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OPTIMUM DESIGN OF STIFFENED PLATES FOR DIFFERENT LOADS AND SHAPES OF RIBS

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Dedicated to Professor József FARKAS on the occasion of his seventy-fifth birthday

Abstract. In this overview of loaded stiffened plates various plate types, loadings, and stiffener shapes are investigated. Mikami [1] and API [2] methods are used for the optimum design and comparison of the two methods and uniaxially compressed plates stiffened by ribs of various shapes. Both methods consider the effect of initial imperfection and residual welding stresses, but their empirical formulae are different. The elastic secondary deflection due to compression and lateral pressure is calculated using the Paik's solution [3] of the differential equation for orthotropic plates, and the self-weight is also taken into account. Besides this deflection some more deformations are caused by lateral pressure and the shrinkage of longitudinal welds. The unknowns are the thickness of the base plate as well as the dimensions and number of stiffeners. The cost function to be minimized includes two kinds of material and three kinds of welding costs.

Mathematical Subject Classification: 74K20,74P10
Keywords: stiffened plate, welded structures, stability, residual welding distortion, structural optimization, minimum cost design

1. **Introduction**

Stiffened welded plates are widely used in various load-carrying structures, e.g. ships, bridges, bunkers, tank roofs, offshore structures, vehicles, etc. They are subject to various loadings, e.g. compression, bending, shear or combined load. The shape of plates can be square, rectangular, circular, trapezoidal, etc. They can be stiffened in one or two directions by stiffeners of flat, L, trapezoidal or other shape.

Various plate types, loadings and stiffener shapes have been investigated. In this paper two kinds of loads are investigated [6], [7]. These are uniaxial compression and lateral pressure. Structural optimization of stiffened plates has been worked out by Farkas [8], Farkas and Jármai [9], and applied to uniaxially compressed plates with stiffeners of various shapes [10], biaxially compressed plates [11].

This paper contains the minimum cost design of longitudinally stiffened plates using the strength calculation methods. Deflections due to lateral pressure, compression stress and shrinkage of longitudinal welds are taken into account in the stress constraint. The self-weight is added to the lateral pressure. The local buckling constraint of the base plate strips is formulated as well. The cost function includes two kinds of material and three kinds of welding costs. The unknowns are the thickness of the base plate as well as the dimensions and number of stiffeners.

2. Geometric characteristics

The stiffened plates are shown in Figures 1 and 2. The plates are simply supported at four edges. Geometrical parameters of plates with flat, L- and trapezoidal stiffeners can be seen in Figures 3-5.

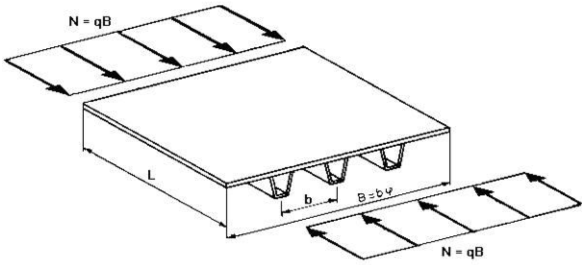

Figure 1. Longitudinally stiffened plate loaded by uniaxial compression

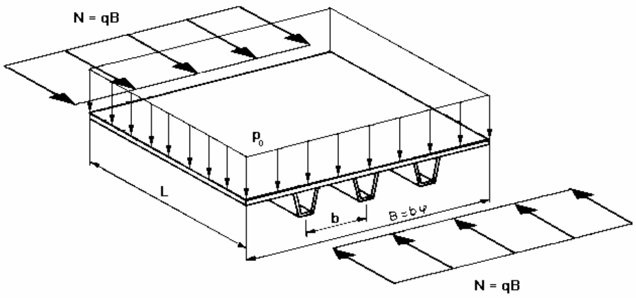

Figure 2. Longitudinally stiffened plate loaded by uniaxial compression and lateral pressure

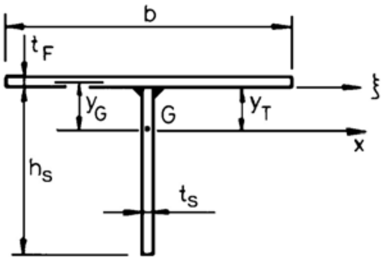

Figure 3. Dimensions of a flat stiffener

The geometrical parameters of the flat stiffener are calculated as follows

$$A_S = h_S t_S, \tag{2.1}$$

$$h_S = 14 t_S \varepsilon, \tag{2.2}$$

$$\varepsilon = \sqrt{235/f_y}, \tag{2.3}$$

$$y_G = \frac{h_S + t_F}{2} \frac{\delta_S}{1 + \delta_S}, \tag{2.4}$$

$$\delta_S = \frac{A_S}{b t_F}, \tag{2.5}$$

$$I_x = \frac{b t_F^3}{12} + b t_F y_G^2 + \frac{h_S^3 t_S}{12} + h_S t_S \left(\frac{h_S}{2} - y_G \right)^2, \tag{2.6}$$

$$I_S = h_S^3 \frac{t_S}{3}, \tag{2.7}$$

$$I_t = \frac{h_S t_S^3}{3}. \tag{2.8}$$

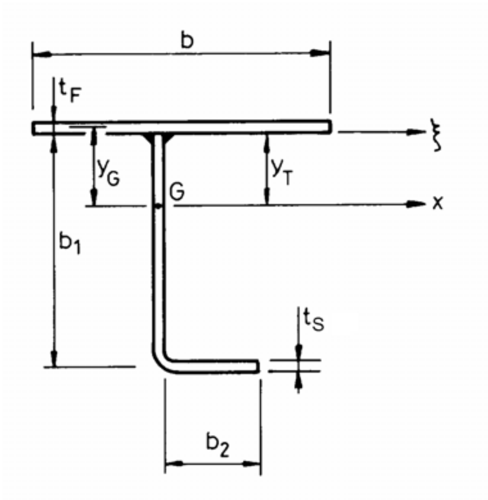

Figure 4. Dimensions of an L-stiffener

The calculations of geometrical parameters of the L-stiffener are

$$A_S = (b_1 + b_2)\, t_S \tag{2.9}$$

$$b_1 = 30 t_S \varepsilon, \tag{2.10}$$

$$b_2 = 12.5 t_S \varepsilon, \tag{2.11}$$

$$y_G = \frac{b_1 t_S \dfrac{b_1 + t_F}{2} + b_2 t_S \left(b_1 + \dfrac{t_F}{2} \right)}{b t_F + A_S}, \tag{2.12}$$

$$I_x = \frac{bt_F^3}{12} + bt_F y_G^2 + \frac{b_1^3 t_S}{12} + \\ + b_1 t_S \left(\frac{b_1}{2} - y_G\right)^2 + b_2 t_S \left(b_1 - y_G\right)^2, \tag{2.13}$$

$$I_S = \frac{b_1^3 t_S}{3} + b_1^2 b_2 t_S, \tag{2.14}$$

$$I_t = \frac{b_1^3 t_S}{3} + \frac{b_2^3 t_S}{3}. \tag{2.15}$$

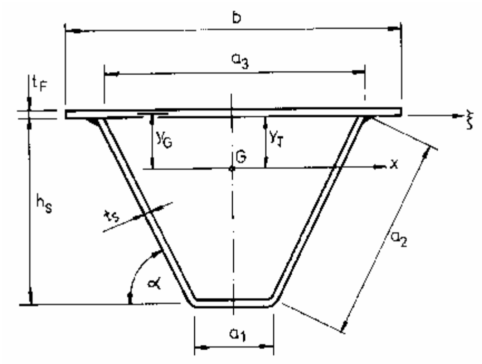

Figure 5. Dimensions of a trapezoidal stiffener

The calculations of geometrical parameters of the trapezoidal stiffener are

$$A_S = (a_1 + 2a_2)\, t_S, \tag{2.16}$$

$a_1 = 90$ [mm], $a_3 = 300$ [mm], thus

$$h_S = \left(a_2^2 - 105^2\right)^{1/2}, \tag{2.17}$$

$$\sin^2\alpha = 1 - \left(\frac{105}{a_2}\right)^2, \tag{2.18}$$

$$y_G = \frac{a_1 t_S \left(h_S + t_F/2\right) + 2a_2 t_S \left(h_S + t_F\right)/2}{bt_F + A_S} \tag{2.19}$$

$$I_x = \frac{bt_F^3}{12} + bt_F y_G^2 + a_1 t_S \left(h_S + \frac{t_F}{2} - y_G\right)^2 + \\ + \frac{1}{6} a_2^3 t_S \sin^2\alpha + 2a_2 t_S \left(\frac{h_S + t_F}{2} - y_G\right)^2, \tag{2.20}$$

$$I_S = a_1 h_S^3 t_S + \frac{2}{3} a_2^3 t_S \sin^2\alpha, \tag{2.21}$$

$$I_t = \frac{4A_P^2}{\sum b_i/t_i}, \tag{2.22}$$

$$A_P = h_S \frac{a_1 + a_3}{2} = 195 h_S. \tag{2.23}$$

3. Design constraints in case of uniaxial compression

3.1. Global buckling of the stiffened plate. According to Mikami [1] the effect of initial imperfections and residual welding stresses is considered by defining buckling curves for a reduced slenderness

$$\lambda = (f_y/\sigma_{cr})^{1/2}\,. \tag{3.1}$$

The classical critical buckling stress for a uniaxially compressed longitudinally stiffened plate is

$$\sigma_{cr} = \frac{\pi^2 D}{hB^2}\left(\frac{1+\gamma_S}{\alpha_R^2} + 2 + \alpha_R^2\right) \qquad \text{for} \qquad \alpha_R = L/B < \alpha_{R0} = (1+\gamma_S)^{1/4}, \tag{3.2}$$

$$\sigma_{cr} = \frac{2\pi^2 D}{hB^2}\left[1 + (1+\gamma_S)^{1/2}\right] \qquad \text{for} \qquad \alpha_R \geq \alpha_{R0}. \tag{3.3}$$

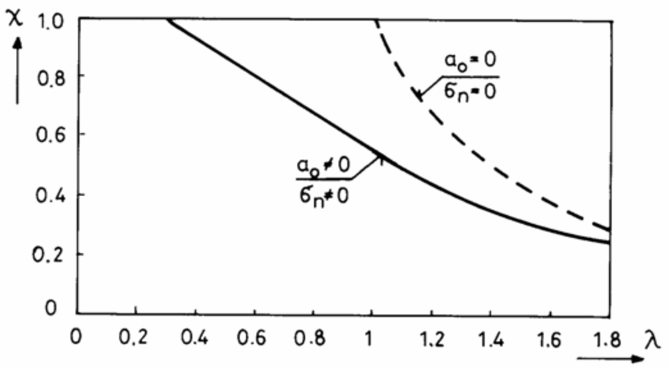

Figure 6. Global buckling curve considering the effect of initial imperfections and residual welding stresses

When the reduced slenderness is known the actual global buckling stress can be calculated according to Mikami [1] as follows

$$\sigma_U/f_y = 1 \qquad \text{for} \qquad \lambda \leq 0.3, \tag{3.4}$$

$$\sigma_U/f_y = 1 - 0.63\,(\lambda - 0.3) \qquad \text{for} \qquad 0.3 \leq \lambda \leq 1, \tag{3.5}$$

$$\sigma_U/f_y = 1/\left(0.8 + \lambda^2\right) \qquad \text{for} \qquad \lambda > 1. \tag{3.6}$$

The global buckling constraint is defined by

$$\frac{N}{A} \leq \sigma_U \frac{\rho_P + \delta_S}{1 + \delta_S}, \tag{3.7}$$

in which δ_S is given by Equation 2.5,

$$A = Bt_F + (\varphi - 1)A_S, \tag{3.8}$$

and the factor is

$$\rho_p = 1 \qquad \text{if} \qquad \sigma_{UP} > \sigma_U, \tag{3.9}$$

$$\rho_P = \sigma_{UP}/f_y \qquad \text{if} \qquad \sigma_{UP} \leq \sigma_U. \tag{3.10}$$

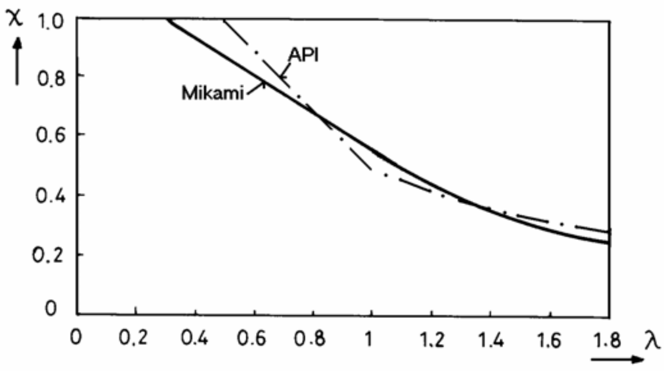

Figure 7. Global buckling curve according to Mikami and API

According to API [2]

$$\sigma_U/f_y = 1 \qquad \text{if} \qquad \lambda \leq 0.5, \tag{3.11}$$

$$\sigma_U/f_y = 1.5 - \lambda \qquad \text{if} \qquad 0.5 \leq \lambda \leq 1, \tag{3.12}$$

$$\sigma_U/f_y = 0.5/\lambda \qquad \text{if} \qquad \lambda > 1. \tag{3.13}$$

The global buckling constraint can be written as follows

$$\frac{N}{A} \leq \sigma_U. \tag{3.14}$$

3.2. **Single panel buckling.** This constraint eliminates the local buckling of the base plate parts between the stiffeners. From the classical buckling formula for a simply supported panel uniformly compressed in one direction

$$\sigma_{crP} = \frac{4\pi^2 E}{10.92}\left(\frac{t_F}{b}\right)^2, \tag{3.15}$$

the reduced slenderness is

$$\lambda_P = \left(\frac{4\pi^2 E}{10.92 f_y}\right)^{1/2} \frac{b}{t_F} = \frac{b/t_F}{56.8\varepsilon}; \quad \varepsilon = \left(\frac{235}{f_y}\right)^{1/2} \tag{3.16}$$

and the actual local buckling stress considering the initial imperfections and residual welding stresses is

$$\sigma_{UP}/f_y = 1 \qquad \text{for} \qquad \lambda_P \leq 0.526, \tag{3.17}$$

$$\frac{\sigma_{UP}}{f_y} = \left(\frac{0.526}{\lambda_P}\right)^{0.7} \qquad \text{for} \qquad \lambda_P > 0.526. \tag{3.18}$$

The single panel buckling constraint is

$$\frac{N}{A} \leq \sigma_{UP}. \tag{3.19}$$

3.3. **Local and torsional buckling of stiffeners.** These instability phenomena depend on the shape of stiffeners and will be treated separately for L stiffener.

The torsional buckling constraint for open section stiffeners is

$$\frac{N}{A} \leq \sigma_{UT}. \tag{3.20}$$

The classical torsional buckling stress is

$$\sigma_{crT} = \frac{GI_T}{I_P} + \frac{EI_\omega}{L^2 I_P}, \tag{3.21}$$

where $G = E/2.6$ is the shear modulus, I_T is the torsional moment of inertia, I_P is the polar moment of inertia and I_ω is the warping constant. The actual torsional buckling stress can be calculated as a function of the reduced slenderness

$$\lambda_T = (f_y/\sigma_{crT})^{1/2}, \tag{3.22}$$

$$\sigma_{UT}/f_y = 1 \qquad \text{for} \qquad \lambda_T \leq 0.45, \tag{3.23}$$

$$\sigma_{UT}/f_y = 1 - 0.53\,(\lambda - 0.45) \qquad \text{for} \qquad 0.45 \leq \lambda \leq 1.41, \tag{3.24}$$

$$\sigma_{UT}/f_y = 1/\lambda^2 \qquad \text{for} \qquad \lambda > 1.41. \tag{3.25}$$

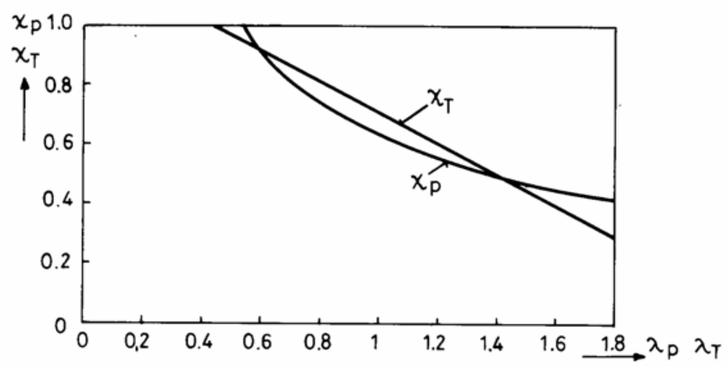

Figure 8. Limiting curves for local plate buckling (χ_P) and torsional buckling of open section ribs (χ_T)

4. Design constraints in case of uniaxial compression and lateral pressure

4.1. Calculation the deflection due to compression and lateral pressure. Paik et al. [3] used the differential equations of large deflection orthotropic plate theory and the Galerkin method to derive the following cubic equation for the elastic deflection A_m of a stiffened plate loaded by uniaxial compression and lateral pressure

$$C_1 A_m^3 + C_2 A_m^2 + C_3 A_m + C_4 = 0, \tag{4.1}$$

where

$$C_1 = \frac{\pi^2}{16}\left(E_x \frac{m^4 B}{L^3} + E\frac{L}{B^3}\right); \quad C_2 = \frac{3\pi^2 A_{om}}{16}\left(E_x \frac{m^4 B}{L^3} + E\frac{L}{B^3}\right),$$

$$C_3 = \frac{\pi^2 A_{om}^2}{8}\left(E_x \frac{m^4 B}{L^3} + E\frac{L}{B^3}\right) + \frac{m^2 B}{L}\sigma_{xav} + \frac{\pi^2}{t_F}\left(D_x \frac{m^4 B}{L^3} + 2H\frac{m^2}{LB} + D\frac{L}{B^3}\right), \tag{4.2}$$

$$C_4 = A_{om}\frac{m^2 B}{L}\sigma_{xav} - \frac{16LB}{\pi^4 t_F}p,$$

$$E_x = E\left(1 + \frac{nA_S}{Bt_F}\right); \quad E_y = E. \tag{4.3}$$

Since the self-weight is taken into account, the lateral pressure is modified as

$$p = p_0 + \frac{\rho V g}{BL}, \tag{4.4}$$

where g is the gravitation constant, 9.81 [m/s^2].

The flexural and torsional stiffnesses of the orthotropic plate are as follows:

$$D_x = \frac{Et_F^3}{12\left(1-\nu_{xy}^2\right)} + \frac{Et_F y_G^2}{1-\nu_{xy}^2} + \frac{EI_x}{b}, \qquad D_y = \frac{Et_F^3}{12\left(1-\nu_{xy}^2\right)}, \tag{4.5}$$

$$\nu_x = \frac{\nu}{0.86}\sqrt{\frac{\dfrac{E}{E_x}\left(\dfrac{Et_F^3}{12} + Et_F y_G^2 + \dfrac{EI_x}{b}\right) - \dfrac{Et_F^3}{12}}{\dfrac{EI_x}{b}\left(\dfrac{E}{E_x}\right)^2}}, \tag{4.6}$$

$$\nu_y = \frac{E}{E_x}\nu_x; \quad \nu_{xy} = \sqrt{\nu_x \nu_y}, \tag{4.7}$$

$$H = \frac{G_{xy} I_t}{b}; \quad G_{xy} = \frac{E}{2\left(1+\nu_{xy}\right)}, \tag{4.8}$$

$$\sum \frac{b_i}{t_i} = \frac{a_1 + 2a_2}{t_S} + \frac{a_3}{t_F}. \tag{4.9}$$

The deflection due to lateral pressure is

$$A_{om} = \frac{5qL^4}{384EI_x}; \quad q = pb; \quad b = B/\varphi. \tag{4.10}$$

The solution of equation (4.1) is

$$A_m = -\frac{C_2}{3C_1} + k_1 + k_2, \tag{4.11}$$

where

$$k_1 = \sqrt[3]{-\frac{Y}{2} + \sqrt{\frac{Y^2}{4} + \frac{X^3}{27}}}; \quad k_2 = \sqrt[3]{-\frac{Y}{2} - \sqrt{\frac{Y^2}{4} + \frac{X^3}{27}}}, \tag{4.12}$$

$$X = \frac{C_3}{C_1} - \frac{C_2^2}{3C_1^2}; \quad Y = \frac{2C_2^3}{27C_1^3} - \frac{C_2C_3}{3C_1^2} + \frac{C_4}{C_1}. \tag{4.13}$$

4.2. **Deflection due to shrinkage of longitudinal welds.** According to [9] the deflection of the plate due to longitudinal welds is as follows

$$f_{\max} = CL^2/8, \tag{4.14}$$

where the curvature for steels is

$$C = 0.844x10^{-3} Q_T y_T / I_x, \tag{4.15}$$

Q_T is the heat input, I_x is the moment of inertia of the cross-section containing a stiffener and the base plate strip of width b, y_T is the weld eccentricity

$$y_T = y_G - t_F/2. \tag{4.16}$$

The heat input for a stiffener is

$$Q_T = 2x59.5a_W^2. \tag{4.17}$$

4.3. **The stress constraint.** The stress constraint includes several effects as follows: the average compression stress and the bending stress caused by deflections due to compression, lateral pressure and the shrinkage of longitudinal welds.

$$\sigma_{\max} = \sigma_{xav} + \frac{M}{I_x} y_G \le \sigma_{UP}, \tag{4.18}$$

where

$$M = \sigma_{xav}\left(A_{0m} + A_m + f_{\max}\right) + \frac{qL^2}{8}, \tag{4.19}$$

According to [1], the calculation of the local buckling strength of a face plate strip of width

$$b1 = \max(a3, b - a3), \tag{4.20}$$

is performed taking into account the effects of initial imperfections and residual welding stresses

$$\sigma_{UP} = f_y \qquad \text{when} \qquad \lambda_P \le 0.526, \tag{4.21}$$

$$\sigma_{UP} = \left(\frac{0.526}{\lambda_P}\right)^{0.7} \qquad \text{when} \qquad \lambda_P \ge 0.526, \tag{4.22}$$

where

$$\lambda_P = \left(\frac{4\pi^2 E}{10.92 f_y}\right)^{1/2} \frac{b_1}{t_F} = \frac{b_1/t_F}{56.8\varepsilon}. \tag{4.23}$$

5. Cost function

The objective function to be minimized is defined as the sum of material and fabrication costs

$$K = K_m + K_f = k_m \rho V + k_f \sum T_i, \tag{5.1}$$

or in another form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m} \left(T_1 + T_2 + T_3 \right), \tag{5.2}$$

where ρ is the material density, V is the volume of the structure, K_m and K_f as well as k_m and k_f are the material and fabrication costs as well as cost factors, respectively, T_i are the fabrication times as follows:

time for preparation, tacking and assembly

$$T_1 = \Theta_d \sqrt{\kappa \rho V}, \tag{5.3}$$

where Θ_d is a difficulty factor expressing the complexity of the welded structure, κ is the number of structural parts to be assembled;

T_2 is time of welding, and T_3 is time of additional works such as changing of electrode, deslagging and chipping. $T_3 \approx 0.3 T_2$, thus,

$$T_2 + T_3 = 1.3 \sum C_{2i} a_{wi}^n L_{wi}, \tag{5.4}$$

where L_{wi} is the length of welds, the values of $C_{2i} a_{wi}^n$ can be obtained from formulae or diagrams constructed using the COSTCOMP [4] software, a_w is the weld dimension.

Welding technology	a_w [mm]	$10^3 C_2 a_w^n$
SAW	0-15	$0.2349 a_w^2$
SMAW	0-15	$0.7889 a_w^2$
GMAW-M	0-15	$0.3258 a_w^2$

Table 1. Welding times versus weld size a_w [mm] for longitudinal fillet welds, downhand position

6. Optimiztion method

Rosenbrock's hillclimb [5] mathematical method is used to minimize the cost function. This is a direct search mathematical programming method without derivatives. The iterative algorithm is based on Hooke & Jeeves searching method. It starts with a given initial value, and takes small steps in the direction of orthogonal coordinates during the search. The algorithm is modified so that secondary searching is carried out to determine discrete values. The procedure finishes when the convergence criterion is satisfied or the iterative number reaches its limit.

7. Numerical data and optimum results

7.1. **Longitudinally stiffened plate loaded by uniaxial compression.** The given data are width $B = 6000$ [mm], length $L = 3000$ [mm], compression force $N = 1.974 \times 10^7$ [N], Young modulus $E = 2.1 \times 10^5$ [MPa] and density $\rho = 7.85 \times 10^{-6}$ [kg/mm^3]. The yield stress is $f_y = 355$ [MPa]. The unknowns – the thicknesses of the base plate and the stiffener and the number of the ribs - are limited in size. For without fabrication cost the welding cost is not considered, the material minima is not shown in Tables 4, 5, 6 and 7.

$$
\begin{aligned}
&3 \le t_F \le 40[\text{mm}],\\
&3 \le t_S \le 12[\text{mm}],\\
&3 \le \varphi \le 10.
\end{aligned}
\tag{7.1}
$$

	k_f/k_m	t_F[mm]	t_S[mm]	ϕ	K/k_m [kg]
Mikami	0	22	6	10	5166
	1	22	6	10	6152
	2	22	6	10	7138
API	0	19	10	10	5224
	1	21	7	10	6249
	2	21	7	10	7367

Table 2. Optimum dimensions with L- stiffener (SAW)

	k_f/k_m	t_F[mm]	t_S[mm]	ϕ	K/k_m [kg]
Mikami	0	9	7	9	3424
	1	12	6	9	4920
	2	17	5	9	6518
API	0	9	7	9	3424
	1	9	7	9	4761
	2	12	6	9	6097

Table 3. Optimum dimensions with trapezoidal stiffener (SAW)

	k_f/k_m	t_F[mm]	t_S[mm]	ϕ	K/k_m [kg]
Mikami	1	22	6	10	7232
	2	24	5	10	8846
API	1	21	7	10	7546
	2	21	7	10	9960

Table 4. Optimum dimensions with L- stiffener (SMAW)

	k_f/k_m	t_F[mm]	t_S[mm]	ϕ	K/k_m [kg]
Mikami	1	19	4	9	6452
	2	19	4	9	8538
API	1	15	5	9	6444
	2	21	3	10	7955

Table 5. Optimum dimensions with trapezoidal stiffener (SMAW)

	k_f/k_m	t_F[mm]	t_S[mm]	ϕ	K/k_m [kg]
Mikami	1	22	6	10	6329
	2	22	6	10	7493
API	1	21	7	10	6462
	2	21	7	10	7793

Table 6. Optimum dimensions with L–stiffener (GMAW-M)

	k_f/k_m	t_F[mm]	t_S[mm]	ϕ	K/k_m [kg]
Mikami	1	11	6	9	4992
	2	16	5	9	6750
API	1	9	7	9	5099
	2	16	5	9	6532

Table 7. Optimum dimensions with trapezoidal stiffener (GMAW-M)

7.2. **Longitudinally stiffened plate loaded by uniaxial compression and lateral pressure.** The given data are width $B = 4000$ [mm], length $L = 6000$ [mm], compression force $N = 1.974 \times 10^7$ [N], Young modulus $E = 2.1 \times 10^5$ [MPa] and density $\rho = 7.85 \times 10^{-6}$ [kg/mm^3]. There are three values of lateral pressure $p_0 = 0.05, 0.1, 0.2$ [MPa] and two values of yield stress $f_y = 255, 355$ [MPa]. The unknowns – the thicknesses of the base plate and the stiffener and the number of the ribs - are limited in size. The results are shown in Tables 8-13. The optimum results are given in bold type.

$$\begin{aligned} 3 \leq t_F \leq 40[\text{mm}], \\ 3 \leq t_S \leq 12[\text{mm}], \\ 3 \leq \varphi \leq 10. \end{aligned} \tag{7.2}$$

f_y [MPa]	p_0 [MPa]	t_F [mm]	t_S [mm]	ϕ	K/k_m [kg] $k_f/k_m = 0$	$k_f/k_m = 1.5$
235	0.1	38	12	10	**8014**	11758
235	0.05	30	12	6	**6127**	8362
355	0.1	28	12	10	**6568**	10137
355	0.05	20	12	9	**4825**	7914

Table 8. Optimum dimensions with flat stiffener for $k_f/k_m = 0$, the material minima

f_y [MPa]	p_0 [MPa]	t_F [mm]	t_S [mm]	ϕ	K/k_m [kg] $k_f/k_m = 0$	$k_f/k_m = 1.5$
235	0.1	38	12	10	8014	**11758**
235	0.05	30	12	6	6127	**8362**
355	0.1	28	12	10	6568	**10137**
355	0.05	21	11	8	4852	**7312**

Table 9. Optimum dimensions with flat stiffener for $k_f/k_m = 1.5$, the cost minima

f_y [MPa]	p_0 [MPa]	t_F [mm]	t_S [mm]	ϕ	K/k_m [kg]	
					$k_f/k_m = 0$	$k_f/k_m = 1.5$
235	0.2	31	12	5	**6993**	8933
235	0.1	21	12	7	**5686**	8230
235	0.05	20	10	7	**4969**	6952
355	0.2	22	12	7	**6107**	8641
355	0.1	18	9	10	**5036**	7389
355	0.05	17	7	10	**4313**	6302

Table 10. Optimum dimensions with L-stiffener for $k_f/k_m = 0$, the material minima

f_y [MPa]	p_0 [MPa]	t_F [mm]	t_S [mm]	ϕ	K/k_m [kg]	
					$k_f/k_m = 0$	$k_f/k_m = 1.5$
235	0.2	34	11	4	7132	**8584**
235	0.1	27	10	5	5888	**7422**
235	0.05	24	8	6	5162	**6564**
355	0.2	28	9	6	6528	**8149**
355	0.1	22	8	7	5247	**6801**
355	0.05	19	8	7	4626	**6129**

Table 11. Optimum dimensions with L-stiffener for $k_f/k_m = 1.5$, the cost minima

f_y [MPa]	p_0 [MPa]	t_F [mm]	t_S [mm]	ϕ	K/k_m [kg]	
					$k_f/k_m = 0$	$k_f/k_m = 1.5$
235	0.2	28	12	4	**6974**	8549
235	0.1	24	10	4	**5723**	6975
235	0.05	18	10	5	**4993**	6466
355	0.2	21	11	5	**6108**	7780
355	0.1	15	10	6	**4944**	6635
355	0.05	13	8	7	**4148**	5611

Table 12. Optimum dimensions with trapezoidal stiffener for $k_f/k_m = 0$, the material minima

f_y [MPa]	p_0 [MPa]	t_F [mm]	t_S [mm]	ϕ	K/k_m [kg]	
					$k_f/k_m = 0$	$k_f/k_m = 1.5$
235	0.2	35	9	3	7250	**8223**
235	0.1	24	10	4	5723	**6975**
235	0.05	23	8	4	5122	**6132**
355	0.2	28	8	4	6530	**7589**
355	0.1	21	7	5	5111	**6284**
355	0.05	16	7	6	4264	**5560**

Table 13. Optimum dimensions with trapezoidal stiffener for $k_f/k_m = 1.5$, the cost minima

8. Conclusions

- The results show that the trapezoidal stiffener is the most economic one. The cost saving can be 69 % compared with various ribs.
- In general the Mikami method gives thinner basic plates than those given by API.
- Materials with higher yield stress give cheaper results. The cost saving can be 40 % compared with the lower one. Higher strength steel is 10 % more expensive.
- In most cases the material and cost minima are different, the number of stiffeners is smaller at cost minima due to welding cost effects. SAW is the cheapest welding process if we do not consider investment cost.
- It can be seen from Tables 8 and 9 that there are no solutions for the highest lateral pressure ($p_0 = 0.2$ [MPa]) for flat stiffeners due to the size limits.
- In case of uniaxially and laterally loaded plate the ratio between material cost and welding cost ranged from 13 % (for flat stiffener, higher yield stress and minimum lateral pressure) to 64 % (in case of trapezoidal stiffener, lower yield stress and maximum lateral pressure).
- For L- and trapezoidal stiffeners the number of stiffeners decreases if the lateral pressure is increased, but it increases if the yield stress of the material is increased.
- For flat stiffeners the number of stiffeners increases if the lateral pressure is increased and the yield stress of the material is increased.

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