yield stress and Young modulus on higher temperature is according to Eurocode 1 [6]. *Fig. 1* shows the reduction factors in the function of temperature between 20 and 1200 C˚.

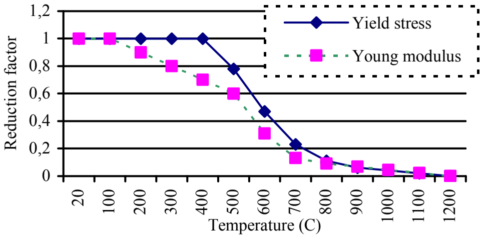

Fig. 1. The yield stress and the Young modulus reduction factors in the function of temperature

7.1 *Calculation of yield strength*

The yield strength at a given temperature can be calculated by $k_{y,\Theta}$ reduction factor

$$f_{y,\Theta} = k_{y,\Theta} f_y \,. \tag{30}$$

7.2 *Calculation of Young modulus*

The yield strength at a given temperature can be calculated by $k_{E,\Theta}$ reduction factor

$$E_{a,\Theta} = k_{E,\Theta} E_a \,, \tag{31}$$

values of $k_{y,\Theta}$ and $k_{E,\Theta}$ can be calculated according to Table 1 and Fig. 4.

2 NUMERICAL EXAMPLE

Minimise the objective function: $f(x_i) \rightarrow \min.$ (32)

Design constraints:

explicit $x_i^L \le x_i \le x_i^U$ (i = 1,2,...,N),

implicit $g_j(x_i) \le 0$ (j = 1;2,..,M).

The objective function is the following:

- mass,
- cost (material-, welding (if any), painting (surface preparation, ground and top coat)),
- cost (material-, welding (if any), painting (intumescent painting)),

The cost of intumescent painting in the function of the protection time is as follows: Intumescent painting, fire protection is 30; 45; 60; 90 min., the painting cost is 3000; 4750; 8600; 125000HUF/m^2 respectively. The Hillclimb optimization technique has been used.

2.1 Data of the numerical example

The centrally compressed column has two pinned ends. The cross section either welded, or rolled. The length varied between 2 – 4 meters. The compression force and the steel grade were constant. The objective function contains not only the material, but the different fabrication costs, like cutting, welding, edge grinding, surface preparation and painting. We would like to compare the elements with different length, force and steel grade.

N_{force}=1600 kN; f_y=235 MPa; E=2,1*10^5 MPa; L=2000/2500/3000/3500/4000 mm;
The unknowns are the welded section dimensions $h=x_1$; $t_w = x_2$; $b= x_3$; $t_f = x_4$; for rolled $h=x_1$ [8].
Cost of the steel k_{st}: $k_{st} = 7.85 * 10^{-6} * (x_1 * x_2 + 2 * x_3 * x_4) * L * 250$.
Cost of the painting k_p: $k_p = (x_1 * L * 2 + 4 * x_3 * L) * (2700 + 4950 + 3000) * 10^{-6}$.
Cost of welding k_w using CO$_2$ technology: $k_w = 2.245 * 10^{-3} * x_2 * x_2 * 2 * L * 220$.

2.2 Optimum results

The optimization is made both for uncovered columns and painted with intumescent painting. The cross sections and the cost elements and the total cost are visible for 30 minute protection time for an uncovered column with different lengths in *Table 1.*

Figs. 2 and 3 show the total cost for a given length (L=4 m). Comparison is made for different fire resistance time without protection and with intumescent painting for both welded and rolled sections. Figures show, that increasing fire resistance time cause exponential increment of the total cost for unprotected welded and rolled sections. Using intumescent painting, the increment of the total cost is much smaller for both sections. Cost saving is up to 57% and 44% for welded and rolled profiles respectively. This shows the economy of the application of intumescent painting, even if the painting is expensive. The increment is larger for welded cross sections than rolled ones. The reason is that welded sections usually have smaller thickness. In case of fire this is uneconomic.

Table 1. Cross sections and the cost elements and the total cost for 30 minute protection time for an *unprotected welded* column with different lengths

30 min. fire protection	L=2000 mm	L=2500 mm	L=3000 mm	L=3500 mm	L=4000 mm
Optimal cross section (mm)	340x10x 180x9	220x7x 220x12	340x10x 200x9	320x9x 230x10	210x6x 210x16
Cross section area (mm^2)	6740	6820	7000	7480	7980
Material cost	26454	34343	40152	51378	67643
Painting cost	21726	28305	30294	41769	58556
Welding cost	19756	24695	14520	28004	14224
Total cost (HUF)	67936	87343	84966	121151	140423

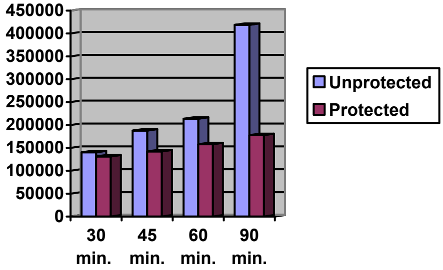

Fig. 2. Total cost of *welded* cross section for column with L=4000 mm.

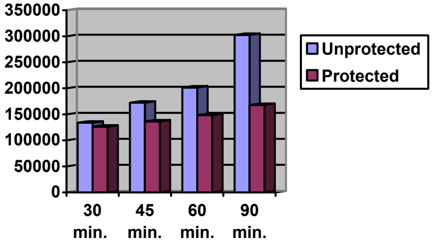

Fig. 3. Total cost of *rolled* cross section for column with L=4000 mm.

2.3 The effect of the column length on the optimum

Optimum depends on the column length. *Fig. 4 and 5* show the differences in the function of the length and fire resistance time for rolled unprotected and protected sections. Total costs are proportional to the length, but the ratios of different cost elements (material, painting, welding) do not depend on this. The great effect of fire resistance time is visible.

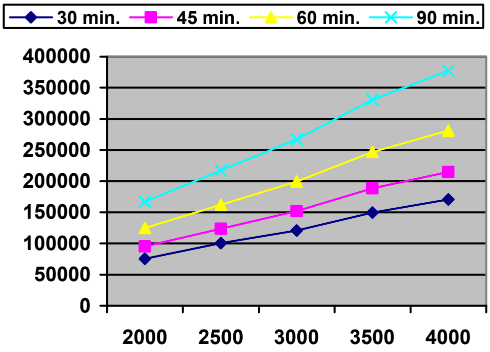

Fig. 4. The total cost (HUF) in the function of the column length (m) for 30-90 minute fire safety for *unprotected rolled* I-section

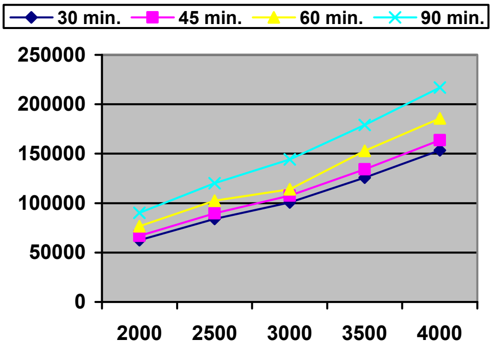

Fig. 5. The total cost (HUF) in the function of the column length (m) for 30-90 minute fire safety for *protected rolled* I-section

Fig. 6 and 7 show the differences in the function of the length and fire resistance time for welded unprotected and protected sections. Total costs are proportional to the length, but the ratios of different cost elements (material, painting, welding) do not depend on this. The great effect of fire resistance time is visible. In the case of welded profiles smaller real optima can be found, because the range of welded plate is larger that of for roller ones. To find discrete values it is easier for welded I-sections.

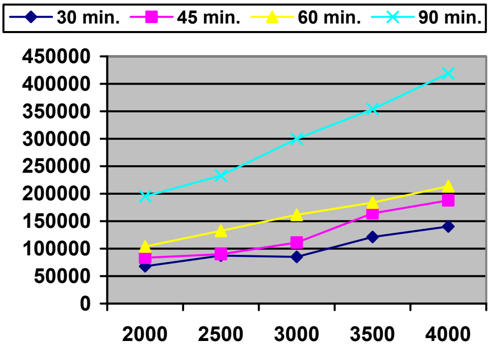

Fig. 6. The total cost (HUF) in the function of the column length (m) for 30-90 minute fire safety for *unprotected welded* I-section

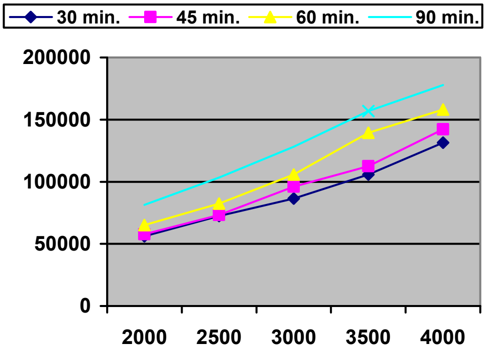

Fig. 7. The total cost (HUF) in the function of the column length (m) for 30-90 minute fire safety for *protected welded* I-section

3 CONCLUSION

The great number of calculations which have been made show, that cost saving can be considerable using intumescent paintings, mainly when fire protection time is high. In these cases the steel material cost is much smaller. For rolled profiles the larger thicknesses have advantages if fire safety. For welded I-sections the greater variety of steel plate thickness has some benefits. Optimization helps to find the best solution in all cases [9].

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