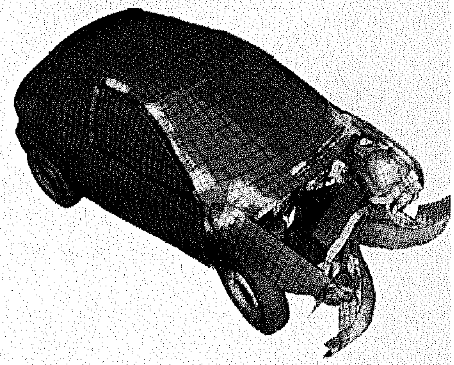

Raimo von Hertzen ja Tapani Halme (t

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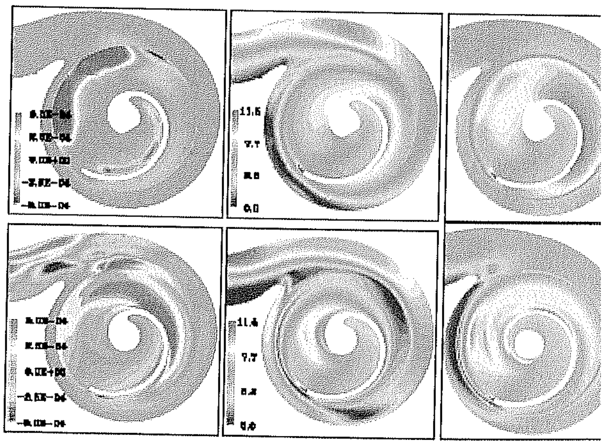

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RAPORTTI
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## IX Suomen Mekaniikkapäivät

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# DESIGN OF ECONOMIC STEEL STRUCTURES

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## ABSTRACT

Design of economic steel structures is an important issue to be competitive. Optimum design, structural analysis, fabrication technologies and economy are in close connection is this process. We have developed a cost calculation system to calculate both material and different fabrication costs, like welding, cutting, grinding, painting, etc. The used optimization techniques can solve highly nonlinear problems. The newly developed evolutionary techniques are very robust. On a simple example we show the application of this kind of approach. The structure is a stiffened plate and we optimize it with different welding technologies.

## 1 INTRODUCTION

People in their everyday life always make optimization on a conscious or a subconscious way „to reach the best, which is possible with the resources available". The consciousness makes the act more efficient. They have always targets to reach and constraints to control them. The birth of optimization methods as mathematical techniques can be dated back to the days of Newton, Lagrange and Cauchy. The further development in optimization was possible by the developments of differential calculus by Newton, Leibnitz, the variational calculus by Bernoulli, Euler, Lagrange and Weierstrass, the introduction of unknown multipliers by Lagrange. The concept of multiobjective optimization was formulated one hundred years ago by Pareto in 1896.

The first written analytical work published on structural optimization was made by Maxwell in 1890, followed by the well-known work of Michell in 1904. These works provided theoretical weight minima of trusses, using highly idealised models, but the analytical way of solution of the structural optimization problem is still usable.

During the Second World War and in the late 1940's and the early 1950's the development of optimization concerned to the minimum weight design of aircraft structural components: columns, stiffened panels, subject to compressive loads and to buckling. Digital computers appear in the early 1950's and gave a strong impulse to the application of linear programming techniques. The applications were focused primarily on steel frame structures.

In the late 1950's and 1960's the applications of structural optimization on lightweight structures concentrated to the aircraft and space industries. This time a some new optimization techniques have been developed by works of Rosenbrock, Box, Powell. The great development of this period is that the finite element method, which is a powerful tool for analysis of complex structures, has been invented by Zienkiewich and applied by many others for structural analysis.

Modern structural optimization can be dated from the paper of Schmit in 1960, who drew up the role of structural optimization, the hierarchy of analysis and synthesis, the use of mathematical programming techniques to solve the nonlinear inequality constrained problems. The importance of this work is that it proposed a new philosophy of engineering design, the structural synthesis, which clarifies the methodology of optimization.

There are several international organizations which deal with optimisation, probably the largest of them is the International Society of Structural and Multidisiplinary Optimization (ISSMO) which has its own journal Structural and Multidisciplinary Optimization (Springer Verlag) and regularly organises conferences.
The International Institute of Welding (IIW) also deals with cost calculations (Journal Welding in the World), they have annual assembly each year. Also there are a great number of other conferences and courses which have been organized connected to these two main fields. At the University of Miskolc we have organised several conferences (Farkas & Jármai (Eds.) 1996, Jármai (Ed.) 1997, Jármai & Farkas (Eds.) 2003), also courses in CISM, Italy (Farkas & Jármai 1996, Jármai & Farkas (Eds.) 1999).

## 2 DESIGN VARIABLES, OBJECTIVE FUNCTIONS, CONSTRAINTS AND PREASSIGNED PARAMETERS

The objective function (more functions at multiobjective optimization), the design variables, the preassigned parameters and the constraints describe an optimization problem.

### 2.1 *Design variables and preassigned parameters*

The quantities, which describe a structural system can be divided into two groups: preassigned parameters and design variables. The difference between them is that the members of the first group are fixed during the design, the second group is the design variables, which are varied by the optimization algorithm. These parameters can control the geometry of the structures. It is the designer choice, which quantities will be fixed or varied. They can be cross-sectional areas, member sizes, thicknesses, length of structural elements, mechanical or physical properties of the material, number of elements in a structure (topology), shape of the structure, etc.

### 2.2 *Constraints*

Behaviour means those quantities that are the results of an analysis, such as forces, stresses, displacements, eigenfrequencies, loss factors etc. These behaviour quantities form usually the constraints. A set of values for the design variables represents a design of the structure. If a design meets all the requirements, it will be called feasible design. The restrictions that must be satisfied in order to produce a feasible design are called constraints. There are two kinds of constraints, explicit and implicit ones.

*Explicit constraints*
Explicit constraints which restrict the range of design variables may be called size constraints or technological constraints. These constraints may be derived from various considerations such as functionality, fabrication, or aesthetics. Thus, a size constraint is a specified limitation, upper or lower bounds on a design variable. Examples of such constraints include minimum slope of a portal frame structure, minimum thickness of a plate, minimum or maximum ratio of a box section height and width, etc.

*Implicit constraints*
Constraints derived from behaviour requirements are called behavioural constraints. Limitations on the maximum stresses, displacements, or local and overall buckling strength, eigenfrequency, damping are typical examples of behavioural constraints. The behaviour constraints can be regarded as implicit variables. The behavioural constraints are often given by formulae presented in design codes or specifications. Other part of the behavioural constraints are computed by numerical technique such as FEM. In any case the constraints can be evaluated by analytical

technique. From a mathematical point of view, all behavioural constraints may usually be expressed as a set of inequalities.

### 2.3 *Objective function*

In most practical cases an infinite number of feasible designs exists. In order to find the best one, it is necessary to form a function of the variables to use it for comparison of design alternatives. The objective function (also termed the cost, or merit function) is the function whose least, or greatest value is sought in an optimization procedure. It is usually a nonlinear function of the variables $\boldsymbol{x}$, and it may represent the mass, the cost of the structure, or any other function, which extremum can give a possible and useful solution of the problem. The minimization of $f(x)$ is equivalent with the maximization of $-f(x)$.

## 3 DIVISIONS IN OPTIMIZATION TECHNIQUES

The different single-objective optimization techniques make the designer able to determine the optimum sizes of structures, to get the best solution among several alternatives. The efficiency of these mathematical programming techniques is different. A large number of algorithms has been proposed for the nonlinear programming solution Himmelblau (1972), Vanderplaats (1984), Schittkowski et al (1994), Snyman (2005). Each technique has its own advantages and disadvantages, no one algorithm is suitable for all purposes. The choice of a particular algorithm for any situation depends on the problem formulation and the user.

The general formulation of a single-criterion nonlinear programming problem is the following:

$$\text{minimize} \quad f(x) \quad x = \{x_1, x_2, ..., x_N\} \tag{1}$$

$$\text{subject to} \quad g_j(x) \le 0, \quad j = 1,2,...,P \tag{2}$$

$$h_i(x) = 0 \quad i = P+1,...,P+M \tag{3}$$

$f(x)$ is a multivariable nonlinear function, $g_j(x)$ and $h_i(x)$ are nonlinear inequality and equality constraints respectively.

The optimization models can be very different from each other.

- *Analytical and numerical*
- *Unconstrained and constrained*
- *Single- and multivariable*
- *Single- and multiobjective*
- *Discrete and nondiscrete*
- *Structure free and structure dependent techniques*
- *Single- and multilevel optimization*

Detailed description is given in (Farkas & Jármai 1997, Jármai & Iványi 2001, Farkas & Jármai 2003).

## 4 COST ELEMENTS

The cost of the structure can be calculated from the material and the various fabrication costs, where one should consider the cost differences between different technologies and also their effects on the structure. The fabrication cost at welded steel structures can be welding, flattening, cleaning, painting, cutting, grinding, etc. (Peurifoy 1975, Volkov 1978, Yeo 1983, Winkle 1986, Ramirez & Touran 1991). If one does not consider the costs elements directly, but the fabrication times, which are available for a given technology, it is easier to calculate later the real cost in a given country (Jármai & Farkas 1999).

4.1 *Material cost*

The material cost can be calculated as

$$K_m = k_m \rho V, \qquad (4)$$

where $K_m$ [in \$ or in any other currency] is the material cost, $k_m$ [\$/kg] is the corresponding material cost factor, $\rho$ [kg/mm$^3$] is material density, $V$ [mm$^3$] is the volume of the structure. The range of $k_m$ is between 0.5 – 1 [\$/kg] according to the producers' pricelists.

4.2 *Fabrication cost*

The fabrication cost can be expressed as (Pahl & Beelich 1992)

$$K_f = k_f \sum_i T_i\,, \qquad (5)$$

where $K_f$ [\$] is the fabrication cost, $k_f$ [\$/min] is the corresponding fabrication cost factor, $T_i$ [min] are production times. It is assumed that the value of $k_f$ is constant for a given manufacturer. If not, it is possible to apply different fabrication cost factors simultaneously in Eq. (5).

4.2.1 *Fabrication times for welding*

The most important times related to welding are as follows: preparation, assembly, tacking, time of welding, changing the electrode, deslagging and chipping.

*Calculation of the times of preparation, assembly and tacking*

The times of preparation, assembly and tacking can be calculated with an approximation formula as follows

$$T_{w1} = C_1 \Theta_{dw} \sqrt{\kappa \rho V}\,, \qquad (6)$$

where $C_1$ is a parameter depending on the welding technology (usually equal to 1), $\Theta_{dw}$ is a difficulty factor, $\kappa$ is the number of structural elements to be assembled. Formula (6) can be approximately derived from Lihtarnikov (1968).

The difficulty factor expresses the complexity of the structure. Difficulty factor values depend on the kind of structure (planar, spatial), the kind of members (flat, tubular). The range of values proposed is between 1-4 (Farkas & Jármai 1997).

*Calculation of real welding time*

The welding technologies applied are given in Table 1. Real welding time can be calculated on the following way

$$T_{w2} = \sum_i C_{2i} a_{wi}^2 L_{wi}\,, \qquad (7)$$

where $a_{wi}$ is weld size, $L_{wi}$ is weld length, $C_{2i}$ and $n$ are constants for different welding technologies. $C_2$ contains not only the differences between welding technologies but the time differences between positional (vertical, overhead) and normal welding as well (see Farkas&Jármai 2003).

*Calculation of additional fabrication actions time*

There are some additional fabrication actions to be considered such as changing the electrode, deslagging and chipping. The time of these is as follows

$$T_{w3} = \sqrt{\Theta_{dw}} \sum_i C_{3i} a_{wi}^2 L_{wi} . \tag{8}$$

Formulae (6,7,8) was proposed by Pahl & Beelich (1982) and used in (Farkas 1992, Farkas & Jármai 1993, Jármai & Farkas 1999).

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Ott & Hubka (1985) proposed that $C_3$ = (0.2-0.4) $C_2$ on average $C_3 = 0.3C_2$. Thus, the modified formula for $T_{w2}$+$T_{w3}$ neglecting $\sqrt{\Theta_d}$ , is

$$T_{w2} + T_{w3} = 1.3 \sum C_{2i} a_{wi}^2 L_{wi} . \tag{9}$$

In the negligence of $\sqrt{\Theta_{dw}}$ it is assumed that the difficulty factor should be considered only for $T_{w1}$.

The software COSTCOMP (1990) was developed by the Netherlands Institute of Welding. It gives welding times and costs for different welding technologies (Bodt 1990) on the basis of theoretical and experimental investigations. Considering the times given by companies all over the world and the times calculated by COSTCOMP here Eq. (6) is used for $T_{w1}$ and the other times are calculated with a generalized formula, where the power of $a_w$ is $n$, which is some cases equal to 2, or close to it.

$$T_{w2} + T_{w3} = 1.3 \sum C_{2i} a_{wi}^n L_{wi} . \tag{10}$$

The different welding technologies are shown in Table 1. The weld types are given are as follows: fillet welds, V-, X-, T-, 1/2 V-, T-, U-, Y- butt welds and the double version of T-, U-, Y- butt welds and the K-butt weld.

Table 1. Welding technologies applied

| | |
|---|---|
| SMAW | Shielded Metal Arc Welding |
| SMAW HR | Shielded Metal Arc Welding High Recovery |
| GMAW-C | Gas Metal Arc Welding with $CO_2$ |
| GMAW-M | Gas Metal Arc Welding with Mixed Gas |
| FCAW | Flux Cored Arc Welding |
| FCAW-MC | Metal Cored Arc Welding |
| SSFCAW (ISW) | Self Shielded Flux Cored Arc Welding |
| SAW | Submerged Arc Welding |
| GTAW | Gas Tungsten Arc Welding |

Using COSTCOMP the welding times $T_{w2}$ (min) were calculated versus weld size $a_W$ (mm) for all kind of welding types in downhand position. The values of power $n$ in Eq. (7) come form curve fitting calculations.

The welding times $T_{w2}$ (min/mm) versus weld size $a_W$ (mm) also were calculated for longitudinal fillet welds and for longitudinal V butt welds in positional welding, which means not downhand, but vertical or overhead positions.

Figure 1 shows the welding times for longitudinal V butt welds in decreasing order SMAW, SMAW-HR, GMAW-C, GMAW-M, FCAW, FCAW-MC, ISW and SAW. The highest being SMAW and the lowest is SAW.

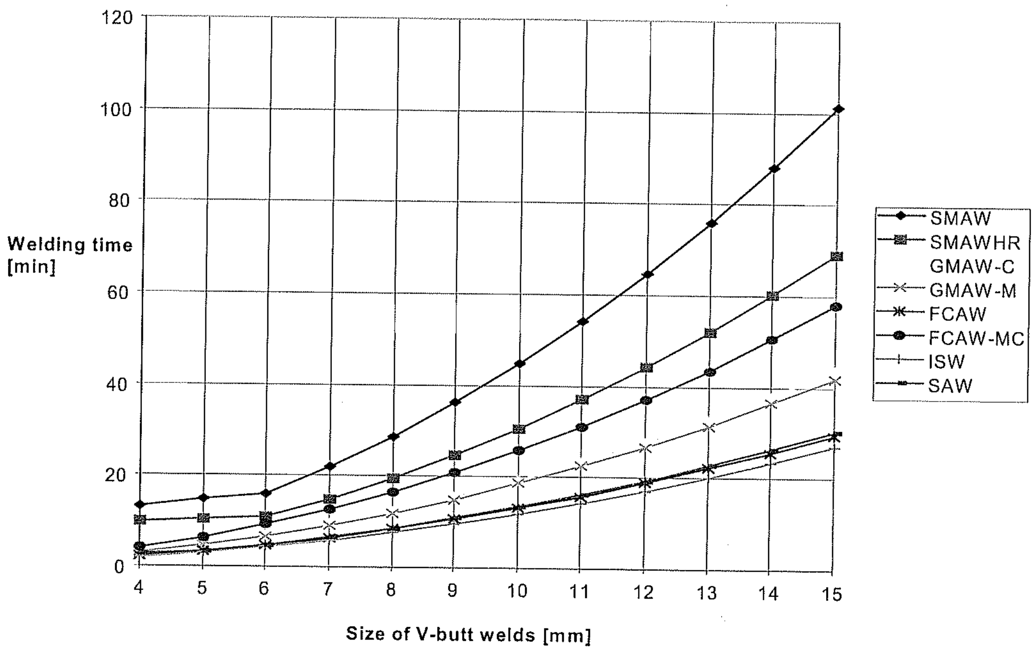



Figure 1. Welding times $T_{w2}$ (min/mm) versus weld size $a_W$ (mm) for downhand position

*Calculation of the times of special welding technologies*

The arc-spot welding is used for many structures, where only one side welding is possible. The production time is given by

$$T_{w4} = n_S T_S \,, \tag{11}$$

where $n_S$ is the number of spots, $T_S$ is the time of welding one spot weld and of transferring the electrode to the next spot. $T_S$ depends on the welding equipment and the degree of automation (Jármai et al. 1999).

4.2.2 *Fabrication times of post-welding treatments*

To increase the dynamic behaviour of welded structures, often post weld treatments (PWT) are used (Jármai et al. 2000). These treatments are grinding, TIG dressing, hammer- and shot peening, ultrasonic impact treatment (UIT). Time for PWT is

$$T_{PWT} = T_0 L_t \,, \tag{12}$$

where $T_0$ is the specific time (min/mm), $L_t$ is the treated weld length (mm). Table 2 shows the specific times for the given PWT.

Table 2. Time needed for different PWT techniques

| Method | $T_0$ (min/m) |
|---|---|
| Grinding | 60 |
| TIG dressing | 18 |
| Hammer peening | 4 |
| UIT | 15 |

### 4.2.3 *Time for flattening plates*

The smallest possible initial imperfection is important at the stability behaviour of plated structures that is why flattening plates can be necessary depending on the producer. In the catalogue of different companies one can find the times for flattening plates ($T_{FP}$ [min]) versus a plate thickness ($t$ [mm]) and the area of the plate ($A_p$ [mm$^2$]). Based on curve fitting calculations the time function can be written in the form:

$$T_{FP} = \Theta_{df}\left(a_e + b_e t^3 + \frac{1}{a_e t^4}\right)A_p , \tag{13}$$

where $a_e$=9.2*10$^{-4}$ [min/mm$^2$], $b_e$= 4.15*10$^{-7}$ [min/mm$^5$], $\Theta_{df}$ is the difficulty parameter ($\Theta_{df}$ = 1,2 or 3). The difficulty parameter depends on the form of the plate.

### 4.2.4 *Surface preparation time*

The surface preparation means the surface cleaning, sand spraying, etc. The surface cleaning time can be defined versus the surface area ($A_s$ [mm$^2$]) as follows:

$$T_{SP} = \Theta_{ds} a_{sp} A_s , \tag{14}$$

where $a_{sp}$ = 3*10$^{-6}$ [min/mm$^2$], $\Theta_{ds}$ is a difficulty parameter.

### 4.2.5 *Painting time*

The painting means making the ground- and the topcoat. The painting time can be given versus the surface area ($A_s$ [mm$^2$]) as follows:

$$T_P = \Theta_{dp}(a_{gc} + a_{tc})A_s , \tag{15}$$

where $a_{gc}$ = 3*10$^{-6}$ [min/mm$^2$] , $a_{tc}$ = 4.15*10$^{-6}$ [min/mm$^2$], $\Theta_{dp}$ is a difficulty factor, $\Theta_{dp}$=1,2 or 3 for horizontal, vertical or overhead painting. Tizani et al. (1996) proposed a value for painting 14.4 [$/m$^2$].

### 4.2.6 *Plate cutting and edge grinding times*

The cutting and edge grinding can be made by different technologies, like Acetylene, Stabilized gasmix and Propane with normal and high speed.

The cutting time can be calculated also by COSTCOMP. The normal speed acetylene has the highest time and the high-speed propane has the smallest cutting time (Fig. 2).

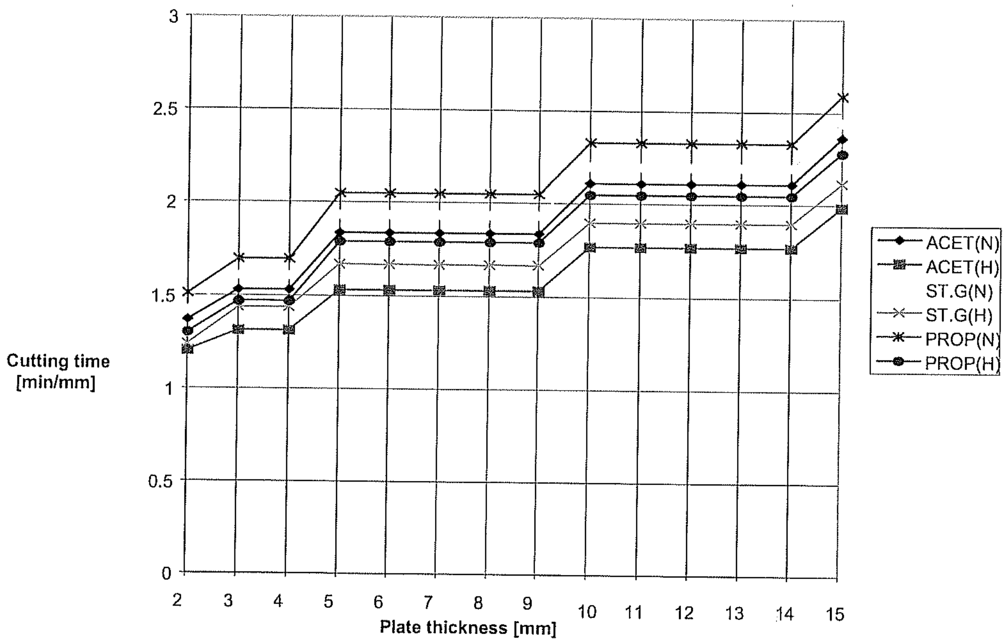



Figure 2. Cutting time for 1 mm length of plates, $T_{CP}$ (min/mm) versus thickness for fillet, T-, V-, 1/2 V butt welds

The cutting cost function can be formulated versus the thickness ($t$ [mm]) and cutting length ($L_c$ [mm]):

$$T_{CP} = \sum_i C_{CPi} t_i^n L_{ci} \,, \tag{15}$$

where $t_i$ the thickness in [mm], $L_{ci}$ is the cutting length in [mm]. The value of $n$ comes from curve fitting calculations.

4.2.7 *Times of hand cutting and machine grinding of strut ends*

At tubular structures a main part of the total cost is the cost of hand cutting and machine grinding of strut ends. We use the following formula (Farkas & Jármai 1997)

$$T_{CG} = \Theta_{dc} \sum_i \frac{2\pi d_i}{\sin \varphi}\left(4.54 + 0.4229 t_i^2\right), \tag{16}$$

where the fabrication cost factor is taken on the basis of Tizani et al. (1996) as Ł25/h = 40$/h = 0.6667 [$/min], and the difficulty factor is considered as $\Theta_{dc} = 3$. The diameter of the brace is $d_i$ in m, thickness is $t_i$ in mm. $\varphi$ is the angle between the two members (chord and brace) connected.

Note that Glijnis (1999) proposed a formula for one strut end in the case of oxyfuel cutting on CNC machine as follows:

$$K_{CG}(\$) = \frac{2.5\pi d_i}{(350 - 2t_i)0.3 \sin \varphi_i} \tag{17}$$

where 350 mm/min is the cutting speed, 0.3 is the efficiency factor, $d_i$ and $t_i$ are in mm.

4.2.8 *Total cost function*

The total cost function can be formulated by adding the previous cost functions together (depending on the structure some can be zero).

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left(T_{w1} + T_{w2} + T_{w3} + T_{w4} + T_{PWT} + T_{FP} + T_{SP} + T_P + T_{CP} + T_{CG}\right) \qquad (18)$$

Taking $k_m$ = 0.5-1 \$/kg, $k_f$ =0 -1 \$/min. The $k_f/k_m$ ratio varies between 0 - 2 kg/min. If $k_f/k_m$ = 0, then we get the mass minimum. If $k_f/k_m$ = 2.0 it means a very high labour cost (Japan, USA), $k_f/k_m$ = 1.5 and 1.0 means a West European labour cost, $k_f/k_m$ = 0.5 means the labour cost of developing countries. Even if the production rate is similar for these cases, the difference between costs due to the different labour costs is significant.

## 5 NUMERICAL EXAMPLE

We show the cost calculations at stiffened plates, where the welding cost is larger.

### 5.1 *Welded stiffened plate*

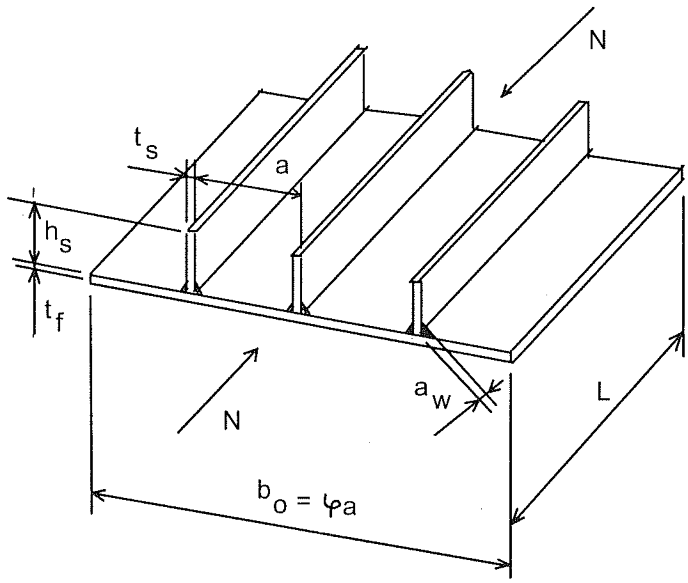



Figure 3. Stiffened plate

The problem is to minimise the cost of a stiffened plate considering the stress, overall and local buckling constraints in the case of different welding technologies.

The stiffened plates are widely applied in bridge and ship structures. Since the welding cost is a great part of the total cost, it is economic to optimize these structural components for minimum cost (Farkas & Jármai 1993, Jármai 2000a, 2000b).

The cost function is calculated according to Eq (18), where

$A=b_0t_f+\varphi h_s t_s$, $\Theta_{dw} = 3$, $\kappa=\varphi+1$, $L_w=2L\varphi$ and $\varphi$ is the number of stiffeners.

The stiffeners are welded to the plate by double fillet welds. The welding costs can be calculated for different welding technologies (Fig. 1).

The main data for the optimization are as follows:

Young modulus of the steel is $E$ = 2.1*10[5] MPa, material density is $\rho$ = 7.85*10[-6] kg/mm[3], Poisson parameter is $\nu$ = 0.3, yield stress is $f_y$ = 235 MPa, width of the plate is $b_0$=4200 mm and the plate length is $L$=4000 mm.
The compression force is

$$N = f_y b_0 t_{f\,max} = 235 * 4200 * 20 = 1.974 * 10^7 \text{ (N)} \tag{19}$$

The independent design variables are as follows (Fig. 3):
Thickness of the plate ($t_f$ ), height and thickness of the stiffeners ($h_s$, $t_s$) and the number of stiffeners ($\varphi = b_0/a$).

5.2 *Design constraints*

a) Overall buckling design rules, according to API (1987) for the compressed plate with uniform distance stiffeners ( Fig. 3).

$$N \le \chi f_y A \tag{20}$$

where, $\chi$ is the buckling constraints, versus the reduced slenderness factor:

$$\chi = 1 \quad \text{when} \quad \bar{\lambda} \le 0.5,$$
$$\chi = 1.5 - \bar{\lambda} \quad \text{when} \quad 0.5 \le \bar{\lambda} \le 1,$$
$$\chi = \frac{0.5}{\bar{\lambda}} \quad \text{when} \quad \bar{\lambda} \ge 1 \quad , \tag{21}$$

and

$$\bar{\lambda} = \frac{b_0}{t_f}\sqrt{\frac{12(1-\nu^2)f_y}{E\pi^2 k}}, \tag{22}$$

$$k_{min} = min(k_F, k_R), \tag{23}$$

$$k_R = 4\varphi^2 . \tag{24}$$

$$k_F = \frac{(1+\alpha^2)^2 + \varphi\gamma}{\alpha^2(1+\varphi\delta_P)} \quad \text{when } \alpha = \frac{L}{b_0} \le 4\sqrt{1+\varphi\gamma} \tag{25}$$

and

$$k_F = \frac{2\left(1+\sqrt{1+\varphi\gamma}\right)}{1+\varphi\gamma} \quad \text{when } \alpha \ge 4\sqrt{1+\varphi\gamma} \tag{26}$$

where

$$\delta_P = \frac{h_s t_s}{b_0 t_f}, \tag{27}$$

$$\gamma = \frac{EI_s}{b_0 D}, \tag{28}$$

$$I_s = \frac{h_s^3 t_s}{3}, \tag{29}$$

$$D = \frac{Et_f^3}{12(1-\nu^2)}. \tag{30}$$

Eq (28) can be rewritten as

$$\gamma = 4(1-\nu^2)\frac{h_s^3 t_s}{b_0 t_f^3} = 3.64\frac{h_s^3 t_s}{b_0 t_f^3}. \tag{31}$$

where $I_s$ 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 torsional stiffness of the main plate.
b) Buckling constraint of the stiffener is (Eurocode 3 1992):

$$\frac{h_s}{t_s} \leq \frac{1}{\beta_s} = 14\sqrt{\frac{235}{f_y}} \qquad (32)$$

The size constraints for the variables are as follows:

- $t_f = 6 - 20$ mm,
- $h_s = 84 - 280$ mm,
- $t_s = 6 - 25$ mm,
- $\varphi = 4 - 15$ mm.

The elements of cost function for the welded stiffened plate are as follows
Size of welded joint $a_w = t_s$
Cross section area $A = b_0 t_f + \varphi h_s t_s$
Material cost $\rho V = \rho LA$
Fabrication costs $k_f/k_m \sum_i T_i$

$T_{1w} = C_1 \Theta_{dw} \sqrt{\kappa \rho V}$, where $\rho = 7.85*10^{-6}$, $C_1 = 1$, $\kappa = \varphi + 1$, $\Theta_{dw} = 2$

$T_{2w} + T_{3w} = 1.3 \sum C_{2i} a_{wi}^n L_{wi}$ where $C_{2i} = 0.7889$, $n = 2$ for SMAW, $L_{wi} = 2 L \varphi$

$T_{FP} = \Theta_{de}\left(a_e + b_e t^3 + \frac{1}{a_e t^4}\right) A_p$ where $a_e = 9.2*10^{-4}$, $b_e = 4.15*10^{-7}$, $t = t_s$, or $t_f$,

$A_p = \varphi h_s L$ or $b_0 L$, $\Theta_{de} = 1$,

$T_{SP} = \Theta_{ds} a_{sp} A_s = 5*10^{-7}$ where $a_{sp} = 3*10^{-6}$, $A_s = \varphi h_s L + b_0 L$, $\Theta_{ds} = 1$,

$T_P = \Theta_{dp}(a_{gc} + a_{tc}) A_s$ where $a_{gc} = 3*10^{-6}$, $a_{tc} = 4.15*10^{-6}$, $A_s = \varphi h_s L + b_0 L$, $\Theta_{dp} = 2$,

$T_{CG} = \sum_i C_{CGi} t_i^n L_{ci}$ where $C_7 = 1.1388$, $t = t_s$ or $t_f$, $n = 0.25$, $L_{ci} = (h_s + L)$ or $(b_0 + L)$.

Table 3 shows the optimum discrete sizes of the stiffened plate with different welding technologies.

## 5.3 *Conclusions*

Figures 4 shows the distribution of the total cost. The diagrams illustrate that this distribution depends on the welding technologies, the type of welding, the ratio of material and fabrication specific costs and the structure type too.

The welding technologies in Figure 4 are given in decreasing order relating to the welding time and cost. The differences are great among them. The welding time and cost is the greatest for SMAW, the quickest and cheapest are the SAW, FCAW and ISW. For stiffened plates using SMAW 46% of the total cost is the welding cost, using SAW, this is only 20%.

The mass of stiffened plate is $\rho LA$ = 3258 kg (Table 3), the fabrication cost is 100 (15559-3258) / 15559 = 79 % of the total cost.

Table 3. Optimum rounded sizes of welded stiffened plates in mm with fillet welds using different welding technologies for $k_f/k_m$=2.0

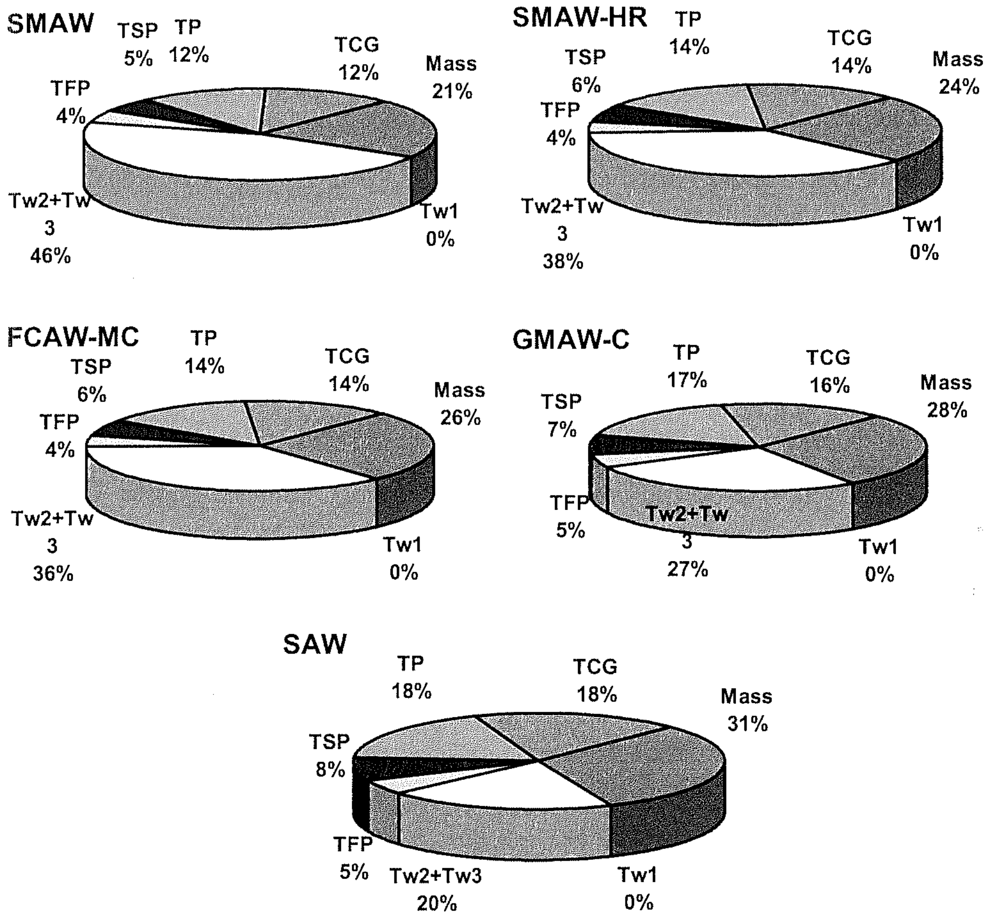
| Welding technology | $k_f/k_m$ | $h_s$ | $t_f$ | $\varphi$ | $t_s$ | $\rho V$ (kg) | $K/k_m$ (kg) |
|---|---|---|---|---|---|---|---|
| SMAW | 0.0 | 210 | 17 | 13 | 11 | 2737 | 2737 |
| | 0.5 | 230 | 17 | 6 | 19 | 3242 | 6313 |
| | 1.0 | 235 | 17 | 6 | 19 | 3258 | 9409 |
| | 1.5 | 235 | 17 | 6 | 19 | 3258 | 12484 |
| | 2.0 | 235 | 17 | 6 | 19 | 3258 | **15559** |
| SMAW HR | 0.0 | 210 | 17 | 13 | 11 | 2737 | 2737 |
| | 0.5 | 230 | 17 | 6 | 19 | 3242 | 5749 |
| | 1.0 | 230 | 17 | 6 | 19 | 3242 | 8257 |
| | 1.5 | 230 | 17 | 6 | 19 | 3242 | 10764 |
| | 2.0 | 235 | 17 | 6 | 19 | 3258 | **13306** |
| FCAW-MC | 0.0 | 210 | 17 | 13 | 11 | 2737 | 2737 |
| | 0.5 | 230 | 17 | 6 | 19 | 3242 | 5553 |
| | 1.0 | 230 | 17 | 6 | 19 | 3242 | 7864 |
| | 1.5 | 230 | 17 | 6 | 19 | 3242 | 10175 |
| | 2.0 | 235 | 17 | 6 | 19 | 3258 | **12521** |
| GMAW-C<br>GMAW-M | 0.0 | 210 | 17 | 13 | 11 | 2737 | 2737 |
| | 0.5 | 230 | 17 | 6 | 19 | 3242 | 5299 |
| | 1.0 | 230 | 17 | 6 | 19 | 3242 | 7357 |
| | 1.5 | 235 | 17 | 6 | 19 | 3258 | 9444 |
| | 2.0 | 230 | 17 | 6 | 19 | 3242 | **11471** |
| SAW<br>ISW<br>FCAW | 0.0 | 210 | 17 | 13 | 11 | 2737 | 2737 |
| | 0.5 | 230 | 17 | 6 | 19 | 3242 | 5064 |
| | 1.0 | 230 | 17 | 6 | 19 | 3242 | 6886 |
| | 1.5 | 230 | 17 | 6 | 19 | 3242 | 8707 |
| | 2.0 | 235 | 17 | 6 | 19 | 3258 | **10564** |

Cost savings can be achieved using a cheaper welding technology, like SAW instead of SMAW or GMAW, if it is possible. Table 4 shows the cost savings for the two different structures and for the five different groups of welding. For stiffened plates the cost savings can be 32 % of the total cost. All compared results are optimized.

Table 4 Cost savings using different welding technologies

| Welding technology | Stiffened plate | |
|---|---|---|
| $k_f/k_m$=2.0 | Total cost | Cost savings in % |
| SMAW | 15559 | 0 |
| SMAW-HR | 13305 | 14 |
| FCAW-MC | 12521 | 20 |
| GMAW-C | 11471 | 27 |
| SAW | 10560 | 32 |

Figure 4. The total cost distribution of the welded stiffened plate with fillet welds using different welding technologies for $k_f/k_m$=2.0




There are a great number of examples published on different fields to demonstrate the usability of optimisation forming a structure or a system to be more reliably and more economic. For example for bridgedecks (Jármai et al. 1997), for pipelines (Jármai & Lukács 1999), for sugar drying (Szabó & Jármai 2000), for furnace wall structures (Szűcs et al. 1997), etc.

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