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Minimum Cost Design of Ring-stiffened Cylindrical Shells Subject to Axial Compression and External Pressure

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1. Abstract
The buckling strength for both load cases is calculated according to American Petroleum Institute design rules [1]. Since the API interaction curves are too complicate, i.e. need an iteration process, we use here the simpler linear interaction relation according to ECCS Recommendations [2]. The design constraints relate to the general and local shell buckling as well as to limitation of imperfections. Ring stiffeners of welded box section are used to avoid tilting of flat stiffeners. The effect of imperfections caused by shrinkage of circumferential welds is considered by an imperfection factor proposed by Farkas [3]. The cost function includes the material and fabrication costs. For the calculation of welding costs we use our recently developed formulae [4]. For the constrained function minimization two effective mathematical methods are used. Recently we have worked out the case of external pressure [5]. In an illustrative numerical problem the total shell length and the shell radius is given, the unknowns are the shell thickness, the dimensions and number of ring stiffeners. The cost comparison shows that, using the optimum number of stiffeners significant cost savings can be achieved in the design stage by optimization.

2. Keywords: welded structures, stiffened shells, shell buckling, minimum cost design, particle swarm optimization.

3. Design constraints

3.1 Axial compression (dimensions according to Fig. 1.) $\sigma_D = \frac{F}{2\pi R t} \le \eta\sigma_U$, (1)

3.2 External pressure and interaction

$$p_D = \gamma_b p \frac{R}{t} \le p_U \quad \text{if} \quad \sigma_D \le \frac{R p_U}{2t}, \tag{2}$$

$$\frac{p_D}{p_U} + \frac{\sigma_D - \frac{R p_U}{2t}}{\eta\sigma_U - \frac{R p_U}{2t}} \le 1 \quad \text{if} \quad \sigma_D > \frac{R p_U}{2t}, \tag{3}$$

$$p_U = \min(\eta_L \sigma_{UL}, \eta_G \sigma_{UG}), \tag{4}$$

$$\eta\sigma_U = \eta\alpha_{xg}(1.5 - 50\beta)0.605\frac{Et}{R}\sqrt{\overline{A}_r + 1}, \quad \overline{A}_r = \frac{A_r}{L_r t}, \tag{5}$$

A_r is the cross-sectional area of a ring-stiffener, L_r is the distance between ring-stiffeners. For $\overline{A}_r \ge 0.2$, $\alpha_{xg} = 0.72$.

η is the plastic reduction factor, β is the imperfection factor.

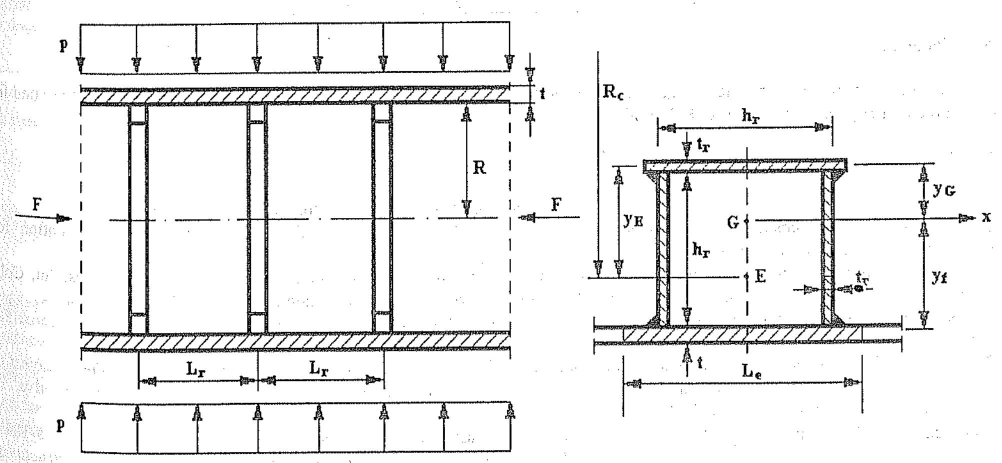

Figure 1. The ring-stiffened shell and the cross-section of a ring-stiffener

Data: length of shell L_b = 15 m, welded from 5 m long segments, radius of shell R = 1850 mm, intensity of the external pressure p = 0.5 MPa, the compression force is $F = 10^7$ N, yield stress of steel f_y = 355 MPa. To avoid tilting of ring-stiffeners, welded square box section is used, which is characterized by the height h_r and thickness t_r. Considering the local buckling constraint of the stiffener flange as active, we use the following correlation between the height and thickness

$$t_r = \delta_r h_r; \delta_r = 1/42\varepsilon; \varepsilon = \sqrt{235/f_y}; \delta_r = 1/34 . \quad (6)$$

The cross-sectional area of a stiffener is $A_r = 3h_r t_r = 3\delta_r h_r^2$. (7)

The ultimate local and global buckling strengths are

$\sigma_{UL} = \alpha_L p_{eL} \frac{R}{t} K_L$ $\alpha_L = 0.8$ is the imperfection factor, and for our numerical example $K_L = 1$. (8)

$$\sigma_{UG} = \frac{\alpha_G}{1.2} p_{eG} \frac{R}{t} K_G , \quad (9)$$

$\alpha_G = 0.8$ is the imperfection factor, the factor of 1.2 is recommended to avoid the mode interaction (coupled instability).

4. The cost function

The cost function includes the material, fabrication and painting costs: $K = K_M + K_F + K_P$. (10)

The fabrication cost function is formulated according to the fabrication sequence.

5. Optimization techniques and results

We have used two conceptually different optimization techniques. One of them is the Rosenbrock's Hillclimb technique [6], which is very quick, but reliable results need more starting points. The other one is an evolutionary technique, the Particle Swarm Optimization [7,8], which uses the swarm intelligence and has been modified to calculate the discrete optimum [9]. The difference between the best and worst solution indicated in the table is about 5 %. The best solution is written with bold letters.

Table 1. Discrete optima in the function of the number of stiffeners

n_r	t (mm)	t_r (mm)	K ($)
10	12	5	40182
11	12	5	40727
12	11	5	39233
13	11	5	39775
14	11	5	40317
15	**10**	**5**	**38823**
16	10	5	39362
17	10	5	39901
18	10	5	40439
19	9	5	38944
20	9	5	39480

6. Acknowledgements

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