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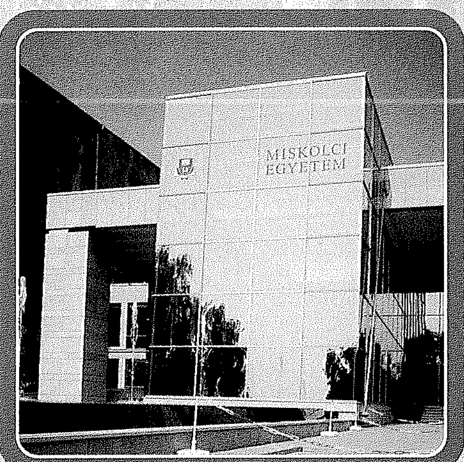

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3.7 Effects of Residual Stresses on Optimum Design of Stiffened Plates

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Abstract

In this overview of uniaxially compressed stiffened plates various types of loadings, and stiffener shapes are investigated. The global buckling strength of welded stiffened plates is calculated according to Mikami and Niwa. This method considers the effect of initial imperfection and residual welding stresses. The aim of the present study is to apply Okerblom's constraint to investigate the effect of the deflection of the plate due to longitudinal welds for the optimum design. The unknowns are the thickness of the base plate as well as the dimensions and number of stiffeners.

Keywords: *stiffened plates, plate buckling, deflection, residual stresses, optimum design*

1 Introduction

Welded stiffened 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 with stiffeners of L, trapezoidal or other shape.

In this overview of uniaxially compressed stiffened plates (Figure 1.) various types of loadings and stiffener shapes are investigated. The global buckling strength of welded stiffened plates is calculated according to Mikami & Niwa (1996). This method considers the effect of initial imperfection and residual welding stresses. Structural optimization of stiffened plates has been worked out by Farkas (1984), Farkas & Jármai (1997) and applied to uniaxially compressed plates with stiffeners of various shapes (Farkas &Jármai (2000), biaxially compressed plates (Farkas et al. (2001)).

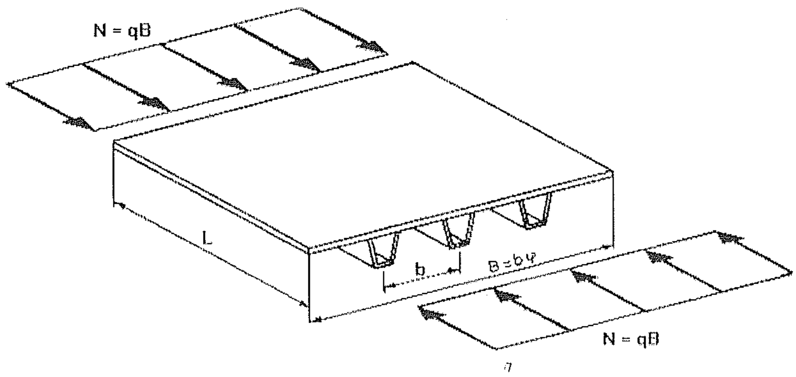

Figure 1. A uniaxially compressed longitudinally stiffened plate

The aim of the present study is to apply Okerblom's constraint to investigate the effect of the deflection of the plate due to longitudinal welds for the optimum design. In the minimum cost design the characteristics of the optimal structural version are sought which minimize the cost function and fulfil the design constraints. First, the special calculations of L- and trapezoidal stiffeners and design constraints are treated, then the general formulae for the cost function is described.

2 Geometric characteristics

Geometrical parameters of plates with L- and trapezoidal stiffeners can be seen in Figure 2.

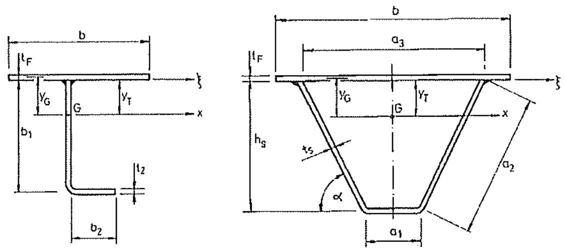

Figure 2. Dimensions of a L- and a trapezoidal stiffeners

The calculations of geometrical parameters of the L-stiffener are

$$A_s = (b_1 + b_2)t_s \tag{1}$$

$$b_1 = 30t_s\varepsilon \tag{2}$$

$$b_2 = 12.5t_s\varepsilon \tag{3}$$

$$y_G = \frac{b_1 t_s \dfrac{b_1 + t_f}{2} + b_2 t_s\left(b_1 + \dfrac{t_f}{2}\right)}{bt_f + A_s} \tag{4}$$

$$I_x = \frac{bt_f^3}{12} + bt_f y_G^2 + \frac{b_1^3 t_s}{12} + b_1 t_s\left(\frac{b_1}{2} - y_G\right)^2 + b_2 t_s\left(b_1 - y_G\right)^2 \tag{5}$$

$$I_S = \frac{b_1^{\,3} t_s}{3} + b_1^{\,2} b_2 t_s \tag{6}$$

$$I_t = \frac{b_1 t_s^{\,3}}{3} + \frac{b_2 t_s^{\,3}}{3} \tag{7}$$

The calculations of geometrical parameters of the trapezoidal stiffener are

$$A_S = \left(a_1 + 2a_2\right)t_S \tag{8}$$

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

$$h_S = \left(a_2^2 - 105^2\right)^{1/2} \tag{9}$$

$$\sin^2\alpha = 1-\left(\frac{105}{a_2}\right)^2 \tag{10}$$

$$y_G = \frac{a_1 t_S\left(h_S + t_F/2\right) + 2a_2 t_S\left(h_S + t_F\right)/2}{bt_F + A_S} \tag{11}$$

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

$$I_S = a_1 h_S^3 t_S + \frac{2}{3}a_2^3 t_S \sin^2\alpha \tag{13}$$

$$I_t = \frac{4A_P^2}{\sum b_i / t_i} \tag{14}$$

$$A_P = h_S \frac{a_1 + a_3}{2} = 195 h_S \tag{15}$$

3 Global buckling of the stiffened plate

According to Mikami the effect of initial imperfections and residual welding stresses is considered by defining buckling curves for a reduced slenderness

$$\lambda = \left(f_y / \sigma_{cr}\right)^{1/2} \tag{16}$$

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

$$\sigma_{cr} = \frac{\pi^2 D}{hB^2}\left(\frac{1+\gamma_S}{\alpha_R^2} + 2 + \alpha_R^2\right) \quad \text{for} \quad \alpha_R = L/B < \alpha_{R0} = (1+\gamma_S)^{1/4} \tag{17}$$

$$\sigma_{cr} = \frac{2\pi^2 D}{hB^2}\left[1 + \left(1+\gamma_S\right)^{1/2}\right] \quad \text{for} \quad \alpha_R \ge \alpha_{R0} \tag{18}$$

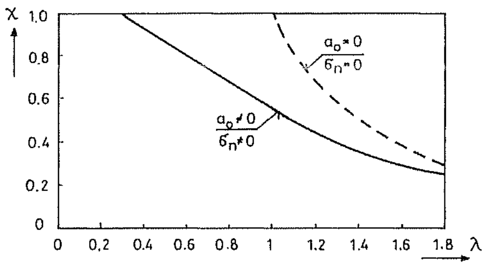

Figure 3. Global buckling curve considering the effect of initial imperfections $(a_0 \neq 0)$ and residual welding stresses $(\sigma_R \neq 0)$

Knowing the reduced slenderness the actual global buckling stress can be calculated according to Mikami as follows (Figure 3)

$$\sigma_U / f_y = 1 \quad \text{for} \quad \lambda \le 0.3 \tag{19}$$

$$\sigma_U / f_y = 1 - 0.63(\lambda - 0.3) \quad \text{for} \quad 0.3 \leq \lambda \leq 1 \tag{20}$$

$$\sigma_U / f_y = 1/\left(0.8 + \lambda^2\right) \quad \text{for} \quad \lambda > 1 \tag{21}$$

The global buckling constraint is

$$\frac{N}{A} \leq \sigma_U \frac{\rho_P + \delta_S}{1 + \delta_S} \tag{22}$$

where

$$A = Bt_f + (\varphi - 1)A_S \tag{23}$$

$$\delta_S = \frac{A_S}{bt_f} \tag{24}$$

and the ρ_P factor is

$$\rho_P = 1 \quad \text{if} \quad \sigma_{UP} \rangle \sigma_U \tag{25}$$

$$\rho_P = \sigma_{UP} / f_y \quad \text{if} \quad \sigma_{UP} \langle \sigma_U \tag{26}$$

4 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 uniformly compressed in one direction

$$\sigma_{crP} = \frac{4\pi^2 E}{10.92}\left(\frac{t_F}{b}\right)^2 \tag{27}$$

the reduced slenderness is

$$\lambda_P = \left(\frac{4\pi^2 E}{10.92 f_y}\right)^{1/2} \frac{b}{t_F} = \frac{b/t_F}{56.8\varepsilon}; \qquad \varepsilon = \left(\frac{235}{f_y}\right)^{1/2} \tag{28}$$

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

$$\sigma_{UP} / f_y = 1 \quad \text{for} \quad \lambda_P \leq 0.526 \tag{29}$$

$$\frac{\sigma_{UP}}{f_y} = \left(\frac{0.526}{\lambda_P}\right)^{0.7} \quad \text{for} \quad \lambda_P \geq 0.526 \tag{30}$$

The single panel buckling constraint is

$$\frac{N}{A} \leq \sigma_{UP} \tag{31}$$

5 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

$$\frac{N}{A} \le \sigma_{UT} \tag{32}$$

The classical torsional buckling stress is

$$\sigma_{crT} = \frac{GI_T}{I_P} + \frac{EI_\omega}{L^2 I_P} \tag{33}$$

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 in the function of the reduced slenderness

$$\lambda_T = \left(f_y / \sigma_{crT}\right)^{1/2} \tag{34}$$

$$\sigma_{UT} / f_y = 1 \quad \text{for} \quad \lambda_T \le 0.45 \tag{35}$$

$$\frac{\sigma_{UT}}{f_y} = 1 - 0.53\left(\lambda_T - 0.45\right) \quad \text{for} \quad 0.3 \le \lambda_T \le 1.41 \tag{36}$$

$$\frac{\sigma_{UT}}{f_y} = \frac{1}{\lambda_T^2} \quad \text{for} \quad \lambda_T \ge 1.41 \tag{37}$$

6 Distortion constraint

In order to assure the quality of this type of welded structures large deflections due to weld shrinkage should be avoided. It has been shown that the curvature of a beam-like structure due to shrinkage of longitudinal welds can be calculated by relatively simple formulae (Farkas & Jármai 1998). The allowable residual deformations f_0 are prescribed by design rules. For compression struts Eurocode 3 (1992) prescribes $f_0 = L/1000$, thus the distortion constraint is defined as

$$f_{max} = CL^2 / 8 \le f_0 = L/1000 \tag{38}$$

where the curvature is for steels

$$C = 0.844x10^{-3} Q_T y_T / I_x \tag{39}$$

Q_T is the heat input caused by welding for Submerged Arc Welding (SAW) is

$$Q_T = 1{,}3 * 59{,}5 a_W{}^2 \tag{40}$$

and y_T is the weld eccentricity

$$y_T = y_G - t_F / 2 \tag{41}$$

I_x is the moment of inertia of the cross-section containing a stiffener and the base plate strip of width b in the case of trapezoidal stiffeners, instead of b the larger value of $a_3 = 300$ [mm] and $b_3 = b$ - 300 [mm] should be considered.

7 Cost function

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

$$K = K_m + K_f = k_m \rho V + k_f \sum T_i \tag{42}$$

or in another form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}(T_1 + T_2 + T_3) \tag{43}$$

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

$$T_1 = \Theta_d \sqrt{\kappa \rho V} \tag{44}$$

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. $T_3 \approx 0.3T_2$, thus,

$$T_2 + T_3 = 1.3 \sum C_{2i} a_{wi}^n L_{wi} \tag{45}$$

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 (1990) software, a_w is the weld dimension.

For SAW (Submerged Arc Welding) welded fillet welds

$$C_2 a_w^n = 0.2349x10^{-3} a_w^2 \tag{46}$$

8 The method of optimization

Rosenbrock's hillclimb (Rosenbrock 1960) 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 it takes small steps in direction of orthogonal coordinates during the search. The algorithm is modified that secondary searching is carried out to determine discrete values. The procedure finishes in case of convergence criterion is satisfied or the iterative number reaches its limit.

9 Numerical example

The given data are width B = 4200 [mm], length L = 9000 [mm], compression force N = 1.974x10^7 [N], Young modulus E = 2.1 x 10^5 [MPa], density ρ = 7.85x10^{-6} [kg/mm^3] and the yield stress is f_y = 355 [MPa]. The plate is simple supported on four edges. The unknowns – the thicknesses of the base plate and the stiffener and the number of the ribs - are limited in size as follows:

$$3 \le t_f \le 40 \text{ [mm]} \tag{47}$$

$$3 \le t_s \le 10 \text{ [mm]} \tag{48}$$

$$3 \le \varphi \le 15 \tag{49}$$

9.1 *Results for L- stiffeners*

Table 1. Optimization results with L- stiffeners without distortion constraint

k_f/k_m	t_f *[mm]*	t_s *[mm]*	φ	K/k_m *[kg]*
0	28	10	15	11728
1	40	10	4	13687
2	40	10	4	14773

Table 2. Optimization results with L- stiffeners with distortion constraint

k_f/k_m	t_f *[mm]*	t_s *[mm]*	φ	K/k_m *[kg]*
0	28	10	15	11728
1	37	10	6	13699
2	37	10	6	15198

9.2 *Results for trapezoidal stiffeners*

Table 3. Optimization results with trapezoidal stiffeners without distortion constraint

k_f/k_m	t_f *[mm]*	t_s *[mm]*	φ	K/k_m *[kg]*
0	27	10	7	11014
1	31	10	5	12987
2	37	10	3	14194

Table 4. Optimization results with trapezoidal stiffeners with distortion constraint

k_f/k_m	t_f *[mm]*	t_s *[mm]*	φ	K/k_m *[kg]*
0	27	10	7	11014
1	29	10	6	13228
2	29	10	6	15349

10 Conclusions

Cost comparisons of structural versions obtained for a given numerical example by minimum cost design show the following:
The results show that the trapezoidal stiffener is the most economic one.
The distortion constraint in this case is significant, since the weld length is relatively large. It needs higher strength, so the number of the stiffeners is higher. Therefore, the cost is higher too.

The cost difference between the lower and higher fabrication cost is significant, which emphasizes the necessity of optimization.

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