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MINIMUM COST DESIGN OF A RING-STIFFENED CYLINDRICAL SHELL LOADED BY EXTERNAL PRESSURE

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Abstract: *The aim of this paper is to find the minimum cost of a ring-stiffened circular cylindrical shell loaded by external pressure. The minimum cost is given by the optimum dimensions, which can be calculated by an optimization technique. The calculation shows that the cost reduction has an effect reducing the shell diameter. The decrease in diameter restricted by a production constraint, that the inner diameter should be minimum of 2 m, to allow the welding and painting within the shell. This paper describes the optimization of this kind of structure considering cost calculation, which includes not only the material, but welding and painting costs as well.*
Keywords: *stiffened shell, minimum cost design, ring stiffeners*

1. INTRODUCTION

Cylindrical shell used in various structures, such as pipelines, offshore structures, columns and towers, bridges, silos, etc. shell is stiffened against buckling of the ring - stiffeners or stringers or perpendicular. The efficiency depends on the type of stiffening load. In many cases, the loads and brace studied in comparison with the cost of realistic numerical models and concluded by the structural design aspects of the optimized versions [1,2,3,4,5].
Since in Eurocodes [6] design method for stiffened shell buckling is not given, the design rules of Det Norske Veritas [7] are used. In this new investigation newer DNV shell buckling formulae are applied.
Optimum design of ring-stiffened cylindrical shells has been treated in [8, 9]. Results of model experiments for cylindrical shells used in offshore oil platforms have been published by Harding [10]. Cho and Frieze [11] have compared the proposed strength formulation with DNV rules, British Standard BS 5500 and experimental results.
The tripping of open section ring-stiffeners is treated by Huang and Wierzbicki [12]. Buckling solutions for shells with various end conditions, stiffener geometry and under various pressure distributions have been presented by Wang et al. [13] and by Tian et al. [14].
In Akl et al. [15] the adopted approach aims at simultaneously minimizing the shell vibration, associated sound radiation, weight of the stiffening rings as well as the cost of the stiffened shell. The production cost as well as the life cycle and maintenance costs, are computed using the Parametric Review of Information for Costing and Evaluation (PRICE) model (PRICE System, Mt. Laurel, N.J. 1999) without any detailed cost data.
In the optimization process the optimum values of shell diameter and thickness as well as the number and dimensions of ring-stiffeners are sought to minimize the structural volume or cost. In order to avoid tripping welded square box section stiffeners are used, their side length and thickness of plate elements should be optimized.
Besides the constraints on shell and stiffener buckling the fabrication constraints can be active. To make it possible the welding of stiffeners inside the shell the minimum shell diameter should be fixed (2000 mm). The calculations show that the volume and cost decreases when the shell diameter is decreased. Thus, the shell diameter can be the fixed minimum value. Another fabrication constraint is the limitation of shell and plate thickness (4 mm).
The remaining unknown variables can be calculated using the two buckling constraints and the condition of volume or cost minimization. The relation between the side length and plate thickness of ring-stiffeners is determined be the local buckling constraint. To obtain the optimum values of variables a relative simple systematic search method is used.

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

1.1 Characteristics of the optimization problem

Given data: external pressure intensity p = 0.5 N/mm^2, safety factor γ = 1.5, shell length L = 6000 mm, steel yield stress f_y = 355 MPa, elastic modulus E = 2.1x10^5 MPa, Poisson ratio ν = 0.3, density ρ = 7.85x10^{-6} N/mm^3, the cost constants are given separately.
Unknown variables: shell radius R, shell thickness t, number of spacing between ring-stiffeners n, thus, the spacing between stiffeners is $L_r = L/n$, the side length of the square box section stiffener h_r, the thickness of stiffener plate parts t_r.

1.2 Constraint on shell buckling

According to the DNV rules [7]

$$\sigma = \frac{\gamma p R}{t} \le \frac{f_y}{\sqrt{1+\lambda^4}}, \lambda = \sqrt{\frac{f_y}{\sigma_E}} \tag{1}$$

$$\sigma_E = \frac{C\pi^2 E}{12\left(1-\nu^2\right)}\left(\frac{t}{L_r}\right)^2 \tag{2}$$

$$C = \psi\sqrt{1+\left(\frac{\rho_1 \xi}{\psi}\right)^2}, \psi = 4, \rho_1 = 0.6 \tag{3}$$

$$\xi = 1.04\sqrt{Z}, Z = \frac{L_r^2}{Rt}\sqrt{1-\nu^2} \tag{4}$$

1.3 Constraint on ring-stiffener buckling

The moment of inertia of the effective stiffener cross-section should be larger than the required one

$$I_x \ge I_{req} \tag{5}$$

The effective shell length between ring-stiffeners is the smaller of

$$L_e = \frac{1.56\sqrt{Rt}}{1+12\frac{t}{R}} \text{ or } L_r \tag{6}$$

The distance of the gravity centre of the effective ring-stiffener cross-section (Fig. 1)

$$y_E = \frac{L_e t\left(h_r + \frac{t+t_r}{2}\right) + h_r t_r\left(h_r + t_r\right)}{3t_r h_r + L_e t} \tag{7}$$

The moment of inertia of the effective stiffener cross-section

$$I_x = \frac{t_r h_r^3}{6} + 2t_r h_r\left(\frac{h_r + t_r}{2} - y_E\right)^2 + h_r t_r y_E^2 + \frac{L_e t^3}{12} + L_e t\left(h_r + \frac{t+t_r}{2} - y_E\right)^2 \tag{8}$$

The relation between h_r and t_r is determined by the local buckling constraint

$$t_r \ge \delta h_r, \delta = \frac{1}{42\varepsilon}, \varepsilon = \sqrt{\frac{235}{f_y}} \tag{9}$$

For $f_y = 355 \quad \delta = 1/34$, the required t_r is rounded to the larger integer, but $t_{r\min}$ = 4 mm.
The required moment of inertia

$$I_{req} = \frac{\gamma p R R_0^2 L_r}{3E}\left[1.5 + \frac{3E y_E 0.005R}{R_0^2\left(\frac{f_y}{2} - \sigma\right)}\right] \tag{10}$$

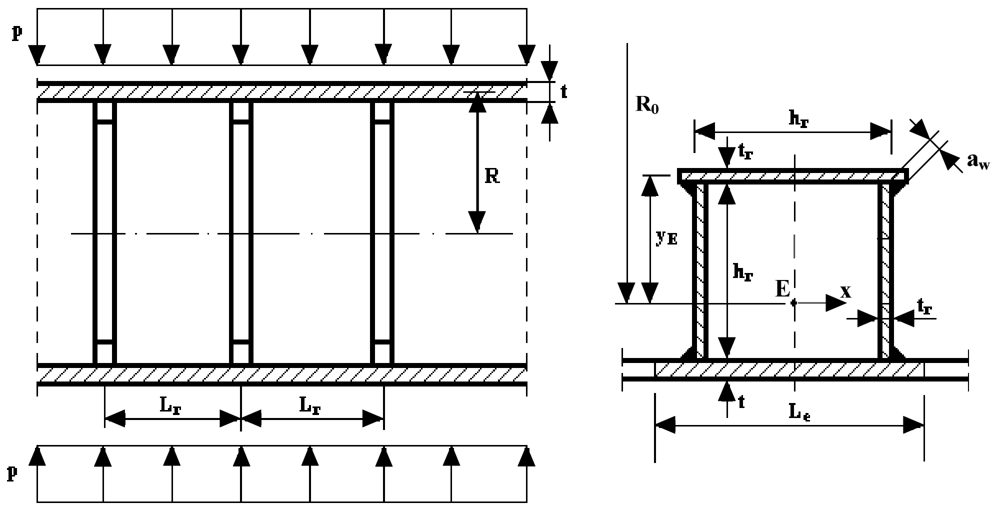

Fig. 1 Ring-stiffened cylindrical shell loaded by external pressure

1.4 The cost function

The cost function contents the cost of material, assembly, welding and painting and is formulated according to the fabrication sequence.
The cost of assembly and welding is calculated using the following formula [1,2,3,5]

$$K_w = k_w\left(C_1\Theta\sqrt{\kappa\rho V} + 1.3\sum_i C_{wi}a_{wi}^n C_{pi}L_{wi}\right) \tag{11}$$

where k_w [\$/min] is the welding cost factor, C_1 is the factor for the assembly usually taken as C_1 = 1 min/kg$^{0.5}$, Θ is the factor expressing the complexity of assembly, the first member calculates the time of the assembly, κ is the number of structural parts to be assembled, ρV is the mass of the assembled structure
The second member estimates the time of welding, C_w and n are the constants given for the specified welding technology and weld type, C_p is the factor of welding position (for downhand 1, for vertical 2, for overhead 3), L_w is the weld length, the multiplier 1.3 takes into account the additional welding times (deslagging, chipping, changing the electrode).

The fabrication sequence is as follows:

(a) Welding the unstiffened shell from curved plate parts of dimensions 6000x1500 mm and of number

$$n_p = \frac{2R\pi}{1500},$$

which should be rounded to the larger integer. Use butt welds of length

$$L_{w1} = n_p L, \quad \Theta = 3, \kappa_1 = n_p, V_1 = 2R\pi L t, k_W = 1, \tag{12}$$

welding technology SAW (submerged arc welding)

for t = 4-15 mm C_{W1} = 0.1346x10^{-3} and n_1 = 2, (13a) for $t > 15$ mm $C_{W1} = 0.1033\text{x}10^{-3}$ and $n_1 = 1.9$, (13b)

$$K_{W1} = k_W\left(\Theta\sqrt{\kappa_1 \rho V_1} + 1.3 C_{W1} t^{n_1} L_{W1}\right). \tag{14}$$

(b) Welding the ring-stiffeners separately from 3 plate parts with 2 fillet welds (GMAW-C –gas metal arc welding with CO_2):

$$K_{W2} = k_W\left(\Theta\sqrt{3\rho V_2} + 1.3x0.3394x10^{-3} a_W^2 L_{W2}\right) \tag{15}$$

where

$$V_2 = 4\pi h_r t_r\left(R - \frac{h_r}{2}\right) + 2\pi h_r t_r\left(R - h_r\right) \tag{16}$$

$$L_{W2} = 4\pi\left(R - h_r\right), a_W = 0.7 t_r \tag{17}$$

(c) Welding the (n+1) ring-stiffeners into the shell with 2 circumferential fillet welds (GMAW-C)

$$K_{W3} = k_W\left(\Theta\sqrt{(n+2)\rho V_3} + 1.3x0.3394x10^{-3} a_W^2 L_{W3}\right) \tag{18}$$

where

$$V_3 = V_1 + (n+1)V_2, L_{W3} = 4R\pi(n+1) \tag{19}$$

Material cost

$$K_M = k_M \rho V_3, k_M = 1 \text{ \$/kg} \tag{20}$$

Painting cost

$$K_P = k_P S_P, k_P = 28.8x10^{-6} \text{ \$/mm}^2, \tag{21}$$

$$S_P = 2R\pi L + 2R\pi\left[L - (n+1)h_r\right] + 2\pi\left(R - h_r\right)h_r(n+1) + 4\pi\left(R - \frac{h_r}{2}\right)h_r(n+1) \tag{22}$$

The total cost

$$K = K_M + K_{W1} + (n+1)K_{W2} + K_{W3} + K_P \tag{23}$$

1.5 Results of the optimization

In the following the minimum cost design is obtained by a systematic search using a MathCAD algorithm. For a shell thickness t the number of stiffeners n is determined by the shell buckling constraint (Eq. 1) and the stiffener dimensions (h_r and t_r) are determined by the stiffener buckling constraint (Eq. 5).

The search results for R = 1851 and 1500 (Tables 1 and 2) show that the volume and cost decreases when the radius is decreased. Thus, the realistic optimum can be obtained by taking the radius as small as possible. This minimum radius is determined by the requirement that the internal stiffeners should easily be welded inside of shell, i.e. R_{min} = 1000 mm. Therefore the more detailed search is performed for this radius (Table 3).

Table 1: Systematic search for R = 1850 mm. Dimensions are in mm. The minimum cost is marked by bold letters

t	n	$\sigma<\sigma_{adm}$ MPa	h_r	t_r	$I_x>I_{req}$ x10^{-4} mm^4	V x10^{-5} mm^3	K \$
11	7	126<152	180	6	3352>3341	10490	18770
12	6	115<143	180	6	3530>3502	10830	18640
13	5	106<124	190	6	4245>4014	11290	18650
14	4	99<109	200	6	5050>4888	11710	**18620**
15	4	92<121	200	6	5252>4718	12400	19390

Table 2: Systematic search for R = 1500 mm. Dimensions are in mm. The minimum cost is marked by bold letters

t	n	$\sigma<\sigma_{adm}$ MPa	h_r	t_r	$I_x>I_{req}$ x10^{-4} mm^4	V x10^{-5} mm^3	K $
8	10	140<157	160	5	1745>1616	6830	13890
9	8	125<140	160	5	1590>1550	6870	13250
10	6	112<115	160	5	1995>1885	7130	**12900**
11	5	102<106	150	5	2109>2102	7480	12950
12	5	93<120	160	5	2217>2003	8050	13570

It can be seen from Table 3 that the optima for minimum volume and minimum cost are different. It is caused by the larger value of fabrication (welding and painting) cost. The details of the cost for K = 7221 $ are given in Table 4.

Table 3: Systematic search for R = 1000 mm. Dimensions are in mm. Optima are marked by bold letters

t	n	$\sigma<\sigma_{adm}$ MPa	h_r	t_r	$I_x>I_{req}$ x10^{-4} mm^4	V x10^{-5} mm^3	K $
5	16	150<156	110	4	402>364	3192	8338
6	12	125<141	100	4	353>296	**3177**	7631
7	9	107<123	100	4	387>336	3343	7321
8	7	94<111	100	4	419>400	3579	7244
9	5	83<90	110	4	572>557	3854	**7221**
10	4	75<82	120	4	759>703	4186	7419
11	3	68<69	130	4	982>953	4505	7598

Table 4: Details of the minimum cost in $. (The sum of the welding and painting costs is $4196)

K_M	K_{W1}	$(n+1)K_{W2}$	K_{W3}	K_P	K
3025	673	474	665	2384	7221

6 CONCLUSIONS

The structural volume and the cost decrease when the shell radius is decreased. Thus, the shell radius should be taken as small as possible. The minimum radius is determined by the limitation that the internal ring-stiffeners should welded into the shell (R_{min} = 1000 mm).

The shell thickness and the number of ring-stiffeners can be calculated using the constraint on shell buckling. In order to avoid ring-stiffener tripping, welded square box section rings are used. The dimensions of the rings can be determined from the constraint on ring-stiffener buckling. The constraints on buckling are formulated according to the newer DNV design rules.

In the cost function the costs of material, assembly, welding and painting are formulated. The welding cost parts are calculated according to the fabrication sequence. The optima for minimum volume and minimum cost are different, since the fabrication cost parts are relative high as compared to the whole cost.

The ring-stiffening is very effective, since in the case of n = 1 (only 2 end stiffeners) the required shell thickness is t = 18 mm, the volume is V = 7144x10^{-3} mm^3 and the cost is K = $10450, i.e. the cost savings achieved by ring-stiffeners is (10450-7221)/10450x100 = 31%.

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