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# THE EFFECT OF LOW COST TECHNOLOGIES IN THE DESIGN OF WELDED STRUCTURES

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## ABSTRACT

A contribution to the interaction of design and fabrication is presented. Cost functions are formulated for simple structures welded with different technologies by using the COSTCOMP software. In the case of an illustrative numerical example of a stiffened plate the FSQP mathematical optimization computer method is used to determine the optimal structural versions which minimize the cost function and fulfil the design constraints on global and local buckling. The comparison of optimal versions shows the cost savings achievable by applying the low cost automatic submerged arc welding instead of manual or semi-automatic methods. Since the optimal structural dimensions are different for various welding methods the designer should consider the fabrication aspects as well.

## INTRODUCTION

The economy of welded structures plays an important role in the research and production, therefore it is included in the work of IIW Commission XV.It needs a cooperation of designers and manufacturers, so it is a main task for the new Subcommission XV-F "Interaction of design and fabrication".

The decrease of costs may be achieved by various ways. One efficient way is to use the mathematical optimization methods. In structural optimization the version is sought which minimizes the objective function and fulfils the design constraints [*Farkas* 1984]. As objective function the mass (weight) is often defined, but the minimum weight design does not give the optimal version for minimum cost. Therefore it is needed to define a more complex cost function including not only the material but also the fabrication costs.

In the recent publications [*Farkas* 1990, 1991, 1992] the first author has used a relatively simple cost function proposed by *Pahl and Beelich* [1982]. These authors have given the production times only for SMAW (shielded metal arc welding) and GMAW-C (gas metal arc welding with $CO_2$).Their values have been modified [*Farkas and Jármai* 1993a] using some other publications [*Ott and Hubka* 1985, *Aichele* 1985].

To apply these cost calculations for another welding technologies, mainly for SAW (submerged arc welding), the *COSTCOMP* [1990] software has been used [*Bodt* 1990]. The values of COSTCOMP enable us to define cost functions for different welding technologies.

The aim of the present study is to apply the minimum cost design procedure for simple welded structures to show the advantage of automatic welding technology by cost comparisons.

## A BRIEF SURVEY OF SELECTED LITERATURE

The article of *Drews and Starke* [1990] deals with the economy of robotization. The efficiency of automation should be increased by reducing the time of fixturing, tooling, programming and testing.

*Horikawa, Nakagomi et al.* [1991] proposed various modifications in structural design for efficient application of welding robots.

The study of *Fern and Yeo* [1990] compared the effective deposition rates of various semi-automated and mechanised welding processes considering flat, horizontal, vertical and overhead welding positions. Helpful hints have been given to improve the design.

*Chalmers* [1986] dealt with fabrication costs of ship structures analysing the material and labour costs and giving useful comments for design.

*Forde, Leung and Stiemer* [1984] have treated the design/fabrication interaction and have proposed an information system to give designers more information about costs.

*Sen, Shi and Caldwell* [1989] have treated the minimum weight and cost design of stiffened, corrugated and sandwich panels used in ship structures, but a detailed cost analysis has not been given.

The study of *Malin* [1985-86] gives a good view on effective automation of welding operation and describes some economic aspects for automation.

*Pedersen and Nielsen* [1987] have treated the minimum weight and cost design of a stiffened plate used in ships considering also the cost of welding without any cost analysis.

## THE COST FUNCTION

Although the whole production cost depends on many parameters and it is very difficult to express their effect mathematically, a simplified cost function can serve as a suitable tool for comparisons useful for designers and manufacturers.

As used in the first author's previous publications the cost function can be expressed as

$$K = K_m + K_f = k_m \rho V + k_f \sum_i T_i \tag{1}$$

where $K_m$ and $K_f$ are the material and fabrication costs, respectively, $k_m$ and $k_f$ are the corresponding cost factors, $\rho$ is the material density, $V$ is the volume of the structure, $T_i$ are the production times. Eq.(1) can be written in the following form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}(T_1 + T_2 + T_3) \tag{2}$$

where

$$T_1 = C_1 \delta \sqrt{\kappa \rho V} \tag{3}$$

is the time for preparation, assembly and tacking, $\delta$ is a difficulty factor, $\kappa$ is the number of structural elements to be assembled.

$$T_2 = \sum_i C_{2i} a_{wi}^n L_{wi} \tag{4}$$

is the time of welding, $a_{wi}$ is the weld size, $L_{wi}$ is the weld length, $C_{2i}$ and $n$ are constants given for different welding technologies.

$$T_3 = \sum_i C_{3i} a_{wi}^n L_{wi} \tag{5}$$

is the time of additional fabrication actions such as changing the electrode, deslagging and chipping.

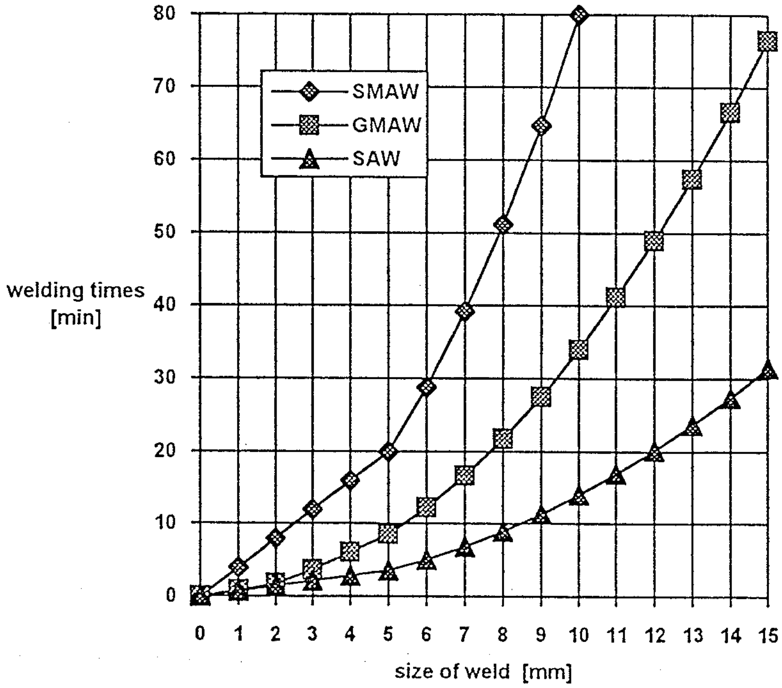

Fig. 1. Welding times for fillet welds of size $a_w$

Table 1. Welding times $T_2$ (min) in function of weld size $a_w$ (mm) for longitudinal fillet welds downhand position (see also Fig.1.)

| Welding method | $a_w$ (mm) | $10^3 T_2 = 10^3 C_2 a_w^n$ |
|---|---|---|
| SMAW | 2 - 5<br>5 - 15 | $4.0\ a_w$<br>$0.8\ a_w^2$ |
| GMAW-C | 2 - 5<br>5 - 15 | $1.70\ a_w$<br>$0.34\ a_w^2$ |
| SAW | 2 -5<br>5 - 15 | $1.190\ a_w$<br>$0.238\ a_w^2$ |

*Ott and Hubka* [1985] proposed that $C_{3i} = 0.3\ C_{2i}$, so

$$T_2 + T_3 = 1.3 \sum_i C_{2i} a_{wi}^n L_{wi} \tag{6}$$

Values of $C_{2i}$ and $n$ may be given according to *COSTCOMP* [1990] as follows. The COSTCOMP software gives welding times and costs for different technologies. To compare the costs of different welding methods and to show the advantages of automation, the manual SMAW, semi-automatic GMAW-C and automatic SAW methods are selected for fillet welds. The analysis of COSTCOMP data resulted in constants given in Fig. 1. and Table 1.

It should be noted that in values for SAW a multiplying factor of 1.7 is considered since in COSTCOMP different cost factors are given for various welding methods.

## NUMERICAL EXAMPLE OF A STIFFENED PLATE

In order to show the effect of various welding methods on the optimal dimensions, weight and cost of a welded structure, an illustrative numerical example is chosen and the structural versions optimized for different welding methods are compared to each other.

Stiffened panels are widely used in bridge and ship structures, so it is of interest to study the minimum cost design of such structural elements. On the other hand, it has been shown [*Farkas and Jármai* 1993b] that the fabrication cost of a welded stiffened plate represents a significant part of the total cost.

The design rules of *API* [1987] are used here for the formulation of the global buckling constraint for uniaxially compressed plate longitudinally stiffened by equally spaced uniform flat stiffeners of equal cross sections (Fig.2). The cost function is defined according to Eqs (2,3,6)

$$\frac{K}{k_m} = \rho L A + \frac{k_f}{k_m}\left(\delta\sqrt{\kappa\rho L A} + 1.3 C_2 a_w^n L_w\right) \tag{7}$$

where $A = b_o t_f + \varphi h_S t_S$ ; $\delta = 3$ ; $\kappa = \varphi + 1$ ; $L_w = 2L\varphi$ ; $\varphi$ is the number of stiffeners.

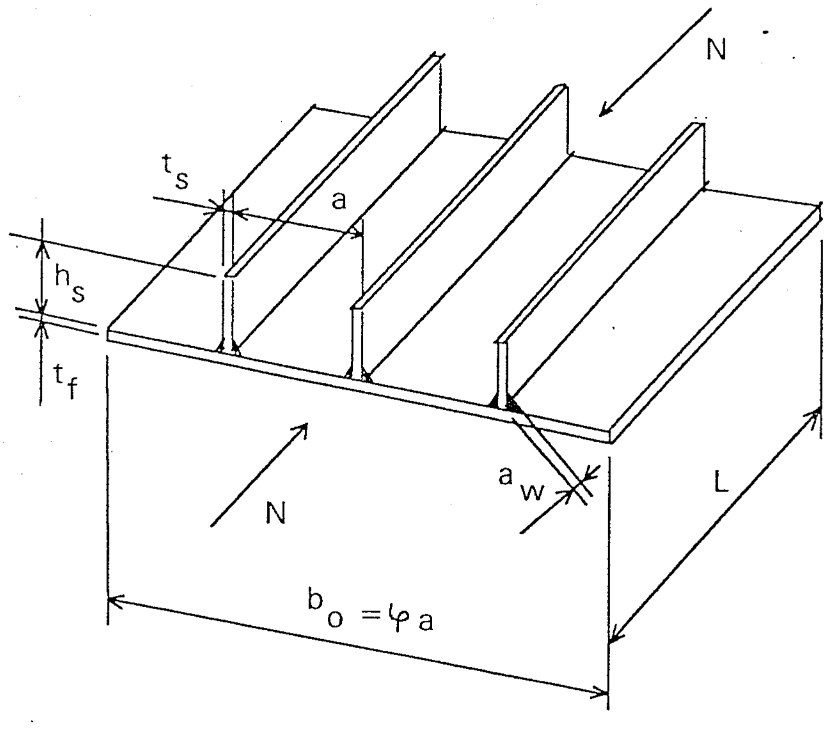

Fig. 2. Uniaxially compressed longitudinally stiffened plate

In order to produce internationally usable solutions, the following ranges of $k_m$ and $k_f$ are considered. For steel Fe 360 $k_m$ = 0.5 - 1.2 \$/kg, for fabrication including overheads $k_f$ = 15 - 45 \$/manhour = 0.25 - 0.75 \$/min. Thus the ratio $k_f/k_m$ may vary in the range 0 - 1.5 kg/min. The value $k_f/k_m = 0$ corresponds to the minimum weight design.

The flat stiffeners are welded by double fillet welds, the size of welds is taken as $a_w = 0.5 t_S$. The welding costs are calculated for SMAW, GMAW-C and SAW according to Table 1.

In the optimization procedure the given data are as follows. The modulus of elasticity for steel is $E = 2.1\times10^5$ MPa, the material density is $\rho = 7.85*10^{-6}$ kg/mm$^3$ , the Poisson's ratio is $\nu = 0.3$, the yield stress is $f_y = 235$ MPa, the plate width is $b_o = 4200$ mm, the length is $L = 4000$ mm. The axial compressive force is

$$N = f_y b_o t_{fmax} = 235*4200*20 = 1.974*10^7 \text{ [N]}$$

The variables to be optimized are as follows (Fig.2): the thickness of the base plate $t_f$, the sizes of stiffeners $h_S$ and $t_S$ and the number of stiffeners $\varphi = b_o/a$.

*The overall buckling constraint* is given by

$$N \le \chi f_y A \tag{8}$$

where the buckling factor $\chi$ is given in function of the reduced slenderness $\bar{\lambda}$

$$\chi = 1 \quad \text{for} \quad \bar{\lambda} \le 0.5 \tag{9a}$$

$$\chi = 1.5 - \bar{\lambda} \quad \text{for} \quad 0.5 \le \bar{\lambda} \le 1 \tag{9b}$$

$$\chi = 0.5/\bar{\lambda} \quad \text{for} \quad \bar{\lambda} \ge 1 \tag{9c}$$

where

$$\bar{\lambda} = \frac{b_0}{t_f}\sqrt{\frac{12(1-\nu^2)f_y}{E\pi^2 k}} \tag{10}$$

$$k = min\,(k_R, k_F); \qquad k_R = 4\varphi^2 \tag{11a,b}$$

$$k_F = \frac{(1+\alpha^2)^2 + \varphi\gamma}{\alpha^2(1+\varphi\delta_P)} \quad \text{when} \quad \alpha = \frac{L}{b_0} \le \sqrt[4]{1+\varphi\gamma} \tag{11c}$$

$$k_F = \frac{2(1+\sqrt{1+\varphi\gamma})}{1+\varphi\gamma} \quad \text{when} \quad \alpha \ge \sqrt[4]{1+\varphi\gamma} \tag{11d}$$

$$\delta_P = \frac{h_S t_S}{b_0 t_f}; \quad \gamma = \frac{EI_S}{b_0 D}; \quad I_S = \frac{h_S^3 t_S}{3}; \quad D = \frac{E t_f^3}{12(1-\nu^2)} \tag{11e}$$

so

$$\gamma = 4(1-\nu^2)\frac{h_S^3 t_S}{b_0 t_f^3} = 3.64\frac{h_S^3 t_S}{b_0 t_f^3} \tag{11f}$$

$I_S$ is the moment of inertia of one stiffener about an axis parallel to the plate surface at the base of the stiffener, $D$ is the flexural stiffness of the base plate.

*The constraint on local buckling of a flat stiffener* is defined by means of the limiting slenderness ratio according to *Eurocode 3* [1992]

$$\frac{h_S}{t_S} \le \frac{1}{\beta_S} = 14\sqrt{\frac{235}{f_y}} \tag{12}$$

The optimization procedure is carried out by using the software for *the feasible sequential quadratic programming FSQP method* developed by *Zhou and Tits* [1992] and for *the Rosenbrock's Hillclimb method.* Rounded values are computed by a complementary special program.

The ranges of unknowns are taken as follows (in mm): $t_f = 6 - 20$, $h_S = 84 - 280$, $t_S = 6 - 25$, $\varphi = 4 - 15$.

The computational results are summarized in Tables 2 and 3.

Table 2. Optimal versions of a uniaxially compressed longitudinally stiffened plate, double fillet welds carried out by different welding methods, dimensions in mm

| *Welding method* | $k_f/k_m$ | $t_f$ | $h_S$ | $t_S$ | $\varphi$ | $A$ (mm$^2$) | $K/k_m$ (kg) |
|---|---|---|---|---|---|---|---|
| SMAW | 0.00 | 9.7 | 202 | 14.4 | 15.0 | 84584 | 2656 |
| | 0.10 | 11.7 | 204 | 17.4 | 11.7 | 90372 | 3572 |
| | 0.18 | 13.8 | 217 | 15.6 | 9.5 | 89923 | 3688 |
| | 0.20 | 17.1 | 225 | 17.9 | 7.0 | 99632 | 4057 |
| | 0.50 | 19.3 | 232 | 16.6 | 5.7 | 103068 | 4867 |
| | 1.00 | 20.0 | 233 | 16.7 | 5.4 | 104956 | 6425 |
| | 1.50 | 20.0 | 234 | 16.7 | 5.3 | 104730 | 7919 |
| GMAW-C | 0.0 | 9.7 | 202 | 14.4 | 15.0 | 84584 | 2656 |
| | 0.3 | 12.0 | 206 | 17.6 | 11.1 | 102069 | 3754 |
| | 0.5 | 15.4 | 222 | 15.9 | 8.0 | 93118 | 3823 |
| | 1.0 | 17.3 | 228 | 16.4 | 6.7 | 97615 | 4661 |
| | 1.5 | 20.0 | 234 | 16.7 | 5.3 | 104730 | 5262 |
| SAW | 0.0 | 9.7 | 202 | 14.4 | 15.0 | 84584 | 2656 |
| | 0.5 | 12.0 | 212 | 16.3 | 11.2 | 89067 | 3727 |
| | 1.0 | 15.2 | 222 | 15.9 | 8.2 | 92730 | 4194 |
| | 1.5 | 17.3 | 228 | 16.3 | 6.7 | 97602 | 4737 |

Table 3. Rounded values of those given in Table 2.

| *Welding method* | $k_f/k_m$ | $t_f$ | $h_S$ | $t_S$ | $\varphi$ | $A$ (mm$^2$) | $K/k_m$ (kg) |
|---|---|---|---|---|---|---|---|
| SMAW | 0.00 | 10 | 200 | 15 | 15 | 88125 | 2732 |
| | 0.10 | 12 | 210 | 15 | 12 | 95880 | 3332 |
| | 0.18 | 14 | 215 | 16 | 10 | 94000 | 3887 |
| | 0.20 | 17 | 225 | 17 | 7 | 98770 | 3926 |
| | 0.50 | 19 | 230 | 17 | 6 | 107970 | 5049 |
| | 1.00 | 19 | 230 | 17 | 6 | 107970 | 6856 |
| | 1.50 | 19 | 230 | 17 | 6 | 107970 | 8664 |
| GMAW-C | 0.0 | 10 | 200 | 15 | 15 | 88125 | 2732 |
| | 0.3 | 14 | 215 | 16 | 10 | 94000 | 3609 |
| | 0.5 | 16 | 220 | 16 | 8 | 98880 | 3904 |
| | 1.0 | 17 | 225 | 17 | 7 | 102970 | 4879 |
| | 1.5 | 19 | 230 | 17 | 6 | 107970 | 5553 |
| SAW | 0.0 | 10 | 200 | 15 | 15 | 88125 | 2732 |
| | 0.5 | 12 | 210 | 15 | 12 | 95880 | 3611 |
| | 1.0 | 16 | 220 | 16 | 8 | 98880 | 4270 |
| | 1.5 | 17 | 225 | 17 | 7 | 102970 | 4913 |

It can be seen that the minimum weight design ($k_f = 0$) results in much more stiffeners than the minimum cost design. The optimal plate dimensions depend on cost factors $k_f/k_m$ and $C_2$ , so the results illustrate the effect of the welding technology on the structure and costs.

It should be noted that, in the case of SMAW, the $\varphi_{\mathrm{opt}}$ values are very sensitive to $k_f/k_m$ , so in Tables 2-3 more $k_f/k_m$-values are treated.

For $k_f/k_m$ = 1.5 the cost savings achieved by using SAW instead of SMAW or GMAW-C are 100 (7919 - 4737) / 7919 = 40% and 100 (5262 - 4737) / 5262 = 10%.

In the case of SMAW and $k_f/k_m$ = 1.5 the material cost component is $\rho LA$ = 3289 kg, so the fabrication cost represents 100 (7919 - 3289) / 7919 = 58% of the whole cost, this significant part of costs affects the dimensions and the economy of stiffened plates.

## CONCLUSIONS

a) Cost functions are formulated by means of the COSTCOMP software for longitudinal fillet welds carried out with manual SMAW, semi-automatic GMAW-C and automatic SAW method in downhand position.

b) Using these cost functions the optimal dimensions of a stiffened plate are computed which minimize the total cost and fulfil the design constraints on overall and local buckling.

c) The comparison of optimal solutions shows that significant cost savings may be achieved by using SAW instead of SMAW or GMAW-C.

d) Numerical computations show that the optimal dimensions of a stiffened plate depend on the applied welding method and illustrate the necessity of cooperation between designers and fabricators.

e) Comparison of optimal solutions for minimum weight ($k_f/k_m$ = 0) and minimum cost shows that the fabrication cost affects significantly the optimal dimensions, therefore the consideration of the total cost function results in more economic structural versions.

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## SESSION 3
## DEVELOPMENTS IN ROBOTIZED WELDING SYSTEMS/DEVELOPPEMENTS DANS LE DOMAINE DU SOUDAGE ROBOTISE