Fabrication cost calculations and minimum cost design of welded structural parts

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Abstract

In order to minimize the cost of welded structures, optimization studies should be performed, which need mathematical formulation of the cost function. The previously used *Pahl-Beelich* method is modified by using the *COSTCOMP* program to have cost functions for various welding methods. Illustrative numerical examples of a welded box beam and that of a stiffened plate show the influence of fabrication cost on the optimal sizes of the structure. It is shown that the optimal sizes depend on welding method, so, to achieve economic structures, the designer should consider also the fabrication aspects.

1. 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 [1]. As objective function the mass (weight) is often defined, but the minimum weight design does not give the optimal version for minimum cost. Therefore a more complex cost function should be defined including not only the material but also the fabrication costs.

In the industry it is common to use the cost/tonne concept [2], but it is not suitable for optimization. If we use a cost/tonne cost factor for fabrication cost, then the material and fabrication costs will give similar, non-conflicting functions, which do not lead to an optimum. To find an optimum we need conflicting functions, thus, we should use a more suitable fabrication cost calculation method based on a more detailed cost analysis.

In the recent publications [3,4,5] the first author has used a relative simple cost function proposed by *Pahl and Beelich* [6]. These authors have given the production times only for SMAW (shielded metal arc welding) and GMAW-C (gas metal arc welding with CO_2). To apply the cost calculations for another welding technologies, mainly for SAW (submerged arc welding), the *COSTCOMP* [7] software has been used [8]. 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 effect of fabrication cost on the optimal sizes of a structure by cost comparisons.

2. Survey of selected literature

Some publications in this field have been earlier mentioned by the first author [9]. Relative cost factors for different welded joints have been given by *Donnelly* [10]. *Likhtarnikov* [11] has analyzed the fabrication times and costs for various building structures. *Aichele's* book [12] contains many useful welding cost data and aspects for economic design of welded structures. In the *Peurifoy's* book [13] cost data can be found for welded joints. *Volkov* [14] has given formulae and factors for fabrication time calculations of roof trusses, columns and crane runway girders of industrial buildings. *Yeo* [15] published a formula and factors for the calculation of welding costs. *Winkle and Baird* [16] have investigated the fabrication cost of stiffened plates used in ship structures.

The article of *Drews and Starke* [17] 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.* [18] proposed various modifications in structural design for efficient application of welding robots. The study of *Fern and Yeo* [19] 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* [20] dealt with fabrication costs of ship structures analyzing the material and labour costs and giving useful comments for design.

Forde, Leung and Stiemer [21] have treated the design/fabrication interaction and have proposed an information system to give designers more information about costs. *Sen, Shi and Caldwell* [22] 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* [23] gives a good view on effective automation of welding operation and describes some economic aspects for automation. *Pedersen and Nielsen* [24] 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. *Ramirez and Touran* [25] have described the EXSYS expert system which has two main modules. The first module selects an appropriate welding method and the second one estimates the welding costs.

3. Calculation of fabrication costs

The total cost of a structure can be calculated as

$$K = K_m + K_f + K_{add} \tag{1}$$

where K_m is the material cost, K_f is the fabrication cost and K_{add} are additional costs of non-destructive testing, repair, painting, corrosion protection, transportation, erection, maintenance, etc.

Considering only K_m and K_f, Eq. (1) can be written in the form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m} \sum_i T_i \tag{2}$$

where k_m and k_f are the material and fabrication cost factors, respectively, ρ is the material density, V is the volume of the structure and T_i are the times necessary for fabrication. T_i can be divided in three parts treated as follows.

3.1 Cost of preparation, assembly and tacking

For a plated structure consisting of κ elements the time for this part of fabrication is proportional to the perimeter, for the ith element it is

$$T_i = c_1 P_i$$

The mass of an element is proportional to the square of the perimeter

$$G_i = c_2 P_i^2$$

thus $\qquad P_i = c_3 \sqrt{G_i}$ $\qquad$ and $\qquad T_i = c_4 \sqrt{G_i}$

For the total structure, in average, it is $\qquad G = \kappa G_i$
and

$$T_1 = \kappa \; T_i = c_5 \; \kappa \sqrt{\frac{G}{\kappa}} = c_6 \; \sqrt{G\kappa}$$

This formula has been derived in *Likhtarnikov's* book [11] and applied by *Pahl and Beelich* [6] in the form

$$T_1 = C_1 \; \delta \; \sqrt{G\kappa} \qquad\qquad C_1 = 1.0 \; min/kg^{0.5} \qquad\qquad (3)$$

δ is a difficulty factor, proposed values for it are given in Table 1.

Table 1. Proposed values for the difficulty factor δ. For skewed angle joints add 1-2 points.

Structures	Welds	V-weld 60°	Fillet weld 90°
Planar	long welds flat position	1.0	2.0
Spatial	short welds plate, flat steel	1.5	2.5
Spatial	U-, L-profiles tubes	2.0	3.0
Spatial	I-, T-profiles	2.5	4.0

3.2 Cost of welding

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

where a_w is the weld size, L_w is the weld length, C_2 and n are constants given for different welding technologies. Values of C_2 and n may be given according to *COSTCOMP* [7] as follows. The COSTCOMP software gives welding times and costs for different welding technologies. To show the advantages of automation, the manual SMAW, semi-automatic GMAW-C and automatic SAW methods are selected for fillet and 1/2 V butt welds. The analysis of COSTCOMP data resulted in constants given in Figs 1-2 and Table 2.
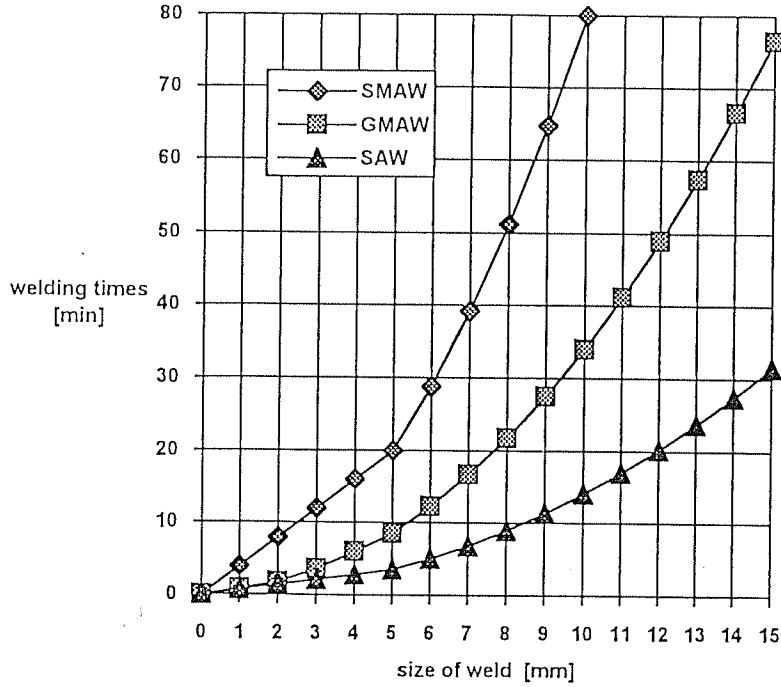
Fig. 1. Welding times for fillet welds of size a_w
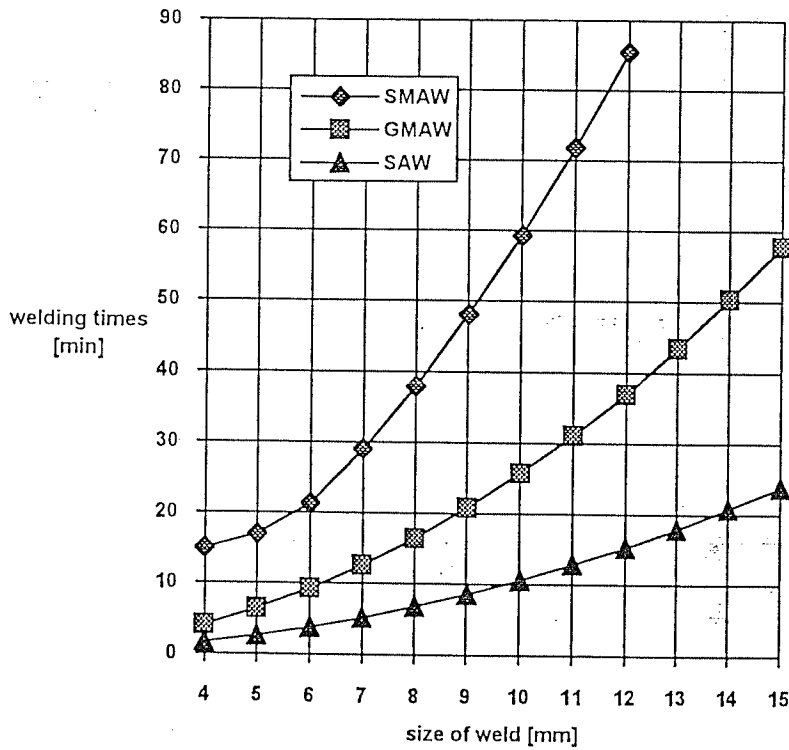

Fig. 2. Welding times for 1/2 V butt welds of size a_w

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.

Table 2. Welding times T_2 (min) in function of weld size a_w (mm) for longitudinal welds, downhand position (see also Figs. 1. and 2.)

Weld type	Welding method	a_w (mm)	$10^3 T_2 = 10^3 C_2 a_w^n$
fillet	SMAW	2-5	$4.0\, a_w$
		5-15	$0.8\, a_w^2$
fillet	GMAW-C	2-5	$1.70\, a_w$
		5-15	$0.34\, a_w^2$
fillet	SAW	2-5	$1.190\, a_w$
		5-15	$0.238\, a_w^2$
1/2 V butt	SMAW	4-15	$0.600\, a_w^2$
1/2 V butt	GMAW-C	4-15	$0.257\, a_w^2$
1/2 V butt	SAW	4-15	$0.181\, a_w^2$

3.3 Time for changing the electrode, deslagging and chipping

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

Ott and Hubka [26] proposed to use values of

$$C_3 = (0.2 - 0.4)\, C_2, \quad \text{in average} \quad C_3 = 0.3 C_2$$

thus

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

3.4 Other cost components

Calculations show that the cost of electrode can be neglected. The cost of surface preparation and painting, as it has been illustrated in a first author's paper [9], significantly affects the optimal sizes of structures. In the mentioned study the painting cost factor $k_p = 12$ $/m² has been considered according to literature sources.

4. Numerical examples

In order to show the effect of various welding methods on the optimal sizes and cost of welded structures, two illustrative numerical examples are worked out and the structural versions optimized for various welding methods are compared to each other.
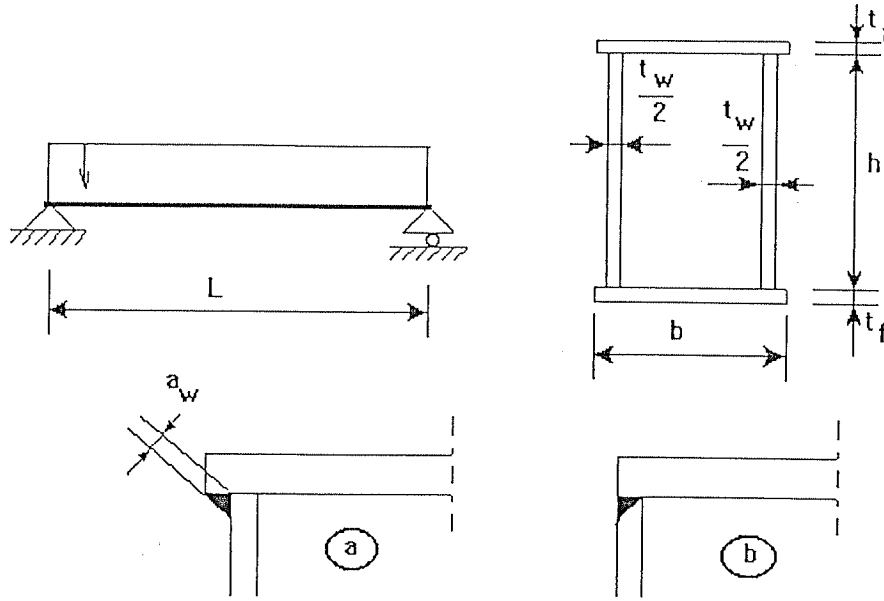
4.1 Welded box beam (Fig.3.)

Fig. 3. Welded box beam a) with fillet welds, b) with 1/2 V butt welds

To simplify the calculations the transverse diaphragms are neglected. The box girder is subjected to a fluctuating load, so the maximal bending moment pulsates between 0 and M_{max} value, number of cycles is $N = 2*10^6$.

Two structural versions are considered as follows: **1)** the box beam is welded by 4 fillet welds (Fig.3a), **2)** the webs are welded to the flanges by 1/2 V butt welds (Fig.3b). All welds are longitudinal and welded in downhand position. For both cases SMAW, GMAW-C and SAW methods are taken into account.

The total cost to be minimized is, according to Eqs (2,3,6)

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

where

$$A = ht_w + 2bt_f,$$

$\delta = 3$, $\kappa = 4$, $L = 20*10^3$ mm, $L_w = 4L$, $\rho = 7.85*10^{-6}$ kg/mm^3, $C_2 a_w^n$ are calculated according to Table 2.

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 of $0 - 1.5$ kg/min. The value $k_f/k_m = 0$ corresponds to the minimum weight design.

Design constraints are formulated according to *Eurocode 3* [27].

Fatigue stress constraint

$$\Delta\sigma = \frac{\Delta M}{W_x} \leq \frac{\Delta\sigma_C}{\gamma_f}, \qquad \Delta M = \frac{M_{max}}{2} \qquad (8)$$

$$\Delta M = 15 * 10^8 \text{ Nmm.}$$

The safety factor against fatigue for accessible joints, non fail-safe structure is $\gamma_f = 1.25$.

The fatigue stress range $\Delta\sigma_C$ for $N = 2 * 10^6$ has to be chosen for the corresponding detail category. For longitudinal fillet or butt welds containing stop/start positions (SMAW, GMAW) $\Delta\sigma_C = 100$ MPa, for automatic butt welds made from one side only, with backing bar, but without stop/start positions (SAW) $\Delta\sigma_C = 112$ MPa. The moment of inertia and the section modulus are given by

$$I_x = \frac{h^3 t_w}{12} + 2bt_f \left(\frac{h+t_f}{2}\right)^2 ; W_x = \frac{I_x}{(h+t_f)/2} \qquad (9)$$

Local buckling constraints for plate elements using the limiting plate slenderness concept are as follows.

For webs

$$\frac{t_w}{2} \geq \beta_w h; \beta_w = \frac{1}{124\varepsilon} \qquad (10)$$

for compressed flange

$$t_f \geq \delta_f b; \delta_f = \frac{1}{42\varepsilon} \qquad (11)$$

To avoid too thick flange plates an additional restriction is considered:

$$t_f \leq 1.2\delta_f b$$

Since for buckling the maximal normal stress $2\Delta\sigma$ has to be considered,

$$\varepsilon = \sqrt{\frac{235}{2\Delta\sigma/\gamma_f}} \qquad (12)$$

In the optimization procedure the unknown structural sizes h, $t_w/2$, b and t_f are determined which minimize the cost K and fulfil the design constraints.

The ranges of unknowns are taken as follows (in mm): $h = 500 - 1500$, $t_w/2 = 5 - 15$, $b = 300 - 1500$, $t_f = 5 - 25$.

Table 3. Optimal versions of the box beam welded with fillet welds by various welding methods. Rounded values in mm

Welding method	k_f/k_m	h	$t_w/2$	b	t_f	A (mm^2)	K/k_m (kg)
SMAW	0.0	1270	9	725	15	44610	7004
	0.5	1185	8	750	17	44460	8063
	1.0	1125	8	765	18	45540	9321
	1.5	1075	8	800	18	46000	10483
GMAW-C	0.0	1270	9	725	15	44610	7004
	0.5	1230	9	750	16	46140	7897
	1.0	1195	8	755	17	44790	8242
	1.5	1175	8	750	17	44300	8766
SAW	0.0	1195	9	690	15	42210	6626
	0.5	1170	9	700	16	43460	7349
	1.0	1145	9	685	17	43900	7947
	1.5	1130	8	690	17	41540	7991

Table 4. Optimal versions of the box beam welded with 1/2V butt welds by various welding methods. Rounded values in mm

Welding method	k_f/k_m	h	$t_w/2$	b	t_f	A (mm^2)	K/k_m (kg)
SMAW	0.0	1265	9	730	15	44670	7013
	0.5	1010	8	825	19	47510	9715
	1.0	880	7	900	21	50120	11459
	1.5	810	6	960	22	51960	12340
GMAW-C	0.0	1265	9	730	15	44670	7013
	0.5	1120	8	805	17	45290	8219
	1.0	1040	7	810	19	45340	8934
	1.5	965	7	850	20	47510	10201
SAW	0.0	1195	9	690	15	42210	6627
	0.5	1095	9	700	17	43510	7841
	1.0	1025	8	750	18	43400	8514
	1.5	970	7	780	19	43220	8910

The optimization procedure is carried out by using the software for the *Feasible Sequential Quadratic Programming* (FSQP) method developed by *Zhou and Tits* [28] and for the *Rosenbrock's Hillclimb method.* Rounded values are computed by a complementary special program [29].

The results of the optimization are given in Tables 3-4.

It can be seen that the web thickness should be decreased when the fabrication cost increases, to decrease the weld size. If the web sizes decrease the flange sizes should be increased. This tendency is much stronger in the case of butt welds than that of fillet welds. The weight and total cost is larger for butt welds than for fillet welds. The cost savings achieved by using SAW instead of GMAW-C or SMAW in the case of $k_f/k_m = 1.5$ is about 11% and 26%, respectively. The advantage of SAW is that the fabrication cost is smaller and the fatigue stress range is larger since the welding can be carried out without stop/start positions.

4.2 Stiffened plate (Fig.4)

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 [30] that the fabrication cost of a welded stiffened plate represents a significant part of the total cost.

The design rules of *API* [31] 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.4). The cost function is defined according to Eqs (7) in which $A = b_o t_f + \varphi h_s t_s$; $\delta = 3$; $\kappa = \varphi + 1$; $L_w = 2L\varphi$; φ is the number of stiffeners.

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 2.

In the optimization procedure the given data are as follows. The modulus of elasticity for steel is $E = 2.1*10^5$ 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

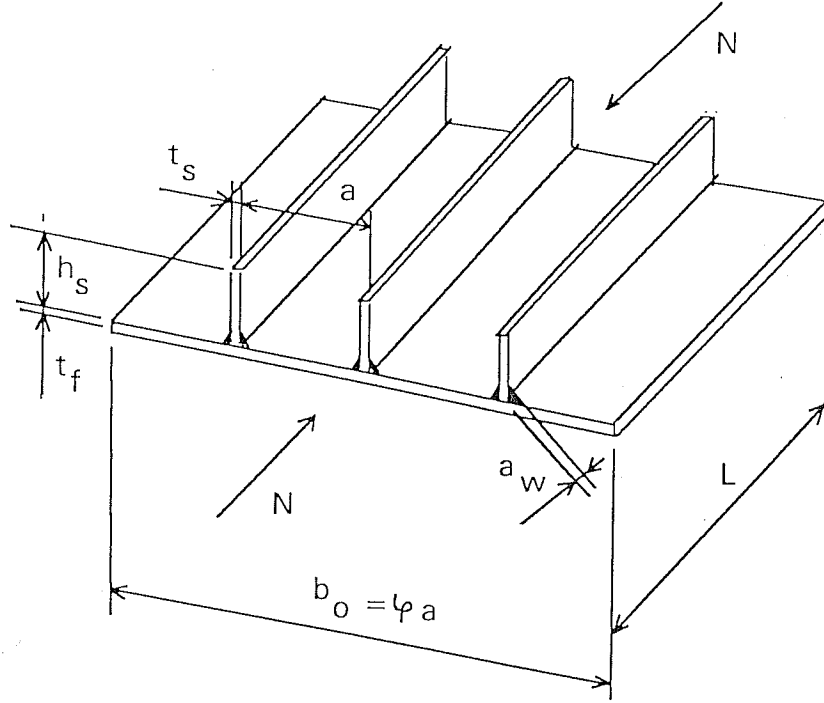$$N = f_y b_o t_{fmax} = 235*4200*20 = 1.974*10^7 \text{ [N]}$$

Fig. 4. Uniaxially compressed longitudinally stiffened plate

The variables to be optimized are as follows (Fig.4): the thickness of the base plate t_f, the sizes of stiffeners h_s and t_s and the number of stiffeners $\varphi = b_0/a$.

The overall buckling constraint is given by

$$N \le \chi f_y A \tag{14}$$

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

$$
\begin{array}{llll}
\chi = 1 & \text{for} & \bar{\lambda} \le 0.5 & \text{(15a)} \\
\chi = 1.5 - \bar{\lambda} & \text{for} & 0.5 \le \bar{\lambda} \le 1 & \text{(15b)} \\
\chi = 0.5/\bar{\lambda} & \text{for} & \bar{\lambda} \ge 1 & \text{(15c)}
\end{array}
$$

where

$$\bar{\lambda} = \frac{b_0}{t_f} \sqrt{\frac{12(1 - v^2)f_y}{E\pi^2 k}} \tag{16}$$

$$k = \min(k_R, k_F); \qquad k_R = 4\varphi^2 \tag{17a,b}$$

$$k_F = \frac{(1 + \alpha^2)^2 + \varphi\gamma}{\alpha^2(1 + \varphi\delta_P)} \qquad \text{when} \qquad \alpha = \frac{L}{b_0} \le \sqrt[4]{1 + \varphi\gamma} \tag{17c}$$

$$k_F = \frac{2(1 + \sqrt{1 + \varphi\gamma})}{1 + \varphi\gamma} \qquad \text{when} \qquad \alpha \ge \sqrt[4]{1 + \varphi\gamma} \tag{17d}$$

$$\delta_p = \frac{h_s t_s}{b_0 t_f}; \qquad \gamma = \frac{EI_s}{b_0 D}; \qquad I_s = \frac{h_s^3 t_s}{3}; \qquad D = \frac{Et_f^3}{12(1-\nu^2)} \tag{17e}$$

so $$\gamma = 4(1-\nu^2)\frac{h_s^3 t_s}{b_0 t_f^3} = 3.64\frac{h_s^3 t_s}{b_0 t_f^3} \tag{17f}$$

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* [27].

$$\frac{h_s}{t_s} \leq \frac{1}{\beta_s} = 14\sqrt{\frac{235}{f_y}} \tag{18}$$

The computational results are summarized in Tables 5.

Table 5. Optimal rounded sizes 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	φ	A (mm²)	K/k_m (kg)
SMAW	0.00	10	200	15	15	87000	2732
	0.10	13	210	17	11	91560	3516
	0.18	15	220	16	9	94680	3929
	0.20	16	220	16	8	95360	3945
	0.50	19	230	17	6	103260	5272
	1.00	19	230	17	6	103260	7301
	1.50	19	230	17	6	103260	9330
GMAW-C	0.0	10	200	15	15	87000	2732
	0.3	15	215	16	9	93960	3716
	0.5	16	220	16	8	95360	4146
	1.0	19	230	17	6	103260	5227
	1.5	19	230	17	6	103260	6220
SAW	0.0	10	200	15	15	87000	2732
	0.5	15	220	16	9	94680	3944
	1.0	19	230	17	6	103260	4767
	1.5	19	230	17	6	103260	5530

The optimization procedure is carried out by using the same softwares as mentioned in section 4.1.

The ranges of unknowns are taken as follows (in mm): t_f = 6 - 20, h_s = 84 - 280, t_s = 6 - 25, φ = 4 - 15.

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 φ_{opt} values are very sensitive to k_f/k_m, so in Table 5 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 (9330 - 5530) / 9330 = 41% and 100 (6220 - 5530) / 6220 = 11%.

In the case of SMAW and k_f/k_m = 1.5 the material cost component is ρLA = 103260*7.85*10^{-6}*4*10^3= 3242 kg, so the fabrication cost represents 100(9330 - 3242)/9330 = 65% of the whole cost, this significant part of costs affects the dimensions and the economy of stiffened plates.

5. Conclusions

a) Cost functions are formulated by means of the COSTCOMP software for longitudinal fillet and 1/2 V butt 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 box beam and a stiffened plate are computed which minimize the total cost and fulfil the design constraints.

c) The comparison of optimal solutions shows that significant cost savings may be achieved by using SAW instead of SMAW or GMAW-C. The savings is larger for stiffened plate since the ratio K_f/K is much larger for stiffened plate than that for box beam.

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

e) The automatic welding methods are advantageous not only for welding time reduction but also for higher fatigue design stress, corresponding to detailed category for welds worked out without stop/start positions.

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

g) Comparison of results for fillet and 1/2 V butt welds shows, that box beams with fillet welds are more economic, than those with 1/2 V butt welds.

h) The weight and cost savings achieved by automatic welding depend of the ratio K_f/K. For structures in which the fabrication cost is higher compared to the whole cost, e.g. in stiffened plates, the effect of automatization is higher. For stiffened plates the ratio K_f/K is about 65%, for the box beams calculated in our example this ratio is about 18%.

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