

# **ADVANCED TECHNIQUES AND LOW COST AUTOMATION**

Proceedings of the International Conference held in  
Beijing, China, 5–6 September 1994 under the auspices  
of the International Institute of Welding

# **TECHNIQUES DE POINTE ET AUTOMATISATION A FAIBLE COUT**

Communications présentées à la Conférence Internationale  
tenue a Beijing, China, du 5 au 6 Septembre 1994 sous les auspices  
de l'Institut International de la Soudure

Published on behalf of the  
INTERNATIONAL INSTITUTE OF WELDING

Edité au nom de  
L'INSTITUT INTERNATIONAL DE LA SOUDURE

INTERNATIONAL ACADEMIC PUBLISHERS

(京)新登字 141 号

图书在版编目(CIP)数据

先进技术与低成本自动化：国际焊接学会 1994 年国际会议  
论文集：英文 / 国际焊接学会编. — 北京：万国学术出版社，  
1994.8

ISBN 7-80003-318-X

I.先… II.国… III.焊接-国际会议-文集-英文 IV.  
TG4-53

中国版本图书馆 CIP 数据核字 (94) 第 06837 号

Published by  
**International Academic Publishers**  
137 Chaonei Dajie, Beijing 100010  
The People's Republic of China

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First edition 1994

**Advanced Techniques and Low Cost Automation — Proceedings of the '94 International Conference of International Institute of Welding**  
(先进技术与低成本自动化——国际焊接学会 1994 年国际会议论文集)

ISBN 7-80003-318-X / TG · 22

Printed by the Printing House of China Building Industry Press

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

Prof.Dr.József FARKAS and Assoc.Prof.Dr.Károly JÁRMAI

University of Miskolc, H-3515 Miskolc-Egyetemváros, Hungary

## 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<sub>2</sub>). 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

$$K = K_m + K_f = k_m \rho V + k_f \sum_i T_i \quad (1)$$

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

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

where

$$T_1 = C_1 \delta \sqrt{\kappa \rho V} \quad (3)$$

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

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

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.

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

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

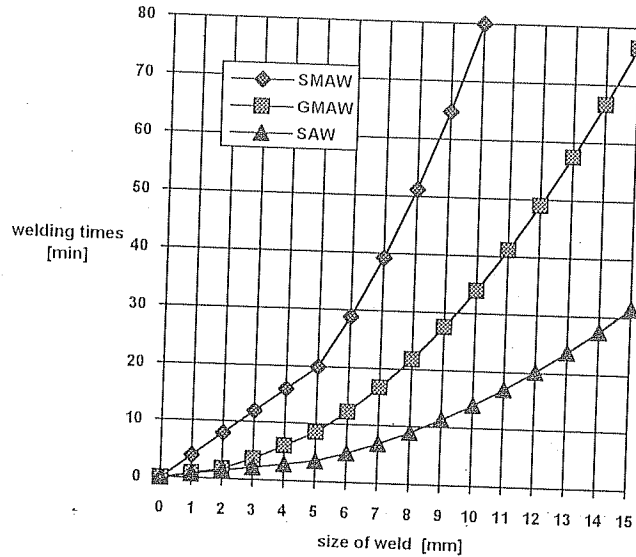


Fig. 1. Welding times for fillet welds of size  $a_w$

Table I. 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	$4.0 a_w$
	5 - 15	$0.8 a_w^2$
GMAW-C	2 - 5	$1.70 a_w$
	5 - 15	$0.34 a_w^2$
SAW	2 - 5	$1.190 a_w$
	5 - 15	$0.238 a_w^2$

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

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

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 I.

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)

$$\frac{K}{k_m} = \rho LA + \frac{k_f}{k_m} (\delta \sqrt{\kappa \rho LA} + 1.3 C_2 a_w^2 L_w) \quad (7)$$

where  $A = b_o t_f + \phi h_s t_s$ ;  $\delta = 3$ ;  $\kappa = \phi + 1$ ;  $L_w = 2L\phi$ ;  $\phi$  is the number of stiffeners.

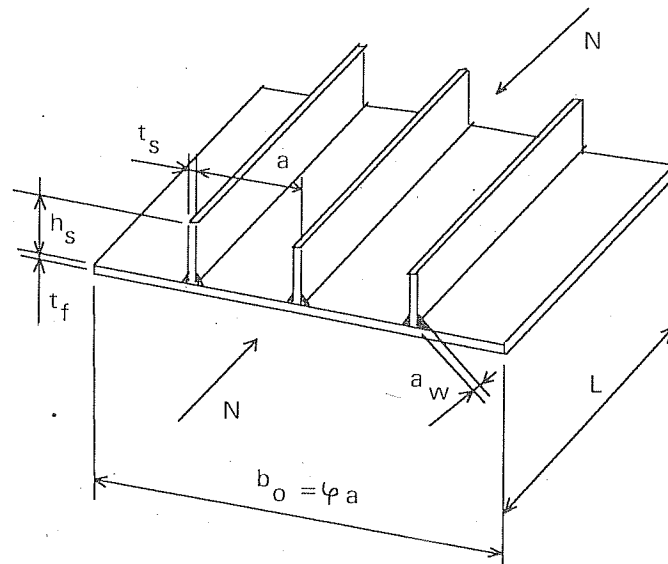


Fig. 2. Uniaxially compressed longitudinally stiffened plate

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  $a_w = 0.5t_s$ . 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  $E = 2.1 \times 10^5$  MPa, the material density is  $\rho = 7.85 \times 10^{-6}$  kg/mm<sup>3</sup>, 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

$$N \leq \chi f_y A \quad (8)$$

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

$$\chi = 1 \quad \text{for} \quad \bar{\lambda} \leq 0.5 \quad (9a)$$

$$\chi = 1.5 - \bar{\lambda} \quad \text{for} \quad 0.5 \leq \bar{\lambda} \leq 1 \quad (9b)$$

$$\chi = 0.5/\bar{\lambda} \quad \text{for} \quad \bar{\lambda} \geq 1 \quad (9c)$$

where

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

$$k = \min(k_R, k_F); \quad k_R = 4\varphi^2 \quad (11a,b)$$

$$k_F = \frac{(1+\alpha^2)^2 + \varphi\gamma}{\alpha^2(1+\varphi\delta_p)} \quad \text{when} \quad \alpha = \frac{L}{b_o} \leq \sqrt[4]{1+\varphi\gamma} \quad (11c)$$

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

$$\delta_p = \frac{h_s t_s}{b_o t_f}; \quad \gamma = \frac{EI_s}{b_o D}; \quad I_s = \frac{h_s^3 t_s}{3}; \quad D = \frac{Et_f^3}{12(1-\nu^2)} \quad (11e)$$

$$\text{so} \quad \gamma = 4(1-\nu^2) \frac{h_s^3 t_s}{b_o t_f^3} = 3.64 \frac{h_s^3 t_s}{b_o t_f^3} \quad (11f)$$

$I_s$  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]

$$\frac{h_s}{t_s} \leq \frac{1}{\beta_s} = 14 \sqrt{\frac{235}{f_y}} \quad (12)$$

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 <sup>2</sup> )	$K/k_m$ (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 <sup>2</sup> )	$K/k_m$ (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  $\varphi_{opt}$  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.

### ACKNOWLEDGEMENTS

The authors would like to thank Andre L. Tits and Jian L. Zhou University of Maryland for the possibility of using the CFSQP algorithm.

This work received support from the Hungarian Fund for Scientific Research Grants OTKA T-T-4479 and T-4407.

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