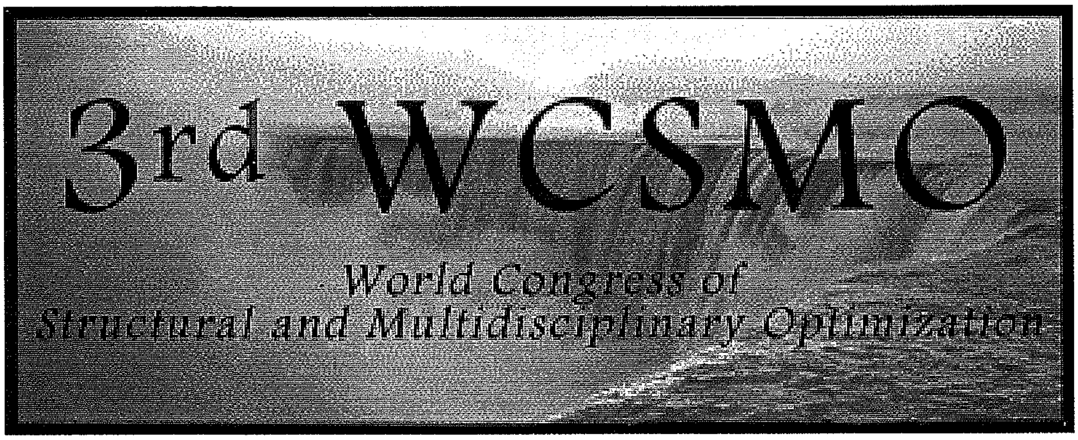

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Optimum design of welded stiffened plates loaded by hydrostatic normal pressure

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1. Abstract

The optimal positions of horizontal stiffeners are computed considering the condition that the base plate parts, having equal thicknesses and loaded by factored bending moments, should be stressed to yield strength. The trapezoidal stiffeners are designed for bending using the stress and local buckling constraints. The optimal number of stiffeners is determined on the basis of material and fabrication cost calculations. It is shown by a numerical example that the non-equidistant stiffener arrangement gives 18% weight and 12-14% cost savings compared to the equidistant one.

2. Keywords

Stiffened plates, minimum cost design, welded structures, hydrostatic pressure

3. Introduction

In the present study the stiffened plate consists of a square base plate of constant thickness and horizontal stiffeners only. This arrangement is selected for its relative simplicity regarding the fabrication. When the stiffeners are equally spaced only the lowest part of the base plate can be stressed to yield strength, thus, these solutions are not optimal. The optimum position of stiffeners can be calculated on the basis of the condition that all parts of the base plate, having the same thickness, should be stressed to yield strength.

For the calculation of the maximum bending moments in simply supported base plate parts due to hydrostatic pressure the values given in tabulated form in [1] are approximated by nonlinear functions of the ratio of side dimensions b/a (Fig.1). The optimum stiffener positions characterized by x_j (Fig.2) are calculated from a set of nonlinear equations using the MathCAD software. Trapezoidal stiffeners are considered (Fig.3) and designed for bending considering also the local buckling constraint.

4. Optimum position of horizontal stiffeners

The thickness of each base plate part can be calculated from the stress constraint

$$\frac{6M}{t_F^2} \le f_y \qquad (1)$$

where M is the factored bending moment, t_F is the base plate thickness, f_y is the yield stress.

The maximum bending moment in a simply supported rectangular plate due to hydrostatic pressure can be obtained using tables given in the book [1] in the form of

$$M_{max} = k_1 p a^2 \qquad (2)$$

where k_1 is given by tabulated values depending on the ratio b/a.

In a plate stiffened by horizontal stiffeners the upper plate part is loaded by a distributed load of triangular shape in which the maximum bending moment arises at point 1 in distance of $a/8$ from the center point O (Fig.1). This bending moment is given by k_1. Tabulated values of k_1 can be approximated in function of $x_0 = b/a$ in the following form

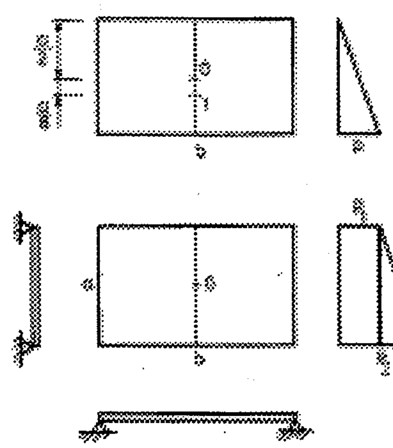

Figure 1. Points where the maximum bending moment arises

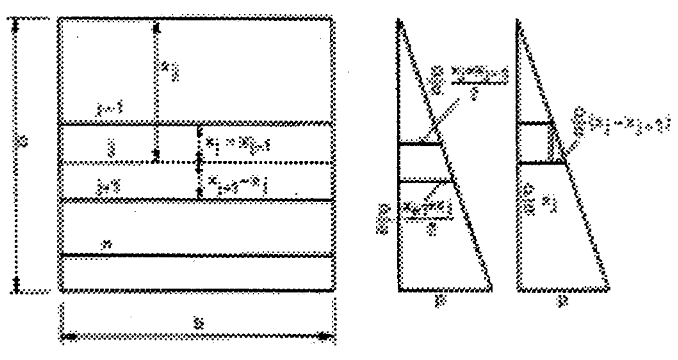

Figure 2. The distances of stiffeners and the pressures for the calculation of bending moments acting on stiffeners

$$10^2 k_1 = \frac{c_1}{1 + d_1 \exp(-f_1 x_0)} \; ; \quad c_1 = 6.2877, \quad d_1 = 12.2974, \quad f_1 = 2.1664 \qquad (3)$$

The maximum bending moment in the plate parts loaded by a distributed load of trapezoidal shape, given by p_1 and p_2, can be calculated adding two moments as follows: one moment is due to uniform loading p_1 and the second is due to triangular loading $p_2 - p_1$. Calculation shows that the resulting moment is larger for point O than that for point 1, thus we use tabulated values for point O.

$$M = k_2 p_1 a^2 + k_3 (p_2 - p_1) a^2 \qquad (4)$$

where k_2 and k_3 can be approximated by functions as follows

$$10^2 k_2 = \frac{c_2}{1 + d_2 \exp(-f_2 x_0)} \; ; \quad c_2 = 12.3044, \quad d_2 = 13.7725, \quad f_2 = 2.1695 \qquad (5)$$

$$10^2 k_3 = \frac{c_3}{1 + d_3 \exp(-f_3 x_0)} \; ; \quad c_3 = 6.1496, \quad d_3 = 13.8096, \quad f_3 = 2.1709 \qquad (6)$$

In the case of n stiffeners the position of the jth stiffener is characterized by x_j (j = 1...n) (Fig.2).
Using these formulae n equations can be written expressing that these bending moments should be equal to each other, since the thickness of the base plate parts is the same.
The set of equations for unknowns x_j is the following:

$$k_1 x_1^3 = k_2 x_1 (x_2 - x_1)^2 + k_3 (x_2 - x_1)^3 \quad \text{in } k_1 \; x_0 = b/x_1 \qquad (7)$$

$$k_1 x_1^3 = k_2 x_{j-1} (x_j - x_{j-1})^2 + k_3 (x_j - x_{j-1})^3 \; ; \text{ in } k_2 \text{ and } k_3 \quad x_0 = b/(x_j - x_{j-1}) \qquad (8)$$

$$k_1 x_1^3 = k_2 x_n (a - x_n)^2 + k_3 (a - x_n)^3 \qquad (9)$$

This set of equations is solved by MathCAD software.
Having obtained the optimal stiffener positions, the required dimensions of trapezoidal stiffeners according to [2] (Fig.3.) can be calculated.

5. The cost function

We have developed on the basis of COSTCOMP software [3,4] a cost function containing the material and fabrication cost [5]

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left[C_1 \Theta_d (\kappa \rho V)^{0.5} + 1.3 T_2\right] \qquad (10)$$

where ρ is the material density, k_f and k_m are the fabrication and material cost factors, respectively, κ is the number of structural elements to be assembled, V is the volume of the structure, Θ_d is the difficulty factor expressing the complexity of a structure (planar or spatial, using simple plates or profiles), the coefficient for the preparation time is C_1 = 1.0 min/kg$^{0.5}$. To give internationally usable results, the ratio of k_f/k_m is varied in a wide range. For steel k_m = 0.5-1.2 \$/kg, for fabrication including overheads k_f = 0-60\$/manhour = 0-1\$/min, thus, the ratio may vary in the range of 0 - 2 kg/min, the value of 0 corresponds to the minimum weight design. The welding time is given by

$$T_2 = \sum_i C_{2i} a_{Wi}^n L_{Wi} \qquad (11)$$

the factor of 1.3 expresses that the additional time for chipping, deslagging and changing the electrode is approximated by $T_3 = 0.3 T_2$. The formulae for $C_2 a_W^n$ are given for various welding technologies and weld types. a_W is the weld size, L_W is the weld length.

6. Numerical example

To illustrate the optimization procedure the following data are taken: $a = b = 6$ m, the intensity of the factored hydrostatic load is $p = \gamma p_0 = 1.5 x 0.036 = 0.054$ N/mm^2, f_y = 235 MPa, ρ =7850 kg/m^3. In the case of the base plate with horizontal stiffeners, it is assumed that the base plate is butt-welded from plate strips of width 1500 mm. A stiffener is welded to the base plate with 2 fillet welds of size $a_W = 0.7 t_S$. The welding times are calculated with the following data: use GMAW-M welding technology (Gas Metal Arc Welding with mixed gas). For

a_W = 10-40 mm X butt welds $\quad C_2 a_W^n = 0.1433\, a_W^{1.9035}$

a_W = 4-15 mm V butt welds $\quad C_2 a_W^n = 0.1861 a_W^2$

a_W = 0-15 mm fillet welds $\quad C_2 a_W^n = 0.3258 a_W^2$

and L_W is calculated in m. The difficulty factor is chosen for $n = 0$ (base plate without stiffeners) $\Theta_d = 2$, and for n>0 $\Theta_d = 3$.

The results of computations are summarized in Fig. 4. It can be seen that the optimum number of stiffeners is 7 or 8.

For 8 stiffeners K/k_m values for k_f/k_m =0, 1 and 2 are 3937, 6111 and 8285 respectively. It should be noted that, in the case of 8 stiffeners equidistantly arranged, the K/k_m -values for k_f/k_m = 0, 1 and 2 are as follows: 4639, 6972 and 9305, respectively. It means that the non-equidistant arrangement results in savings of 18, 14 and 12%, respectively.

7. Conclusions

The optimum horizontal stiffener positions can be calculated on the basis of the condition that each base plate part, having the same thickness and loaded by bending, should be stressed to yield strength. This non-equidistant stiffener distribution is more economic than the equidistant one. This economy can be verified by cost calculations. In the illustrative numerical example it is shown that the optimum number of stiffeners is 7 or 8 and the non-equidistant stiffener arrangement is 18% lighter and 12-14% cheaper than the equidistant one.

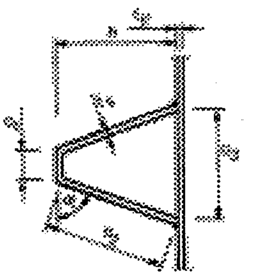

Figure 3. Dimensions of a trapezoidal stiffener

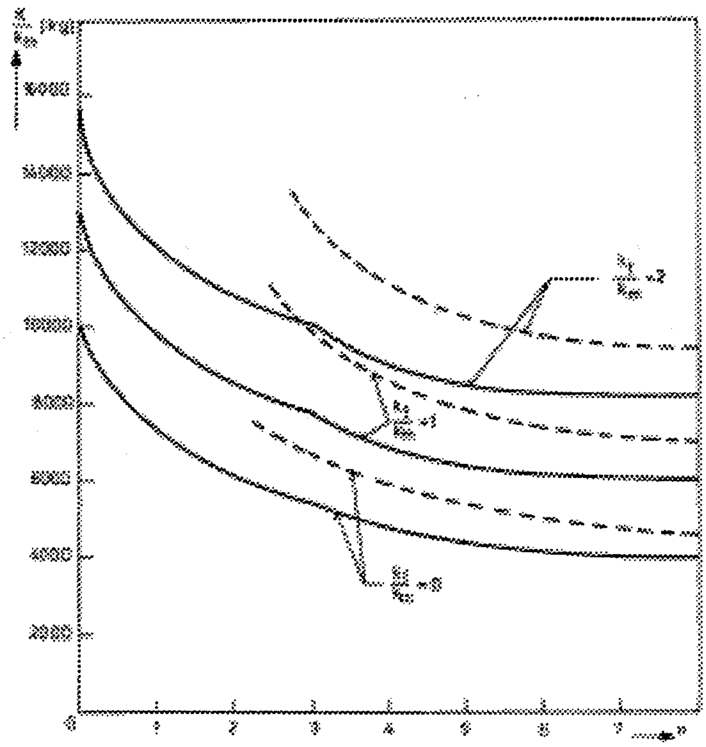

Figure 4. Costs in the function of number of stiffeners in the case of k_f/k_m = 0, 1 and 2. Continuous and dashed lines show the results for non equidistant and equidistant stiffener arrangements, respectively.

The difference between the costs of non-equidistant solutions with 3 or 8 stiffeners for k_f/k_m = 1 is (7749-6111)/6111x100 = 27%, thus, the search for the optimum number of stiffeners results in significant cost savings.

8. Acknowledgement

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