DESIGN, FABRICATION AND ECONOMY OF WELDED STRUCTURES

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2.2 Minimum Cost Design of a Square Box Column Composed from Orthogonally Stiffened Welded Steel Plates

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Abstract

In the previous research the minimum cost design of the uniaxially compressed orthogonally stiffened welded steel plate has been worked out. Based on this result the cost minimization of a cantilever stub column of square box cross section with orthogonally stiffened side plates is formulated and solved. The constraints relate to the overall and stiffener torsional buckling of side plates and to the horizontal displacement of the column top due to a horizontal force. Halved rolled I-section stiffeners are used in both directions. The cost function includes the cost of material, assembly, welding and painting. The variables are the thickness and width of the side plates as well as the dimensions and numbers of stiffeners in both directions. The optimization is performed using the particle swarm algorithm.

Keywords: *buckling of stiffened plates, economy of welded structures, minimum cost design, fabrication costs, stiffened box columns*

1 Introduction

Box beams and columns of large load-carrying capacity are widely applied in bridges, buildings, highway piers, pylons etc. Since the thickness required for an unstiffened box column can be too large, stiffened plate elements should be used.

Steinhardt (1975) has proposed a design method for box beams with stiffened flange plates using formulae for effective plate width. Nakai et al. (1985) have worked out empirical formulae for stiffened box stub-columns subject to combined actions of compression and bending.

Ge et al. (2000) and Usami et al. (2000) have studied the cyclic behaviour and ductility of stiffened steel box columns used as bridge piers. Longitudinal flat plate stiffeners and diaphragms as well as constant compressive axial force and cyclic lateral loading have been considered. Empirical formulae have been proposed for ultimate strength and ductility capacity. Other papers about bridge piers can be found in a conference proceedings as follows: Yamao et al. (2004), Ohga et al.(2004) and Hirota et al. (2004).

In our previous studies it has been shown that, in the case of uniaxial compression, an orthogonal stiffening is more economic than a longitudinal one (Farkas & Jármai 2006). In a study we have worked out a minimum cost design of an orthogonally stiffened plate subject to uniaxial compression (Farkas & Jármai 2007).This method is used in present paper for a square box column constructed from four equal orthogonally stiffened plates.

A cantilever column is loaded by a compression force and a horizontal load, thus, it is subject to compression and bending. From this loading a compression force is calculated for two opposite plate elements, while the remaining plate elements are subject to compression and bending. Since this loading is not so dangerous for the buckling of remaining side plate elements, it is sufficient to design only the two main plate elements. Halved rolled I-section stiffeners are used in both directions.

To show the necessity of stiffening let us design an unstiffened square box column using the following data (Fig.1): $L = 15$ m, $N_F = 34000$ kN, $H_F = 0.1N_F$, the limit of the horizontal displacement on the column top $w_0 = L/1000 = 15$ mm, the steel yield stress $f_y = 355$ MPa, elastic modulus $E = 2.1\text{x}10^5$ MPa.

The limiting plate slenderness is expressed according to Eurocode 3 (2002)

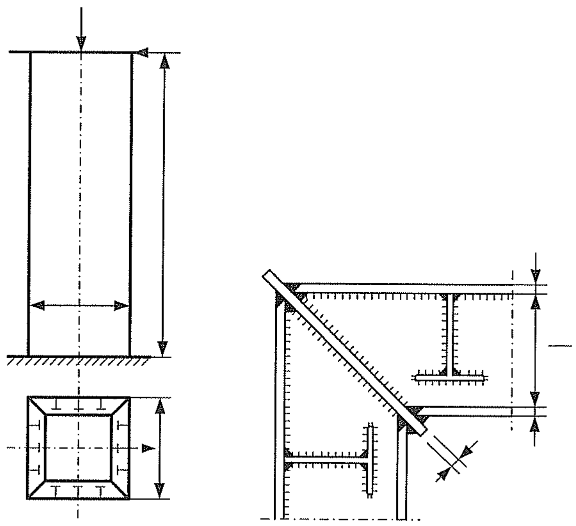

Figure 1. A cantilever stub-column of square box section with orthogonally stiffened side plates and the welded corner

$$b/t \le 1/\delta = 42\varepsilon, \varepsilon = \sqrt{235/f_y}, 1/\delta = 34, t \ge \delta b \quad (1)$$

Taking the last inequality as equality, the cross section area, moment of inertia and section modulus are defined as

$$A = 4bt = 4\delta b^2, I_x = 2\delta b^4/3, W_x = 4\delta b^3/3 \quad (2)$$

The stress and displacement constraints are written as

$$\frac{N_F}{A} + \frac{H_F L}{W_x} \le \frac{f_y}{1.1}, \frac{H_F L^3}{3EI_x} \le w_0 \quad (3)$$

Since the displacement constraint is governing, the required box section width can be calculated as

$$b \ge \sqrt[4]{\frac{H_F L^3}{2\delta E w_0}} = 2805, t = 2805/34 = 82.5 \text{ mm} \quad (4)$$

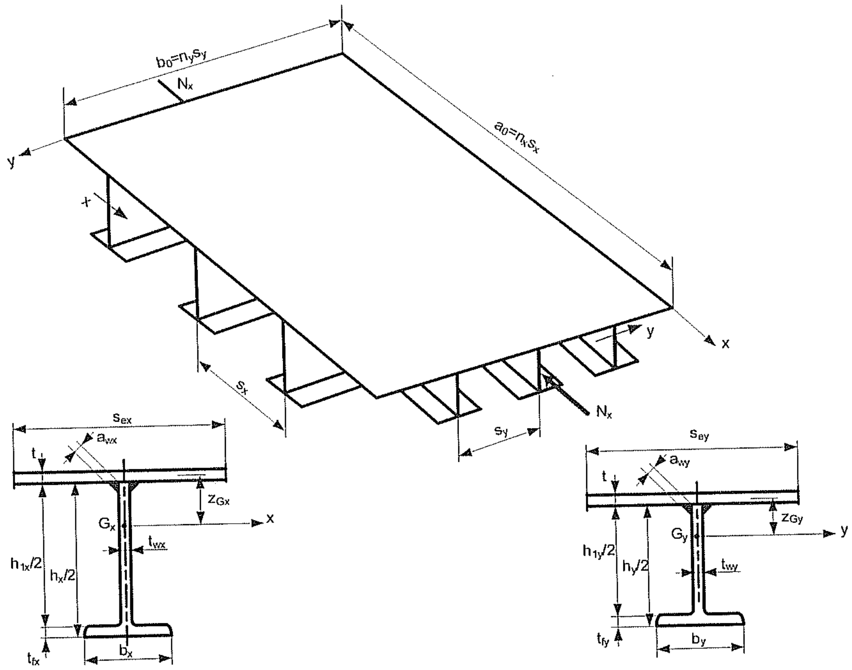

Figure 2. Orthogonally stiffened plate

This thickness is unrealistically large, thus, stiffening is needed.

In the optimum design the following variables should be optimized: the column width b_0, the base plate thickness t, dimensions and number of stiffeners in both directions h_x, h_y, n_x and n_y. It is sufficient to determine the heights h_x and h_y, since the other profile dimensions (b, t_w and t_f) can be calculated using approximate functions determined for a selected series of UB sections according to the Arcelor Mittal catalogue (Sales program 2007).

The buckling constraints are formulated according to the Det Norske Veritas rules (1995).

2 Constraint on overall buckling of a plate element (Fig.1)

$$\sigma = \frac{N_F}{4A_{ey}(n_y - 1)} + \frac{0.1 N_F a_0}{W_\xi} \le \sigma_{cr} = \frac{f_{y1}}{\sqrt{1+\lambda_e^4}} \tag{5}$$

Effective cross-sectional areas ($i = x,y$)

$$A_{ei} = \frac{h_{1i} t_{wi}}{2} + b_i t_{fi} + s_{ei} t, s_y = \frac{b_0}{n_y}, s_x = \frac{a_0}{n_x}. \tag{6}$$

Effective plate widths in two directions

$$s_{ey} = s_y C_y C_\tau , s_{ex} = s_x C_x C_\tau , \quad s_y = b_0 / n_y , s_x = a_0 / n_x \tag{7}$$

$$C_y = \frac{1.8}{\beta_y} - \frac{0.8}{\beta_y^2} , C_x = \frac{1.8}{\beta_x} - \frac{0.8}{\beta_x^2} \tag{8}$$

$$C_\tau = \sqrt{1 - 3\left(\frac{\tau}{f_{y1}}\right)^2} , \quad \tau = \frac{0.1 N_F}{2 b_0 t} \tag{9}$$

$$\beta_y = \frac{s_y}{t}\sqrt{\frac{f_y}{E}} \quad \text{if} \quad \beta_y \geq 1 \tag{10a}$$
$$\beta_y = 1 \quad \text{if} \quad \beta_y < 1$$

$$\beta_x = \frac{s_x}{t}\sqrt{\frac{f_y}{E}} \quad \text{if} \quad \beta_x \geq 1 \tag{10b}$$
$$\beta_x = 1 \quad \text{if} \quad \beta_x < 1$$

The distances of the gravity centres G_i

$$z_{Gi} = \frac{1}{A_{ei}}\left[\frac{h_{1i} t_{wi}}{2}\left(\frac{h_{1i}}{4} + \frac{t}{2}\right) + b_i t_{fi}\left(\frac{h_i + t - t_{fi}}{2}\right)\right], \tag{11}$$

The moments of inertia

$$I_i = s_{ei} t z_{Gi}^2 + \frac{h_{1i}^3 t_{wi}}{96} + \frac{h_{1i} t_{wi}}{2}\left(\frac{h_{1i}}{4} + \frac{t}{2} - z_{Gi}\right)^2 + b_i t_{fi}\left(\frac{h_i + t - t_{fi}}{2} - z_{Gi}\right)^2 \tag{12}$$

The bending stiffnesses

$$B_x = \frac{E I_y}{s_y} ; B_y = \frac{E I_x}{s_x} \tag{13}$$

$$\sigma_E = \frac{N_E s_y}{A_{ey}} , N_E = \frac{\pi^2}{b_0^2}\left(B_x \frac{b_0^2}{a_0^2} + B_y \frac{a_0^2}{b_0^2}\right) \tag{14}$$

$$\lambda_e^2 = \frac{f_{y1}}{\sigma_e}\left[\left(\frac{\sigma}{\sigma_E}\right)^c + \left(\frac{\tau}{\tau_E}\right)^c\right]^{1/c} , \quad c = 2 - \frac{b_0}{s_x} \tag{15}$$

$$\sigma_e = \sqrt{\sigma^2 + 3\tau^2} , \tau_E = \frac{C_1 \pi^2 E}{12\left(1 - \nu^2\right)}\left(\frac{t}{b_0}\right)^2 \tag{16}$$

$$C_1 = 5.34 + 4\left(\frac{b_0}{s_x}\right)^2 \tag{17}$$

$$W_\xi = \frac{I_\xi}{\frac{b_0}{2} - z_{Gy}} \tag{18}$$

$$I_\xi = 2\left\langle\left[I_y + A_{ey}\left(\frac{b_0}{2} - z_{Gy}\right)^2\right](n_y - 1) + I_{\xi 0}\right\rangle \tag{19}$$

If n_y is even

$$I_{\xi 0} = 2\sum_{i=1}^{\frac{n_y}{2}-1}\left(I_0 + A_{ey}s_y^2 i^2\right) \tag{20a}$$

if n_y is odd

$$I_{\xi 0} = 2\sum_{i=1,3,5}^{n_y-2}\left[I_0 + A_{ey}\left(\frac{s_y}{2}\right)^2 i^2\right] \tag{20b}$$

$$I_0 = \frac{b_y^3 t_{fy}}{12} + \frac{s_y^3 t}{12} \tag{21}$$

3 Constraint on stiffener induced failure according to DNV [6]

$$s_{ey1} = (1.1 - 0.1\beta_y)s_y \tag{22}$$

but $s_{ey1.\max} = 1$

$$A_{ey1} = \frac{h_{1y}t_{wy}}{2} + b_y t_{fy} + s_{ey1}t \tag{23}$$

$$z_{Gy1} = \frac{h_{1y}t_{wy}}{2A_{ey1}}\left(\frac{h_{1y}}{4} + \frac{t}{2}\right) + \frac{b_y t_{fy}}{2A_{ey1}}\left(h_{1y} + t - t_{fy}\right) \tag{24}$$

$$I_{y1} = s_{ey1}tz_{Gy1}^2 + \frac{h_{1y}^3 t_{wy}}{96} + \frac{h_{1y}t_{wy}}{2}\left(\frac{h_{1y}}{4} + \frac{t}{2} - z_{Gy1}\right)^2 + I_{y11} \tag{25}$$

$$I_{y11} = b_y t_{fy}\left(\frac{h_y + t - t_{fy}}{2} - z_{Gy1}\right)^2 \tag{26}$$

$$\sigma_{Ex} = \frac{\pi^2 E I_{y1}}{A_{ey1}s_x^2} \tag{26a}$$

Torsional buckling strength is expressed by

$$\sigma_{ET} = \frac{A_w + A_f\left(\frac{t_f}{t_w}\right)^2}{A_{wf}}G\left(\frac{2t_w}{h_1}\right)^2 + \frac{3x2.6\pi^2 EI_z}{A_{wf}s_x^2} \tag{27}$$

where $A_w = \frac{h_1 t_w}{2}, A_f = b_y t_{fy}, A_{wf} = A_w + 3A_f, I_z = \frac{b_y^3 t_{fy}}{12}$ (28)

$$\lambda_T = \sqrt{\frac{f_y}{\sigma_{ET}}} \tag{29}$$

$$\sigma_T = \frac{f_{y1}}{\phi_T + \sqrt{\phi_T^2 - \lambda_T^2}}, \phi_T = 0.5\left(1 + \mu_T + \lambda_T^2\right) \tag{30}$$

$$\mu_T = 0.007(\lambda_T - 0.6) \tag{31}$$

$$\lambda_S = \sqrt{\frac{\sigma_k}{\sigma_{Ex}}} \tag{32}$$

where $\sigma_k = f_y$ if $\lambda_T < 0.6$ (33)

$\sigma_k = \sigma_T$ if $\lambda_T \geq 0.6$

The constraint is formulated as

$$\sigma_1 = \frac{N_x}{n_y A_{ey1}} \leq \sigma_{acr} = \frac{\sigma_k}{\phi + \sqrt{\phi^2 - \lambda_S^2}} \tag{34}$$

where $\phi = 0.5\left(1 + \mu + \lambda_S^2\right)$ (35)

$$\mu = \frac{\delta z_t A_{ey1}}{I_{y1}} \quad \text{if} \quad \lambda_T < 0.6 \tag{36}$$

$$\mu = \frac{2.3\delta z_t A_{ey1}}{I_{y1}} \quad \text{if} \quad \lambda_T \geq 0.6$$

$$\delta = 0.0015 s_x \tag{37}$$

$$z_t = z_{Gy1} + \frac{t_{fy}}{2} \tag{38}$$

4 Constraint on horizontal displacement of the column top

$$w_{\max} = \frac{H_F}{\gamma_M}\frac{L^3}{3EI_\xi} \leq \frac{L}{\phi}, \gamma_M = 1.5, \phi = 1000 \tag{39}$$

5 Constraint on local buckling of face plates connecting the transverse stiffeners

$$t_C \geq \frac{\sqrt{2}h_x}{2x14\varepsilon}, \varepsilon = \sqrt{\frac{235}{\sigma}} \tag{40}$$

6 Numerical data (Fig. 1)

a_0 = 24000, b_0 = 8000 mm, N_x = 3x10^7 [N], steel yield stress f_y = 355 MPa, elastic modulus E = 2.1x10^5 MPa, shear modulus G = 0.81x10^5, density ρ = 7.85x10^{-6} kg/mm^3, Poisson ratio ν = 0.3, selected rolled I-sections UB profiles.

Ranges of unknowns: $4 < t < 20$ mm, $152 < h < 1016$ mm, $4<n<n_{max}$, n_{max} are determined by the following fabrication constraints:

$$\frac{b_0}{n_y} - b_y \geq 300 \text{ mm}, \quad \frac{a_0}{n_x} - b_x \geq 300 \text{ mm}. \tag{41}$$

The other dimensions of a halved rolled I-section are given by approximate functions of h in Appendix.

$$h_1 = h - 2t_f .$$

The discrete values of h are as follows: 152.4, 177.8, 203.2, 257.2, 308.7, 353.4, 403.2, 454.6, 533.1, 607.6, 683.5, 762.2, 840.7, 910.4, 1016 mm.

7 Cost function

The cost function includes the cost of material, assembly, welding as well as painting and is formulated according to the fabrication sequence.

The cost of material

$$K_M = k_M \rho V_2 ; k_M = 1.0 \text{ \$/kg.} \tag{42}$$

Welding of the base plate with butt welds (SAW - submerged arc welding) (Farkas & Jármai 2003). A fabricated plate element has sizes of 6000x1500 mm or less, thus the number of butt welds in x direction is the rounded up value of $n_{px} = a_0/6000$ and in y direction $n_{py} = b_0/1500$.

The fabrication cost factor is taken as $k_F = 1.0$ \$/min, the factor of complexity of the assembly $\Theta_W = 2$:

$$K_{F0} = k_F \left[\Theta_W \sqrt{(n_{px}+1)(n_{py}+1)\rho V_0} + 1.3 C_W t^n \left(n_{px} a_0 + n_{py} b_0 \right) \right], \tag{43}$$

$$V_0 = a_0 b_0 t, \tag{44}$$

$$\text{for } t < 11 \qquad C_W = 0.1346x10^{-3} ; n = 2 , \tag{45a}$$

$$\text{for } t \geq 11 \qquad C_W = 0.1033x10^{-3} ; n = 1.904 . \tag{45b}$$

Welding (n_x-1) stiffeners to the base plate in y direction with double fillet welds (GMAW-C - gas metal arc welding with CO_2):

$$K_{W1} = k_F \left[\Theta_W \sqrt{n_x \rho V_1} + 1.3x0.3394x10^{-3} a_{wx}^2 2 b_0 (n_x - 1) \right], \tag{46}$$

$a_{Wx} = 0.4\, t_{wx}$ but $a_{wx.min} = 3$ mm,

$$V_1 = a_0 b_0 t + \left(\frac{h_{1x} t_{wx}}{2} + b_x t_{fx} \right) b_0 (n_x - 1) \tag{47}$$

Welding of ($n_y - 1$) stiffeners to the base plate in x direction with double fillet welds. These stiffeners should be interrupted and welded with fillet welds to the stiffeners in the y direction.

$$K_{W2} = k_F \left[\Theta_W \sqrt{(n_y n_x - n_x + 1)\rho V_2} + 1.3x0.3394x10^{-3} a_{wy}^2 2 a_0 (n_y - 1) + T_1 \right], \tag{48}$$

$$T_1 = 1.3x0.3394x10^{-3} a_{wy}^2 4 (n_y - 1)(n_x - 1) \left(\frac{h_{1y}}{2} + b_y \right), \tag{49}$$

$a_{Wy} = 0.4\, t_{wy}$ but $a_{Wy.min} = 3$ mm,

$$V_2 = V_1 + \left(\frac{h_{1y} t_{wy}}{2} + b_y t_{fy} \right) a_0 (n_y - 1) \tag{50}$$

Painting cost is calculated as

$$K_P = k_P \Theta_P S_P \tag{51}$$

$k_P = 14.4\text{x}10^{-6}$ \$/mm^2 , $\Theta_P = 2$,

Surface to be painted

$$S_P = 2a_0 b_0 + a_0 (n_y - 1)(h_{1y} + 2b_y) + b_0 (n_x - 1)(h_{1x} + 2b_x) \tag{52}$$

The total cost of a side stiffened plate element

$$K_S = K_M + K_0 + K_{W1} + K_{W2} + K_P \tag{53}$$

In the corners the horizontal stiffeners should be welded together by means of face plates (Fig.1). The cost of these corner welds is expressed as

$$K_C = k_w \left\langle \Theta_w \sqrt{8\rho V} + 1.3x0.3394x10^{-3} x8 \left[0.7a_0 t + (n_x - 1)\left(\frac{h_{1x}}{2} \sqrt{2} a_{wc} + 1.4 b_x t_{fx} \right) \right] \right\rangle \tag{54}$$

$$V = 4V_2 + 4a_0 t_C \left(\frac{h_x}{2} \sqrt{2} + 3t_C \right) \tag{55}$$

$$a_{wc} = 0.4 t_{wx} \quad \text{but} \quad a_{wc.min} = 3 \text{ mm}. \tag{56}$$

The cost of the whole column is given by

$$K = 4K_S + K_C \tag{57}$$

8 Optimization and results

For the optimization the Particle Swarm Optimization (PSO) algorithm is used (Farkas & Jármai 2003). Table 1 shows the results of the optimization. It can be seen that the optimum column width is $b_0 = 4500$ mm and all structural versions fulfil the design constraints.

Table 1. Results of the optimization. The optimum is marked by bold letters. Dimensions in mm, stresses in MPa. For each version $h_y = 152.4$ and $h_x = 177.8$ mm. The allowable deflection is $w_{allow} = 15$ mm

b_0	t	n_y	n_x	σ_e	σ_{ecr}	σ_{acr}	w_{max}	K \$
4000	17	9	8	232	323	250	14.0	81020
4300	13	11	9	261	316	287	13.9	77780
4500	**12**	**11**	**9**	**276**	**310**	**287**	**13.7**	**76990**
4700	11	11	10	297	298	297	13.9	78200
5000	11	11	9	284	284	286	12.0	80340

9 Conclusions

A realistic numerical model of a cantilever stub column of square box section is optimized. The column is subject to compression and bending and is constructed from four equal orthogonally stiffened side plates. The thickness and width of side plates as well as the dimensions and numbers of stiffeners in both directions are calculated to fulfil the constraints and minimize the cost function.

The constraints on overall and stiffener torsional buckling are formulated according to the Det Norske Veritas design rules. The horizontal displacement of the column top is limited. The minimum distance between stiffeners is prescribed to ease the welding of stiffeners to the base plates.

Halved rolled I-profile stiffeners are used in both directions. Their height characterizes the whole profile, since the other dimensions can be expressed by height using approximate functions derived from the data of a profile series selected from available sections.

The cost function is formulated according to the fabrication sequence. The particle swarm mathematical method is suitable for this constrained function minimization problem.

It should be mentioned that the same structure has been optimized as a unstiffened and stringer-stiffened circular cylindrical shell (Farkas et al. 2007) and the result is as follows: the cost of the unstiffened shell with a diameter of 5400 and thickness of 26 mm is 82177 \$, the cost of the stringer-stiffened shell is 83309 \$. It means that the square box column constructed from stiffened plates is more economic than the shell columns.

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Appendix

Table 2. Approximate formulae for the calculation of UB rolled I-profile dimensions b, t_w and t_f in function of x = h

t_w	b	t_f
y=a+bx+cx^2+dx^3+ex^4+ fx^5+gx^6+hx^7+ix^8	y=a+bx+c/x+dx^2+e/x^2+ fx^3+g/x^3+hx^4+ i/x^4+jx^5+k/x^5	y=a+bx+cx^2+dx^3+ex^4+ fx^5+gx^6+hx^7+ix^8
a= 4.598131496764401D0	a= -1108926.658794802D0	a= -26.93816005910891D0
b= -0.1667245062310966D0	b= 2054.96457373585D0	b= 0.7030053260773679D0
c= 0.002662252625070477D0	c= 394347552.4221416D0	c= -0.005693338027675875D0
d= -1.662919418563092D-05	d= -2.475920494568994D0	d= 2.383106288900282D-05
e= 5.425706060478163D-08	e= -91315532919.66857D0	e= -5.605511692214832D-08
f= -1.003562929221022D-10	f= 0.001858445891156483D0	f= 7.662794440441443D-11
g= 1.063362615303672D-13	g= 13189053888762.85D0	g= -5.902409222905948D-14
h= -6.028516555302632D-17	h= -7.856977790442618D-07	h= 2.267417977644635D-17
i= 1.419727611913505D-20	i= -1073670362507492D0	i= -2.999371468428559D-21
	j= 1.422535840934241D-10	
	k= 3.744384150518803D+16	