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COST-EFFECTIVE STRUCTURAL OPTIMIZATION

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Dedicated to Professor István Páczelt on the occasion of his sixtieth birthday

Abstract. A special cost function enables designers to separate the material and fabrication costs to estimate a realistic minimum cost design of welded structures and to show the achievable cost savings. As a review of our research results in this field, numerical examples of I-beams, stiffened box beams, stiffened plates loaded by hydrostatic pressure, Vierendeel trusses, silos and bridge decks illustrate that significant cost savings can be achieved by minimum cost design.

Keywords: Cost function, welded structures

1. Introduction

The aim of optimum design is to find better structural solutions, which are safe and economic. The safety is guaranteed by fulfilling the design constraints and the economy is achieved by minimization of a cost function. Thus, a structural optimization needs a realistic cost function as well as design constraints, which express all the important engineering aspects. The constrained function minimization problem defined above can be solved using efficient computerized mathematical methods.

The aim of the present study is to show that, to bridge the gap between the optimization theory and design practice, it is necessary to include in the optimum design procedure a cost function, which contains not only the material, but also the fabrication costs. The effectiveness of the minimum cost design is illustrated by cost savings achieved for several structural examples.

2. Main phases of the structural optimization

A structural solution is characterized by materials used, dimensions, geometry, topology, profiles, production technology, connections, erection and maintenance. The cost function and the design constraints should contain these characteristics. Certain combinations of these characteristics give possible structural versions and the most suitable optimum solution is selected from these versions. The selection is made by means of comparisons, but only optimized versions can be realistically compared to each other.

The formulation of a cost function as well as the design constraints needs a large analytical research. Optimization means that the designer, on the basis of analytical results, knows the behaviour of a structure in a wide range of loads and characteristics mentioned above.

The optimum design procedure has three main phases as follows:

1. preparation: selection of candidate structural versions, definition of the cost function and the design constraints;
2. constrained function minimization using computerized mathematical methods;
3. evaluation: comparisons, working out design rules and expert systems.

3. The cost function

In the past the aim of aircraft designers was to minimize the structural weight, but now the optimization procedure is much more complex. Schmit [1] has emphasized that, for the development of structural synthesis, cost functions should be used instead of minimum weight design.

In the industrial practice the cost relating to the total weight of a structure is usually calculated. With these data only the minimum weight design can be solved. For a realistic cost minimization the material and fabrication costs should be separated. This necessity can be illustrated by the example of a welded stiffened plate. In this case different numbers of stiffeners give minimum weight and minimum cost. Minimum weight design means many thin stiffeners (like a honeycomb sandwich), but, because of the high welding cost, the optimum number of stiffeners for minimum cost is much smaller. The greater the ratio fabrication cost/total cost, the greater the difference between the minimum weight and cost designs.

In the cost function the material and fabrication costs are included

$$K = K_m + K_f = k_m \rho V + k_f \sum T_i \tag{3.1}$$

where ρ is the material density, V is the volume of structure, k_m and k_f are the material and fabrication cost factors, respectively, T_i are the production times. Equation (3.1) can be written in the form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left(T_1 + T_2 + T_3\right) \ . \tag{3.2}$$

Time for preparation, assembly and tacking can be expressed as

$$T_1 = C_1 \Theta_d \left(\ \rho V\right)^{1/2} \tag{3.3}$$

where $C_1 = 1$ min/kg$^{0.5}$, Θ_d is a difficulty factor expressing the complexity of the structure (planar or spatial, constructed from simple plate elements or profiles), is number of structural elements to be assembled.

Time for welding can be expressed as

$$T_2 = \sum C_{2i} a_{wi}^n L_{wi} \tag{3.4}$$

where a_W is the weld size, L_W is the weld length. Formulae for $C_{2i}a_{wi}^n$ are developed using the COSTCOMP database for different welding technologies and weld types – [2,3].

The additional time for electrode changing, deslagging and chipping can be calculated as

$$T_3 = 0.3T_2 \tag{3.5}$$

The final form of the cost function is

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left(C_1\Theta_d\,(\ \rho V)^{1/2} + 1.3T_2\right) \tag{3.6}$$

The following data of cost factors are used: $k_m = 0.5 - 1.2$ \$/kg, $k_f = 0 - 60$ \$/manhour = 0-1 \$/min. To give internationally usable results, values of $k_f/k_m = 0$, 1 and 2 kg/min are considered, the value of 0 means minimum weight design.

E.g. for fillet welds the welding cost formulae are given in Table 1 – Farkas-Jármai [4], Jármai-Farkas [5].

Welding technology	a_w (mm)	$10^3C_2a_w^n$ (min/mm)
SMAW	0-15	$0.7889a_w^2$
GMAW-C	0-15	$0.3394a_w^2$
GMAW-M	0-15	$0.3258a_w^2$
SAW	0-15	$0.2349a_w^2$

Table 1. Welding times for a weld length unit T_2/L_w (min/mm) of longitudinal fillet welds in normal position in the function of weld size and welding technology

The used abbreviations are as follows: SMAW – shielded metal arc welding, GMAW-C -gas metal arc welding with CO2, GMAW-M- gas metal arc welding with mixgas, SAW- submerged arc welding.

The above described cost function cannot give generally valid values, but it is suitable for realistic comparisons of structural versions. In the cost function only those parts should be considered, which contain the structural parameters to be optimized. For instance, times required for transportation of product elements between fabrication places in a manufacture is not necessary to calculate, since the structural dimensions to be optimized do not vary in such measure, which could affect the transportation times.

4. Design constraints

The development of structural optimization always needs new design aspects to be included in the procedure. In some recent studies we have considered a new design constraint on the limitation of the residual welding distortions. We have shown that our calculation method for residual welding stresses and distortions is suitable for estimation of these phenomena [6] and we have used our simple formulae in the structural optimization to guarantee the quality of welded structures containing eccentric welds, which can cause large deformation due to their shrinkage.

In the mathematical formulation of constraints on stress, fatigue, stability and fabrication requirements we need the up-to-date rules of related design standards. These rules express the safety and quality requirements in relatively simple forms, which are suitable for effective computations. The rules are based on international theoretical and experimental research results. The problem is that standards do not give all important details for design, thus, we should use in many cases more standards to include all the important constraints. For instance, Eurocode 3 [7, EC3 1992] is not completed for all the structural types yet, so we need to use BS (British), DIN (German) or API (American Petroleum Institute) rules as well.

To illustrate the measure of cost savings achievable by structural optimization some examples are shown from our recent studies.

5. Examples of application

5.1. Rolled and welded I-beams. The characteristics of the rolled I-section of UB I 914x419x388 – [7], [8, BS4 1993] – are as follows: the cross-section area is $A = 49400$ mm^2, the elastic section modulus is $W_x = 15.63x106$ mm^3. The optimum web height of the welded I-section having the same section modulus can be calculated as [4,9]

$$h = (3W_0/2\beta)^{1/3} \tag{5.1}$$

where W_0 is the required section modulus. The limiting web slenderness for pure bending according to EC3 is

$$\frac{1}{\beta} = 124\varepsilon \qquad \varepsilon = \left(\frac{235}{f_\theta}\right)^{1/2} \tag{5.2}$$

For the yield stress $f_y = 355$ MPa we obtain $h = 1335$ mm and the web thickness is $t_\omega = \beta h = 13$ mm. The limiting slenderness of the flange $1/\delta = 28\varepsilon$ is and the flange width

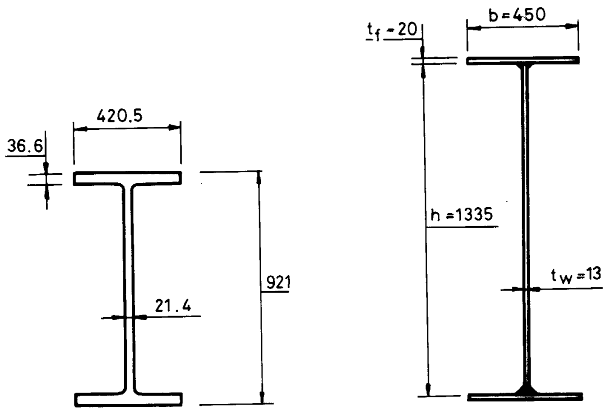

Figure 1: Comparision of a rolled and a welded I beam

is $b = h\,(\beta/2\delta)^{1/2} = 450$ mm, the flange thickness is $t_f = \delta b = 20$ mm. The cross-section area of the welded I-beam is $A = 35355$ mm^2, which is 40% smaller, than that of a rolled beam.

The cost of the welded I-beam of span length 10 m can be calculated using equations (3.2-3.6). Data: $\rho = 7850$ kg/m^3, $k_f/k_m = 1$ kg/min, $\Theta_d = 2$, double fillet welds of size $a_W = 6$ mm, GMAW-M. With these data $K/km = 3567$ kg. For the rolled I-beam we obtain 3878 kg, thus, the welded

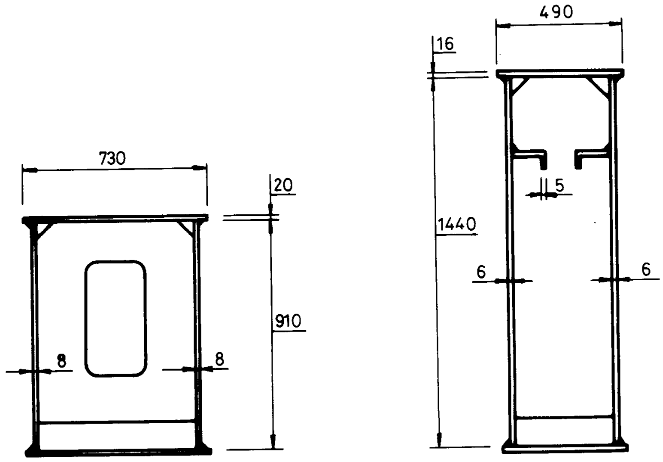

Figure 2: Comparison of box beams without and with longitudinal stiffeners

beam is 9% cheaper than the rolled one. It can be seen from the Figure 1 that this saving is achieved using thinner plates. It should be mentioned that this result is valid for beams in which the effect of shear can be neglected.

5.2. Welded box beams without and with longitudinal stiffeners. The limiting slenderness of a welded box beam loaded in bending can be increased by using longitudinal stiffeners in the 1/5 of the web height (Fig.2), therefore the web thickness can be decreased. The detailed minimum cost design procedures for box beams without and with longitudinal stiffeners, in which the transversal diaphragms and their welds are also considered [10], show that the cost of the box beam with stiffeners is 20% smaller than that of the beam without stiffeners.

5.3. Welded stiffened plates loaded in bending by hydrostatic pressure. For a simply supported base plate the equidistant arrangement of horizontal stiffeners is not optimal, since in this case the base plate parts of equal thickness are loaded by different maximal bending moments. The optimum positions of stiffeners can be calculated using the condition that all the base plate parts should be stressed to yield strength. In the numerical example treated in our study [11] the optimum number of stiffeners is determined as well, which gives the minimum cost of the whole plate structure. Trapezoidal stiffeners designed for bending are considered and the cost of vertical butt welds joining the

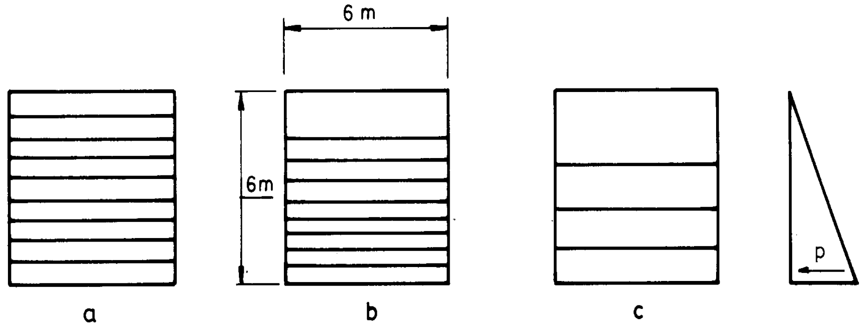

Figure.3: Values of K/k_m (kg) for a stiffened steel plate loaded by hydrostatic pressure: (a) 6972 for 8 stiffeners in equidistant position, (b) 6111 for 8 stiffeners in optimized position, (c) 7749 for 3 stiffeners in optimized position

base plate parts is also taken into account. The detailed calculations show that the optimum number of stiffeners is 8, using optimized stiffener positions 18% cost savings can be achieved compared with 8 stiffeners in equidistant position ($k_f/k_m = 1$). Using 8 stiffeners instead of 3 in optimum positions 31% cost savings can be achieved ($k_f/k_m = 1$), since the plate thicknesses can be decreased (Fig.3).

5.4. Optimum number of columns of a Vierendeel truss. In a numerical example of a simply supported Vierendeel truss (Fig.4.) welded from square hollow section rods the detailed calculations [12] show that the minimum cost can be achieved using 12 columns. The cost difference between structural versions of 10 and 12 columns is 30%.

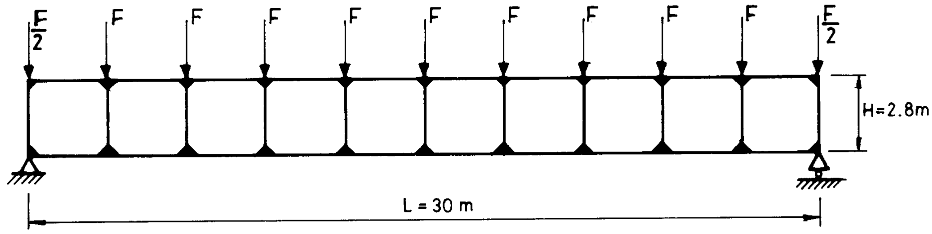

Figure 4: A simply supported Vierendeel truss with parallel chords welded from square hollow section rods

5.5. Welded steel silo. A detailed cost analysis is performed in the case of a silo of capacity 500 m3 loaded by cement powder consisting of a roof, cylindrical bin, ringbeam, hopper and columns [13]. The calculations show that the total cost depends on the ratio bin height/bin radius. The optimal value of this ratio was 6.20, the cost difference between the structural versions of ratio 1.76 and 6.20 was 8%.

5.6. Welded highway bridge deck with trapezoidal longitudinal stiffeners. Most of structural dimensions of a bridge deck should be determined according to standard prescriptions, but the distance of transverse stiffeners can be optimized. In the case of a numerical example treated in our study [14] the optimal distance was 2.5 m. The cost difference between the structural versions of distances 2.5 and 4.0 m was 20%.

6. Conclusions

A relatively simple cost function is proposed for the calculation of material and fabrication costs of welded structures. This cost function enables designers to show the difference between structural versions corresponding to minimum weight and minimum cost. The treated numerical examples show that significant cost savings can be achieved using optimization methods.

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