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## MINIMUM COST DESIGN OF RING-STIFFENED WELDED STEEL CYLINDRICAL SHELLS SUBJECT TO EXTERNAL PRESSURE

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### ABSTRACT

*In structural optimization the optimum values of design variables are sought, which minimize a cost function and fulfil design constraints. Here the variables are the thickness of the cylindrical shell as well as the dimensions and the number of stiffeners. The cost function includes the material, welding and painting costs and is formulated according to the fabrication sequence. The design constraints relate to local and general buckling strength, which is formulated according to rules of the American Petroleum Institute. Three mathematical methods are used for the constrained function minimization, namely the Rosenbrock Hillclimb algorithm, the Leap-frog method and the Differential Evolution technique. Numerical results for the respective optimization procedures are shown for a typical illustrative example.*

**Key Words:** *cylindrical shells, stiffened shells, welded structures, buckling of shells, structural optimization, cost function, constrained optimization algorithms.*

### 1. INTRODUCTION

Cylindrical shells are used in many engineering structures such as towers, large tubulars, offshore and submarine structures. The buckling behaviour of stiffened cylindrical shells has been investigated by several authors, e.g. Harding [1], Dowling and Harding [2], Ellinas et al [3], Frieze et al [4], Shen et al [5], Tian et al [6]. The plastic tripping of ring-stiffeners has been analysed by Huang and Wierzbicki [7]. The determination of the minimum cost design has not yet been dealt with.

A cost function has been developed for welded structures by the first and second authors [8, 9], which enables one to compare different structural versions and to achieve cost savings during the design stage. This cost function includes material and

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fabrication (assembly, welding, painting) costs.

Since this cost function and the design constraints are highly nonlinear, specialized and robust nonlinear mathematical methods are needed for the constrained function minimization. In this study the Rosenbrock Hillclimb method [8], the Leap-frog algorithm [10-12] and the Differential Evolution technique [13,14] are used. The design constraints are formulated according to API rules [15]. A typical numerical example is used for illustration of the respective optimization procedures.

## 2. GEOMETRICAL CHARACTERISTICS

The ring stiffened cylindrical shell considered in this study can be seen in Figure 1. Here the design variables are the shell thickness, denoted by  $t$ , and the height of the square box section stiffener, indicated by  $h_r$ . The optimum number of stiffeners  $n_r$  is also to be determined.

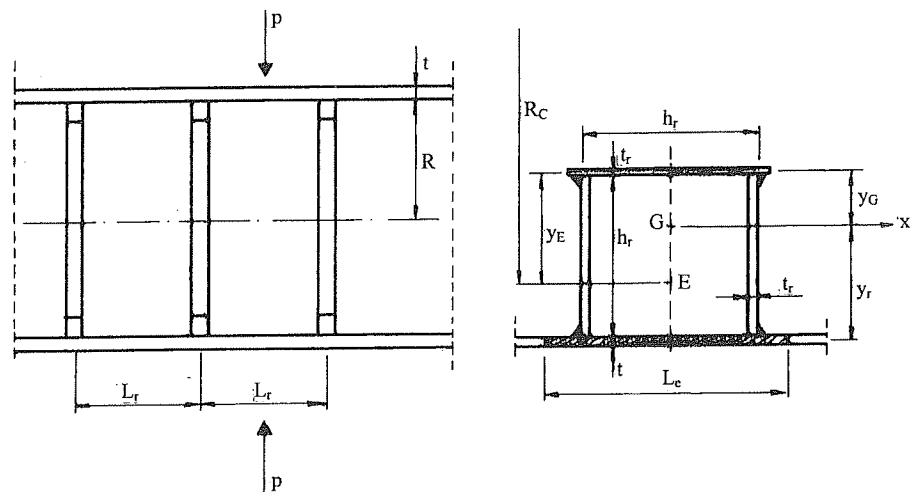


Fig. 1. Ring stiffened cylindrical shell

The length of the shell is given as  $L_b = 15$  m, welded from 5 m long segments, radius of shell  $R = 1850$  mm, intensity of the external pressure  $p = 0.5$  MPa, and yield stress of steel  $f_y = 355$  MPa. To avoid tilting of the ring-stiffeners, welded square box sections are used, each of which is characterized by height  $h_r$  and thickness  $t_r$ . Considering the local buckling constraint of the stiffener flange as active, we use the following relationship between the height and thickness

$$t_r = \delta_r h_r \quad (1)$$

where  $\delta_r = 1/42\varepsilon$  and  $\varepsilon = \sqrt{235/f_y}$

The cross-sectional area of a stiffener is

$$A_r = 3h_r t_r = 3\delta_r h_r^2 \quad (2)$$

The vertical distance of the gravity center of the stiffener box section  $G$  (only stiffener plates are considered) from the upper middle line of the stiffener plate is given by (Fig. 1),

$$y_G = \frac{h_r}{3}; y_r = \frac{2h_r}{3} + \frac{t}{2} \quad (3)$$

and the position of the gravity center  $E$  of the stiffener box section and the effective shell plate, from the upper middle line of the stiffener plate, is given by

$$y_E = \frac{L_c t \left( h_r + \frac{t}{2} \right) + \delta_r h_r^3}{3\delta_r h_r^2 + L_c t} \quad (4)$$

where

$$L_c = 1.1\sqrt{2Rt} \quad \text{if} \quad M_x > 1.56 \quad (5a)$$

$$L_c = L_r \quad \text{if} \quad M_x \leq 1.56 \quad (5b)$$

and where

$$L_r = \frac{L_b}{n_r + 1} \quad \text{and} \quad M_x = \frac{L_r}{\sqrt{Rt}} \quad (5c)$$

The distance of the centroid  $E$  of the cross-section consisting of the stiffener and the effective part of shell is given by

$$R_c = R - \left( h_r - y_E + \frac{t}{2} \right) \quad (6)$$

The moment of inertia of the stiffener and the effective part of shell is

$$I_{er} = \frac{\delta_r h_r^4}{6} + A_r y_r^2 K_G + \frac{L_c t^2}{12} \quad (7a)$$

$$\text{where } K_G = \frac{L_c t}{A_r + L_c t} \quad (7b)$$

### 3. DESIGN CONSTRAINTS

#### 3.1 Constraint on local shell buckling

The local shell buckling constraint is given by

$$\gamma_b P \frac{R}{t} \leq \eta_L \sigma_{UL} \quad (8)$$

where  $\gamma_b = 1.5$  is the safety factor and the plasticity reduction factor  $\eta_L$  is calculated as a function of  $\delta_L = \sigma_{UL} / f_y$  as follows

$$\eta_L = 1 \quad \text{if} \quad \delta_L \leq 0.55 \quad (9a)$$

$$\eta_L = \frac{0.45}{\delta_L} + 0.18 \quad \text{if} \quad 0.55 < \delta_L \leq 1.6 \quad (9b)$$

$$\eta_L = \frac{1.31}{1 + 1.15\delta_L} \quad \text{if} \quad 1.6 < \delta_L < 6.25 \quad (9c)$$

$$\eta_L = \frac{1}{\delta_L} \quad \text{if} \quad \delta_L \geq 6.25 \quad (9d)$$

In the above the ultimate local buckling strength  $\sigma_{UL}$  is determined by

$$\sigma_{UL} = \alpha_L p_{eL} \frac{R}{t} K_L \quad (10)$$

where  $\alpha_L = 0.8$  is the imperfection factor, and for the numerical example to be considered here  $K_L = 1$ , and further

$$p_{eL} = \frac{1.27E}{A^{1.18} + 0.5} \left( \frac{t}{R} \right)^2 \quad \text{if} \quad M_x > 1.5 \text{ and } A = M_x - 1.17 < 2.5 \quad (11a)$$

$$p_{eL} = \frac{0.92E}{A} \left( \frac{t}{R} \right)^2 \quad \text{if} \quad 2.5 < A < 0.208R/t \quad (11b)$$

$$p_{eL} = 0.836C_p^{-1.061} E \left( \frac{t}{R} \right)^3 \quad \text{if} \quad 0.208 < C_p = \frac{A}{R/t} < 2.85 \quad (11c)$$

$$p_{eL} = 0.275E \left( \frac{t}{R} \right)^3 \quad \text{if} \quad C_p > 2.85 \quad (11d)$$

and  $E$  is the Young's modulus for steel.

### 3.2 Constraint on general shell buckling

The general shell buckling constraint is

$$\gamma_b p \frac{R}{t} \leq \eta_G \sigma_{UG} \quad (12)$$

where the plasticity reduction factor  $\eta_G$  is calculated as a function of  $\delta_G = \sigma_{UG} / f_y$ , with the identical formulae as in the case of  $\eta_L$  (Eqs 9a,b,c,d), but with  $\sigma_{UG}$  replacing  $\sigma_{UL}$  and completed by

$$\sigma_{UG} = \frac{\alpha_G}{1.2} p_{eG} \frac{R}{t} K_G \quad (13)$$

where  $\alpha_G = 0.8$  is the imperfection factor and  $K_G$  is defined in Eq. (7). The factor of 1.2 is recommended to avoid the mode interaction (coupled instability). The quantity  $p_{eG}$  appearing in (13) is defined by

$$p_{eG} = \frac{E \frac{t}{R} \lambda_G^4}{(n^2 - 1)(n^2 + \lambda_G^2)^2} + \frac{EI_{cr}(n^2 - 1)}{L_r R_c^2 R} \quad (14)$$

where

$$\lambda_G = \frac{\pi R}{L_b} = \frac{1850\pi}{15000} = 0.3875,$$

and  $n$  is that integer value, which gives the minimum value of  $p_{eG}$ ,  $n_{min} = 2$ ,  $n_{max} = 10$ . For the case considered here  $n = 2$  is used.

#### 4. COST FUNCTION

The cost function  $K$  includes the material  $K_M$ , fabrication  $K_F$  and painting costs  $K_P$ :

$$K = K_M + K_F + K_P \quad (15)$$

The material cost is

$$K_M = k_M \rho V \quad (16)$$

where  $k_M$  (\$/kg) is the material cost factor and the volume of the structure is

$$V = 2\pi R t L_b + n_r \left[ 4\pi \delta_r h_r^2 \left( R - \frac{h_r}{2} \right) + 2\pi \delta_r h_r^2 (R - h_r) \right] \quad (17)$$

where  $n_r$  is the number of ring-stiffeners.

For the fabrication phase the cost is

$$K_F = k_F \left( \Theta_w \sqrt{\kappa \rho V} + 1.3 C_w a_w^n L_w \right) \quad (18)$$

where  $k_F$  (\$/min) is the fabrication cost factor,  $\Theta_w = 3$  is the difficulty factor expressing the complexity of a structure with regard to the assembly. The first term calculates the time for assembly and tacking, where  $\kappa$  is number of structural parts to be assembled, and  $\rho$  denotes the density of steel. The second term calculates the time of welding and of additional tasks such as changing the electrode, deslagging and chipping. The additional tasks are about 30% of the welding time, therefore the welding time is multiplied by 1.3.  $L_w$  is the weld length,  $a_w$  is the weld size.  $C_w$  and  $n$  are given for different welding technologies and weld type (butt or fillet).

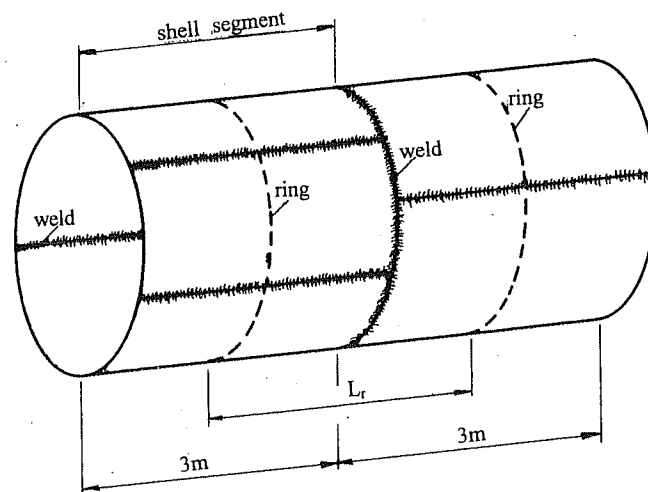


Fig. 2. Shell segments of the cylindrical shell

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

(1) Welding of a shell segment from 3 parts without stiffeners with GMAW-C (Gas Metal Arc Welding with CO<sub>2</sub>) butt welds, and where the number of structural parts to be assembled is 3:

$$K_{F1} = 3\sqrt{3\rho V_S} + 1.3 \times 0.2245 \times 10^{-3} t^2 \times 3L_S \quad (19)$$

where  $L_S = 3000$  mm and  $V_S = 2R\pi L_S$ .

(2) Welding of a ring-stiffener from 3 plate parts with 2 fillet welds of GMAW-C, weld size  $a_W = 0.7t_r$ :

$$K_{F2} = 3\sqrt{3\rho V_r} + 1.3 \times 0.3394 \times 10^{-3} a_W^2 \times 4\pi(R - h_r) \quad (20)$$

where

$$V_r = 4\pi\delta_r h_r^2 \left( R - \frac{h_r}{2} \right) + 2\pi\delta_r h_r^2 (R - h_r).$$

(3) Welding of  $n_r/5$  stiffeners to a shell segment with 2 fillet welds of size  $a_W = 0.7t_r$ , GMAW-C:

$$K_{F3} = 3\sqrt{\left(\frac{n_r}{5} + 1\right)\rho V_3} + 1.3 \times 0.3394 \times 10^{-3} a_W^2 \times 4\pi R n_r / 5 \quad (21)$$

where  $V_3 = V_S + V_r n_r / 5$ .

(4) Welding of 5 stiffened shell segments together with butt welds GMAW-C:

$$K_{F4} = 3\sqrt{5\rho 5V_3} + 1.3 \times 0.2245 \times 10^{-3} t^2 \times 8R\pi \quad (22)$$

Total fabrication cost is therefore

$$K_F = k_F (5K_{F1} + n_r K_{F2} + 5K_{F3} + K_{F4}) \quad (23)$$

Instead of (16) the expression used here for the total material cost is

$$K_M = k_M \rho 5V_3 \quad (24)$$

The painting cost is

$$K_p = k_p \left[ 2R\pi L_b + 2R\pi(L_b - n_r h_r) + 2\pi(R - h_r)n_r h_r + 4\pi n_r h_r \left( R - \frac{h_r}{2} \right) \right] \quad (25)$$

The total cost  $K$  given by (15) is clearly a function of the design variables  $h_r$  and  $t$ , and the number of stiffeners  $n_r$ , and can now be computed by summing (23), (24) and (25).

In the numerical example considered here the following cost factors are used:  $k_M = 1.0$  \$/kg,  $k_F = 1.0$  \$/min,  $k_p = 28.8 \times 10^{-6}$  \$/mm<sup>2</sup>,  $\rho = 7850$  kg/m<sup>3</sup> and  $E = 2.1 \times 10^5$  MPa.

## 5. OPTIMIZATION METHODS AND RESULTS

For the constrained function minimization the following three mathematical methods are used.

### 5.1 Hillclimb method

The first method used is the Rosenbrock method [8], which has been modified to be able to handle discrete values. This method is a direct search mathematical programming method requiring no derivatives. Instead of performing continuous line searches, the algorithm takes discrete steps during searches in orthogonal search directions. In each iteration, the procedure searches successively along  $n$  linearly independent and orthogonal directions, where  $n$  here denotes the number of real variables  $(x_1, x_2, \dots, x_n)$ . When a new point is reached at the end of an iteration, a new set of orthogonal search vectors are constructed. Boundary zones are introduced to slow down the algorithm when it approaches the constraint boundaries. A modified objective function, using penalty functions, are used to handle the constraints. Instead of continually searching in the co-ordinate space corresponding to the directions of the independent variables, the method achieves an improvement after one cycle of co-ordinate searches by lining the search directions up into an orthogonal system, with the overall step of the previous stage as the first building block for the new set of orthogonal directions. After each iteration  $k$ , Rosenbrock's method locates the next design vector  $\mathbf{x}^{(k+1)}$  after completing unidimensional searches from the previous point  $\mathbf{x}^{(k)}$  along a set of orthonormal directions.

### 5.2 Leap-frog method

The dynamic trajectory method, more commonly known as the leap-frog method [10, 11], was originally proposed for the unconstrained minimization of a scalar function  $f(\mathbf{x})$  of  $n$  real variables  $\mathbf{x} = \{x_1, x_2, \dots, x_n\}$ . The algorithm has recently been modified [12] to handle constraints by means of a penalty function formulation. The method possesses the following characteristics: it uses only function *gradient* information  $\nabla f(\mathbf{x})$ , requires no explicit line searches, is extremely robust and handles steep valleys and discontinuities in functions and gradients with ease. The method seeks *low local minima* and can thus be used as a basic component in a methodology for global optimization. Although, for very high accuracy, it may not be as efficient as classical methods when applied to smooth and near-quadratic functions, it is particularly robust and reliable in dealing with the presence of numerical noise in the objective and constraint functions. The method usually converges very quickly to the neighbourhood of the optimum. This is because the fundamental physical principles underlying the method, ensures controlled and stable convergence along a dynamic trajectory towards the optimum.

### 5.3 Differential evolution technique

Price and Storn introduced the Differential Evolution (DE) algorithm in the 90's [13,14]. This method was originally designed to operate on continuous variables, but its improved variant is capable of handling discrete variables as well as mixed design variables. At first sight it seems that, as a case of genetic algorithms (GA's), an advantage of DE is that there is no need for complicate coding. The DE scheme for handling discrete variables is as follows:

Generally, the function to be optimized,  $f$  is of the form:

$$f(y_i) \quad i = 1, \dots, n \quad (26)$$

where  $\mathbf{y} = \mathbf{x} = (x_1, x_2, \dots, x_n) \in R^n$  for continuous variables

$y = \{DISC(x_1), DISC(x_2), \dots, DISC(x_n)\} \in R^n$  for discrete variables  
 DISC() is a function for converting the real value of  $x_i$  to a closest, higher discrete value.  
 Available discrete values are set in advance.  $n$  is the number of design variables.

In order to establish a starting point for optimum seeking, the population must be initialized. The members of initial population  $P_{G=0}$  are chosen randomly within the given boundary constraints.

$$P_0 = x_{i,j,0} = rand_j[0,1] \cdot (x_j^{(U)} - x_j^{(L)}) + x_j^{(L)} \quad i = 1, \dots, NP, \quad j = 1, \dots, n \quad (27)$$

where  $rand_j[0,1]$  denotes a uniformly distributed random value within the range:  $[0.0, 1.0]$ .  $x_j^{(U)}$  is upper and  $x_j^{(L)}$  is lower boundary value for  $x_j$ .  $x_j^{(L)}$  should be lower than the lowest discrete value.  $NP$  is size of the population, which remains constant during the search process. DE's self-referential population reproduction scheme is different from other evolutionary algorithms. From the 1<sup>st</sup> generation forward, vectors in the current population,  $P_G$  are randomly sampled and combined to create candidate vectors for the subsequent generation,  $P_{G+1}$ . The population of candidate, or "trial" vectors,  $P'_{G+1} = U_{i,G+1} = u_{i,j,G+1}$ , is generated as follows:

$$\text{If } rand_j[0,1] \leq CR \text{ or } j=k \text{ then } u_{i,j,G+1} = DISC(v_{i,j,G+1}) \quad (28)$$

$$v_{i,j,G+1} = x_{r_3,j,G} + F \cdot (x_{r_1,j,G} - x_{r_2,j,G})$$

otherwise  $u_{i,j,G+1} = x_{i,j,G}$ ,

where  $i = 1, \dots, NP$ ,  $j = 1, \dots, n$

$k \in \{1, \dots, n\}$ , random parameter index, chosen once for each  $i$

$r_1, r_2, r_3 \in \{1, \dots, NP\}$ , randomly selected, except:  $r_1 \neq r_2 \neq r_3 \neq i$

$CR \in \{0, \dots, 1\}$ ,  $F \in \{0, \dots, 1+\}$

considering that

$$\text{If } u_{i,j,G+1} < x_j^{(L)} \text{ then } u_{i,j,G+1} = DISC(x_j^{(L)}) \text{ or If } u_{i,j,G+1} > x_j^{(U)} \quad (29)$$

$$\text{then } u_{i,j,G+1} = DISC(x_j^{(U)}) \quad \text{otherwise } u_{i,j,G+1} = u_{i,j,G+1}.$$

$F$  and  $CR$  are DE control parameters. Like  $NP$ , both values remain constant during the search process. The upper limit on  $F$  has been empirically determined.  $CR$  is a real-valued crossover factor that controls the probability that a trial vector parameter will come from the randomly chosen, mutated vector,  $v_{i,j,G+1}$ , instead of the current vector,  $x_{i,j,G}$ . Generally, both  $F$  and  $CR$  affect the convergence velocity and robustness of the search process.

The population for the next generation,  $P_{G+1}$ , is selected from the current population,  $P_G$ , and the child population, according to the following rule:

$$\text{If } f(u_{i,G+1}) \leq f(X_{i,G}) \text{ then } X_{i,G+1} = u_{i,G+1}, \quad \text{otherwise } X_{i,G+1} = X_{i,G}. \quad (30)$$

#### 5.4 Optimization and results

The continuous optima obtained by means of the three techniques are shown in Table 1-2 for different numbers of stiffeners. The overall optimum solutions are marked by bold numbers.

Table 1. The continuous / discrete optima for different numbers of stiffeners obtained by the Hillclimb technique

$n_r$	$h_r$ (mm)	$t$ (mm)	$K$ (\$)
5	168.9 / 165	16.1 / 16	44056 / 45970
10	164.0 / 160	11.9 / 12	39948 / 40027
11	154.0 / 155	11.9 / 12	39969 / 40336
12	160.0 / 160	11.1 / 11	39087 / 39160
13	164.1 / 160	10.4 / 11	38907 / 39796
14	159.8 / 155	10.3 / 11	38898 / 40010
<b>15</b>	<b>161.0 / 160</b>	<b>9.8 / 10</b>	<b>38656 / 38964</b>
16	164.1 / 160	9.5 / 10	39036 / 39597
17	143.3 / 140	10.5 / 11	39531 / 40357
20	153.8 / 155	8.9 / 9	39277 / 39456

Table 2. The continuous optima for different numbers of stiffeners determined by the Leap-frog / Differential Evolution techniques (only different solutions are given separately)

$n_r$	$h_r$ (mm)	$t$ (mm)	$K$ (\$)
5	168.9	15.1	44054
10	163.8	11.6	39441
11	162.9	11.2	39094
12	162.0	10.8	38847
13	161.2	10.4	38682
14	160.5	10.1	38586
<b>15</b>	<b>159.8</b>	<b>9.8</b>	<b>38548/38547</b>
16	159.2	9.5	38559
17	158.7	9.3	38613
18	158.2	9.05	38706
19	155.6/155.2	8.95/8.9	38828
20	152.3/152.9	8.91/8.9	38956/38955

The number of steps for Leap-frog was between 209-389. The starting point was always  $\mathbf{x}^0=[200, 20]$ . The number of function evaluations for the Hillclimb algorithm was between 250-1500 per run and for the DE it is 2000-2500, if the population size is 12 and the number of generation is about 180-200.

It can be seen that the optimum number of stiffeners is 15. It should be noted that, in the case of the fabrication sequence described above, only  $n_r = 5, 10$  and 15 can be practically realized. The corresponding optima are very close to each other for the different techniques. The Leap-frog and the Differential evolution methods give almost identical optima.

Comparing the ring-stiffened design with an unstiffened one, it is calculated that, for unstiffened version a shell thickness of  $t = 34$  mm is required. In the case considered here, where  $M_x = 59.81$ ,  $A = 58.64$ ,  $C_p = 1.1094$ ,  $p_{cl} = 0.9761$  MPa and  $1.5 \times 0.5 = 0.75 < 0.8 \times 0.9761 = 0.78$  MPa, is satisfactory. The costs of the unstiffened version are as follows:  $K_{F1} = 2140$  \$,  $K_{F4} = 9916$  \$,  $K_F = 20616$  \$,  $K_M = 46535$  \$,  $K_P = 10043$  \$, the total cost is  $K = 77194$  \$. This is  $100(77194-39026)/39026 = 98\%$  higher than that of the stiffened version.

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