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NEW RESULTS IN THE DESIGN OF WELDED STRUCTURES

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Keywords:

minimum cost design, welded I-beams, post-welding treatments, improvement of fatigue stress range, economy of welded structures

Abstract

We have developed a new cost function containing the material and fabrication costs. Using this cost function it is possible to achieve savings in mass and cost in the design stage. The fabrication cost calculation is based on welding times depending on welding technology, type, size and length of welds. The minimum cost design procedure is applied for computing the economic effect of various post-welding treatments, which improve the fatigue strength of welded structures. Another application shows the economic effect of longitudinal stiffeners in a bent box beam.

1. Introduction

The structural optimization theory is developed in recent years in great measure, but the industrial application is very rare. Our aim is to contribute to the efficient application of optimization in design practice. The best way for this is to show the possibility of cost savings in design stage by using the mathematical optimization methods.

In order to develop a realistic cost function to be minimized, it is necessary to achieve a good cooperation between designers and manufacturers. This necessity has created the IIW Subcommission XV-F "Interaction between design and fabrication". This subcommission enables us to work out and discuss internationally minimum cost design procedures for some characteristic welded structures.

The aim of this paper is to show some of our results in this field. Firstly, the cost function is described, in which we have included the cost of the main fabrication phases of welded steel structures. Secondly, two application examples are treated as follows: (a) the measure of cost savings is computed achievable by using different post-welding treatments to improve the fatigue strength of welded joints; (b) cost savings is computed achievable by applying longitudinal stiffeners in box beams loaded in bending.

It should be mentioned that we have worked out several minimum cost design procedures for welded steel silos, bunkers, conical roofs, highway bridge decks, stiffened plates, sandwich panels and Vierendeel tubular trusses.

2. The cost function

The cost of a structure is the sum of the material, fabrication, transportation, erection and maintenance costs. The fabrication cost elements are costs of welding, cutting, preparation, assembly, tacking, painting, etc. It is very difficult to obtain such cost factors, which are valid all over the world. If we choose times, as the basic data of fabrication phases, we can handle this problem. The fabrication time depends on the technological level of the country and the manufacturer, but it is much closer to the real process to calculate with times. After computing the necessary time for each fabrication phase one can multiply it by a specific cost factor, which can represent the development level differences.

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 [1,2,3]. The artificial intelligence is also applied for cost estimation [4]. In this paper we would like to emphasise the role of fabrication costs, especially the role of welding costs using different welding technologies. We do not consider the amortisation, transportation, erection, maintenance costs, or the variation of exchange rates, etc.

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, ρ is the material density, V is the volume of the structure, T_i are the production times. We assume that the value of k_f is constant for a manufacturer. Eq.(1) can be written in the following form

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7) \tag{2}$$

The different time components can be calculated separately as follows:

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

is the time for preparation, assembly and tacking, Θ_d is a difficulty factor, κ is the number of structural elements to be assembled.

The difficulty factor expresses the complexity of the structure. Proposed values for the difficulty factor Θ_d are between 1 and 4 depending on the structures, position and shape of welded joints.

$$T_2 = \sum_i C_{2i} a_{wi}^{1.5} L_{wi} \tag{4}$$

is the time of welding, a_{wi} is the weld size, L_{wi} is the weld length, C_{2i} are constants given for different welding technologies. For manual-arc welding $C_2 = 0.8*10^{-3}$ and for CO_2-welding $C_2 = 0.5*10^{-3}$ min/mm$^{2.5}$.

$$T_3 = \sqrt{\Theta_d} \sum_i C_{3i} a_{wi}^{1.5} L_{wi} \tag{5}$$

is the time of additional fabrication actions such as changing the electrode, deslagging and chipping. $C_3 = 1.2*10^{-3}$ min/mm$^{2.5}$. Formulae (3,4,5) have been proposed by Pahl and Beelich [1].

Ott & Hubka [2] have proposed that

$C_3 = (0.2\text{-}0.4)C_2$ in average $C_3 = 0.3C_2$. Thus, the modified formula for T_2+T_3, neglecting $\sqrt{\Theta_d}$, is

$$T_2 + T_3 = 1.3 \sum C_{2i} a_{wi}^{1.5} L_{wi} \tag{6}$$

In the negligence of $\sqrt{\Theta_d}$ it is assumed that the difficulty factor should be considered only for T_1.

The software COSTCOMP [5] gives welding times and costs for different welding technologies on the basis of theoretical and experimental investigations. Using Eq. (2) for T_1, the other times are calculated with a generalized formula, where the power of a_w is changed from 1.5 to n

$$T_2 + T_3 = 1.3 \sum C_{2i} a_{wi}^{n} L_{wi} \quad (7)$$

The different welding technologies are SMAW (Shielded Metal Arc Welding), GMAW-C (Gas Metal Arc Welding with CO_2) and SAW (Submerged Arc Welding)

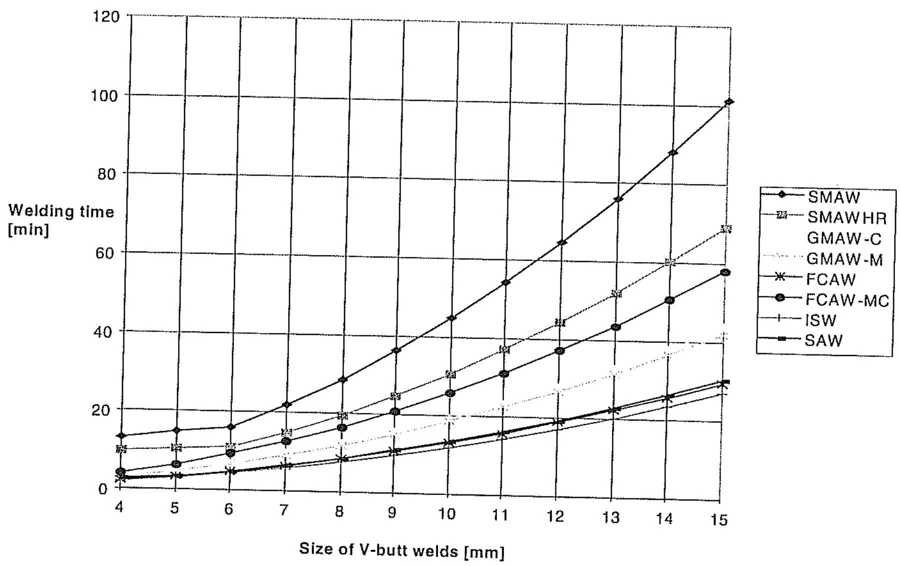


Fig. 1 Welding times T_2 (min/mm) in function of weld size a_w (mm) for longitudinal V butt welds, downhand position

Fig. 1 shows, that the welding times for longitudinal V butt welds in decreasing order is the highest for SMAW, SMAW-HR (high recovery), GMAW-C, GMAW-M (mixed gas), FCAW (flux cored), FCAW-MC (metal cored), ISW (self shielded flux cored) and the lowest for SAW.

In the catalogue of different companies one can find the times for flattening plates (T_4 [min]) in the function of 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:

$$T_4 = \Theta_{de} \left(a_e + b_e t^3 + \frac{1}{a_e t^4} \right) A_p \quad (8)$$

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

The surface preparation means the surface cleaning, sand-spraying, etc.

The surface cleaning time can be defined in the function of the surface area (A_s [mm^2]) as follows:

$$T_5 = \Theta_{ds} a_{sp} A_s \quad (9)$$

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

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

$$T_6 = \Theta_{dp}(a_{gc} + a_{tc})A_s \qquad (10)$$

where $a_{gc} = 3*10^{-6}$ [min/mm^2], $a_{tc} = 4.15*10^{-6}$ [min/mm^2], Θ_{dp} is a difficulty factor, Θ_{dp} =1,2 or 3 for horizontal, vertical or overhead painting.

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.

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

$$T_7 = \sum_i C_{7i} t_i^n L_{ci} \qquad (11)$$

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

The total cost function can be formulated by adding the previous cost functions together like in Eq. 2. Taking k_m = 0.5-1 \$/kg, k_f =0 -1 \$/min. The k_f/k_m ratio varies between 0 - 2 kg/min. The case of k_f/k_m= 0 gives the mass function. 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.

3. Effect of post-welding treatments on the optimum fatigue design of welded I-beams

Fatigue fracture is one of the most dangerous phenomena for welded structures. Welding causes residual stresses and sharp stress concentrations around the weld, which are responsible for significant decrease of fatigue strength. Butt welds with partial penetration, toes and roots of fillet welds are points where fatigue cracks initiate and propagate.

In order to eliminate or decrease the danger of fatigue fracture several methods have been investigated. Post-welding treatments (PWT-s) such as toe grinding, TIG-dressing, hammer peening and ultrasonic impact treatment (UIT) are the most efficient methods. These methods have been tested and a lot of experimental results show their effectiveness and reliability [7,8,9] Measure of improvement can be seen in Table 1. The economy of post-welding treatments is illustrated by means of a numerical example of a simply supported welded I-beam loaded in bending by a pair of pulsating forces. The vertical stiffeners are welded to the I-beam upper flange by double fillet welds, which causes a significant decrease of fatigue stress range. This low fatigue stress range is improved by various post-welding treatments. Based on the published experimental data it is possible to determine the measure of the increase of the fatigue stress range as well as the required treatment time for grinding, TIG dressing, hammer peening and ultrasonic impact treatment [9,10]. Including these data into the minimum cost design procedure it is possible to calculate the cost savings for different treatments. The treatment time is included into the cost function, the improved fatigue stress range is considered in the fatigue constraint. The comparison of costs for optimum structural versions with and without treatments shows the economy of different treatment methods.

Measure of improvement and specific treatment time for various treatments according to the published data *Table 1.*

Method	Ref.	T_0 (min/m)	Improvement %	α	Remark
Grinding	[7]	60	40	1.4	
TIG dressing	[10]	18	40	1.4	can be 70-100%
Hammer peening	[8]	4	100	2.0	can be 175-190%
UIT	[9]	15	70	1.7	

It should be mentioned that we want to calculate with the minimum value of improvement. A value larger than 100% cannot be realized in our numerical example.

In the investigated numerical example transverse vertical stiffeners are welded to a welded I-beam with double fillet welds. PWT is used only in the middle of the span, since near supports the bending stresses are small. The tension part of stiffeners in the middle of span is not welded to the lower flange and to the lower part of the web. Thus, the PWT is needed only for welds connecting the stiffeners to the upper flange (Fig.2). For this reason two types of stiffeners are used as it can be seen in Fig.2.

The total cost function containing the material and fabrication costs is as follows [4]:

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left(\Theta_d \sqrt{\kappa \rho V} + 1.3\sum C_{2i} a_{wi}^n L_{wi} + T_0 L_t\right) \qquad (12)$$

where ρ is the material density, V is the volume of the structure, k_m and k_f are the corresponding cost factors

Time for preparation, assembly and tacking is $T_1 = C_1 \Theta_d \sqrt{\kappa \rho V}$ (13)

Time for welding is $T_2 = \sum C_{2i} a_{wi}^n L_{wi}$ (14)

Time for additional works as deslagging, chipping and electrode changing is $T_3 = 0.3 T_2$ (15)

Time for PWT is $T_4 = T_0 L_t$ (16)

T_0 is the specific time (min/mm), L_t is the treated weld length (mm).

Design constraints are as follows.

The constraint on fatigue stress range can be formulated as

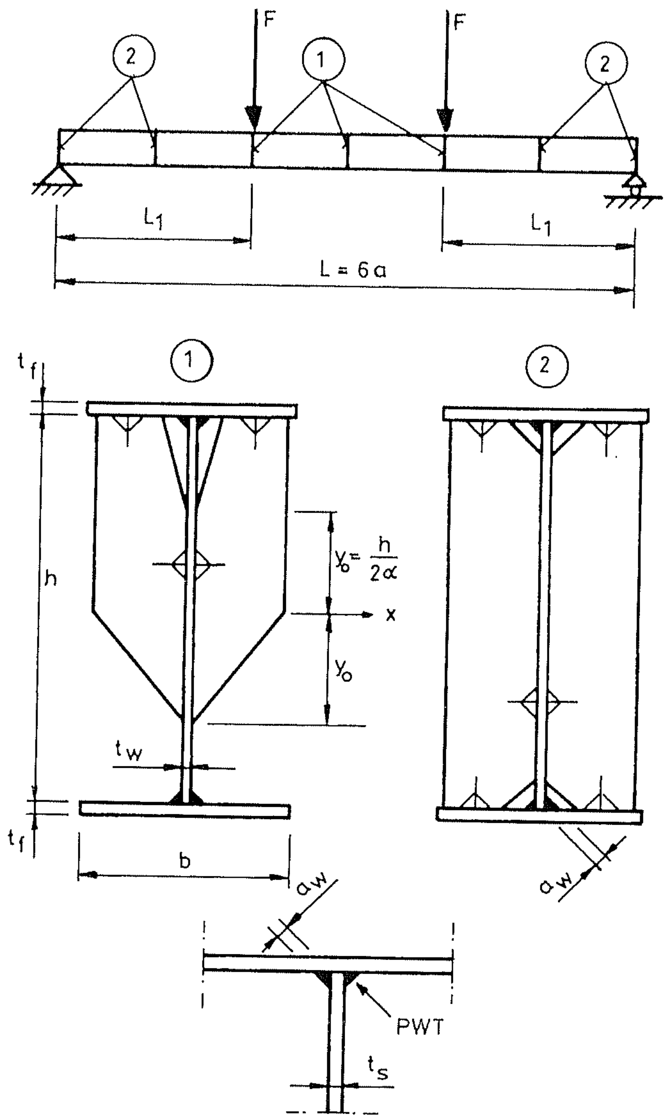
$$\frac{F_{max} L_1}{W_x} \le \frac{\alpha \Delta \sigma_C}{\gamma_{Mf}} \qquad (17)$$

where

$$W_x = \frac{I_x}{\frac{h}{2} + \frac{t_f}{2}}; \quad I_x = \frac{h^3 t_w}{12} + 2bt_f\left(\frac{h}{2} + \frac{t_f}{2}\right)^2 \qquad (18)$$

According to Eurocode 3 (EC3) [6] the fatigue stress range for as welded structure is $\Delta\sigma_C = 80$ MPa, the fatigue safety factor is $\gamma_{Mf} = 1.25$. α expresses the measure of improvement

$$\alpha = \frac{\Delta \sigma_{Cimproved}}{\Delta \sigma_{Caswelded}}. \qquad (19)$$



The beam is loaded by a pair of forces fluctuating in the range of 0 - F_{max} , so the bending stress range is calculated from F_{max}.

Fig. 2. Welded I-beam with vertical stiffeners. Double fillet welds with (1) and without (2) PWT

The constraint on local buckling of the web according to EC3 is

$$\frac{h}{t_w} \le 69\varepsilon; \qquad \varepsilon = \sqrt{\frac{235}{\alpha \Delta\sigma_C / \gamma_{Mf}}} \tag{20}$$

Note that we calculate in the denominator of ε with the maximum compressive stress instead of yield stress.

The constraint on local buckling of the compression flange is

$$\frac{b}{t_f} \leq 28\varepsilon \qquad (21)$$

We treat a numerical example with the following data.
F_{max} = 138 kN, L = 12 m, L_l = 4 m, $\Delta\sigma_C / \gamma_{Mf} = 80/1.25 = 64$ MPa, $\varepsilon = 1.916/\sqrt{\alpha}$;
$\Theta_d = 3$; number of stiffeners is 2x7 = 14, thus $\kappa = 3 + 14 = 17$.
The volume of the structure is

$$V = (ht_w + 2bt_f)L + 4bht_s + 1.5bht_s\left(1 + \frac{1}{\alpha}\right); t_s = 6 \text{ mm} \qquad (22)$$

The second member expresses the volume of stiffeners without PWT, the third member gives the volume of stiffeners with PWT.

For longitudinal GMAW-C (gas metal arc welding with CO_2) fillet welds of size 4 mm we calculate with

$$C_2 a_w^n L_w = 0.3394x10^{-3} x 4^2 x 4L = 260 \text{ min}, \qquad (23)$$

for transverse SMAW (shielded metal arc welding) fillet welds the following formula holds

$$C_2 a_w^n L_w = 0.7889x10^{-3} x 4^2 \left[6\left(b + \frac{2h}{\alpha}\right) + 16(b + h)\right] \qquad (24)$$

For the constrained minimization of the nonlinear cost function the Rosenbrock Hill-climb mathematical programming method is used complementing it with an additional search for optimum rounded discrete values of unknowns. The results of computation, i.e. the unknown dimensions h, t_w, b and t_f as well as the minimum costs for different values of k_f/k_m and α are given in Table 2.

It can be seen from Table 3. that with the various treatment methods the following cost savings can be achieved: grinding 14-15 %, TIG dressing 13–17 %, hammer peening 35-38 %, UIT 26-28 %. Thus, the cost savings are significant the most efficient method is the hammer peening. It can be also seen, that PWT methods affect the optimum dimensions.

Optimum rounded dimensions in mm and K/k_m (kg) values for different k_f/k_m ratios for various PWT-s. k_f/k_m = 0 means the minimum weight design without effect of PWT

Table 2.

PWT	k_f/k_m (kg/min)	h	t_w	B	t_f	K/k_m (kg)
as welded	0	1300	10	320	14	**2191**
	1	1230	10	310	16	3802
	2	1230	10	310	16	5399
Grinding	1	940	9	340	15	3343
	2	890	8	300	19	4704
TIG dressing	1	1000	9	330	14	3235
	2	1110	10	310	12	4770
Hammer peening	1	820	9	310	13	**2762**
	2	820	9	310	13	**3999**
UIT	1	970	10	300	12	3021
	2	810	8	300	17	4202

4. Minimum cost design of longitudinally stiffened box beams

A simply supported beam of span length L = 20 m (Fig.3) is subjected to uniformly distributed factored normal load of intensity p = 73.5 N/mm. It is assumed that the beam is constructed with 11 transverse diaphragms of uniform distance a = 2 m to stabilize the stiffeners against flexural buckling and to avoid distortions of the rectangular box shape. The longitudinal stiffeners are interrupted and welded to diaphragms.

The volume of the structure is $V = AL + 11bht_D/4 + 2A_SL$ (25)
where $A = 2ht_W + 2bt_f$ (26)
The thickness of diaphragms is $t_D = 0.7t_W$, but rounded to 4, 5, 6 mm.
The cross-sectional area of a stiffener is $A_S = (b_1 + b_2)t_S$ (27)
The number of structural elements to be assembled is κ = 4+11+20=35. The difficulty factor is taken as $\Theta_d = 3$.

The following welding times are considered.

4 longitudinal fillet welds of size a_w =0.5t_W, SAW (submerged arc welding), a_w = 0-15 mm

$$T_{21} = 0.2349L(0.5t_W)^2 \times 10^{-3} \quad (L \text{ in mm}) \quad (28)$$

Transverse fillet welds of constant size a_w = 4 mm connecting the diaphragms to the box section, SMAW (shielded metal arc welding)

$$T_{22} = 0.7889 \times 11(b+2h)4^2 \times 10^{-3} \quad (b \text{ and } h \text{ in mm}) \quad (29)$$

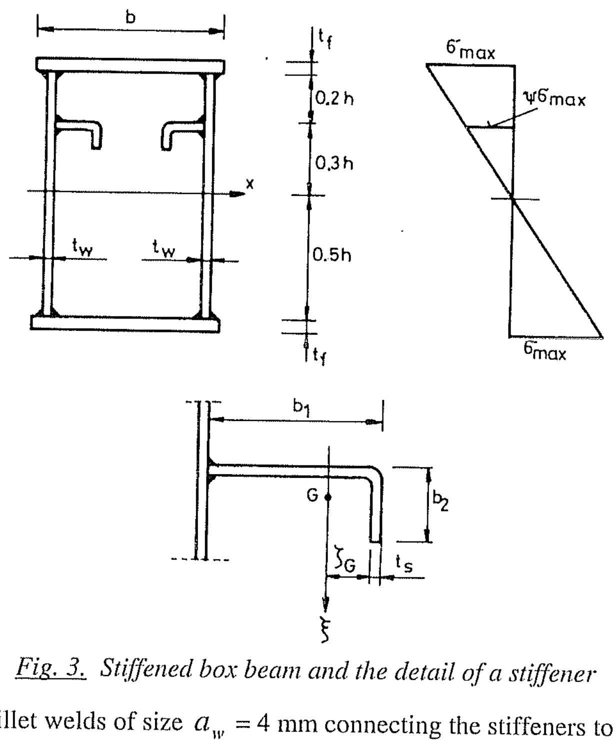


Fig. 3. Stiffened box beam and the detail of a stiffener

2 longitudinal fillet welds of size a_w = 4 mm connecting the stiffeners to the webs GMAW-C (gas metal arc welding with CO_2)

$$T_{23} = 0.3394 \times 2L \times 4^2 \times 10^{-3} \quad (L \text{ in mm}) \quad (30)$$

Transverse fillet welds of size $a_w = 4$ mm connecting the stiffeners to the diaphragms, SMAW

$$T_{24} = 0.7889(42.5 t_S \varepsilon) 4^2 \times 20 \times 10^{-3} \quad (t_S \text{ in mm}) \tag{31}$$

Stress constraint due to bending is

$$M / W_x = pL^2 / (8W_x) \le f_y \tag{32}$$

where the static moment and the moment of inertia are

$$W_x = 2I_x / (h + t_f); \; I_x = h^3 t_W / 6 + b t_f (h + t_f)^2 / 2 \tag{33}$$

Note that the moment of inertia of stiffeners is neglected.

The unknowns in the optimization are as follows: h, b, t_W, t_f, t_S.

The advanced backtrack method was used for optimisation. This is a combinatorial programming technique, which solves nonlinear constrained function minimisation problems by a systematic search procedure. The advantage of the technique, that it uses only discrete variables, so the solution is usable. The general description of backtrack can be found in the works of Golomb & Baumert [14] and Walker [15]. This method was applied to welded girder design by Annamalai [12] and Farkas & Jármai [4].

The algorithm is suitable to find optimum of those problems, which are characterized by monotonically increasing or decreasing objective functions. Thus, the optimum solution can be found by increasing or decreasing the variables.

The original version of backtrack was modified by rebuilding the algorithm so that it is independent from the number of variables, since in the original algorithm all variable value is calculated by the halving procedure, except the last one. Another development is that the Van Wijngaarden-Dekker-Brent method (Brent [13]) was built into the algorithm to calculate the last variable value from the cost function. In case of mass minimization this calculation is relatively easy, because of the linearity, but introducing a nonlinear cost function the analytical solution is in most cases impossible. This method combines root bracketing, bisection and inverse quadratic interpolation to converge from the neighbourhood of a zero crossing. Combines the sureness of bisection with the speed of a high-order method when appropriate.

The optimization of the box beam is performed by Hillclimb and backtrack methods. In the case of longitudinally stiffened box beam the cost function should be minimized considering the constraints. In the case of box beams without stiffeners the following modifications should be used: $t_S = 0$ and $T_{23} = T_{24} = 0$. The results are given in Tables 3 and 4.

Optimum dimensions in mm of the box beam without longitudinal stiffeners obtained by Hillclimb method *Table 3.*

k_f/k_m	h	t_W	B	t_f	K/k_m (kg)
0	1100	9	540	20	6580
1	900	8	740	20	9249
2	910	8	730	20	11474

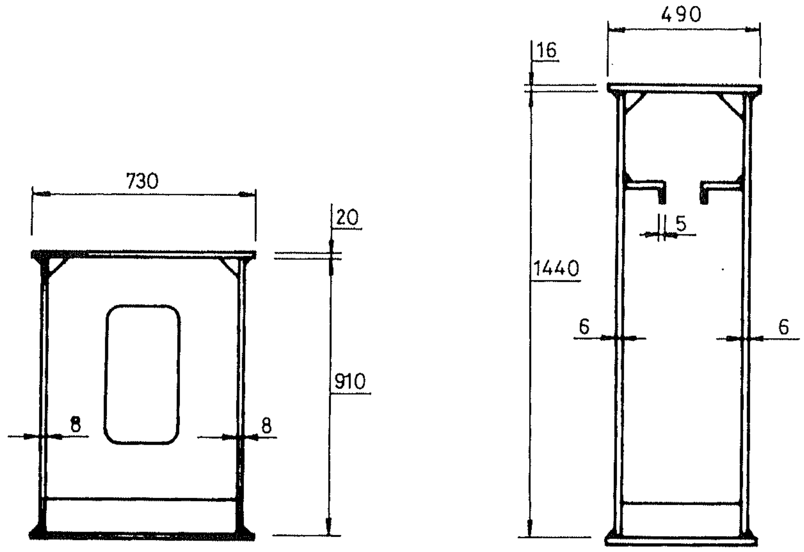


Fig. 4. Optimum sizes of box beams without and with longitudinal stiffeners, for k_f/k_m =2

It can be seen that the results obtained by Hillclimb and backtrack methods are near the same, so obtained for unstiffened and stiffened box beams shows cost savings of 18-21%, so the application of longitudinal stiffeners is economic. Fig. 4 shows the optmized box beams without and with longitudinal stiffeners. It can be seen that the beam with stiffeners is higher and narrower

The optimized values of cross-sectional areas and costs of box beams without and with longitudinal stiffeners placed in a distance of 1/5 web height show that the use of stiffeners results in considerable savings [16].

Optimum dimensions in mm of the box beam with longitudinal stiffeners obtained by Hillclimb and backtrack method. *Table 4.*

method	k_f/k_m	h	t_W	b	t_f	t_S	K/k_m (kg)
	0	1450	6	440	18	5	5610
Hillclimb	1	1450	6	490	16	5	7588
	2	1440	6	500	16	5	9619
	0	1450	6	490	16	5	5591
Backtrack	1	1440	6	470	17	5	7608
	2	1440	6	490	16	5	9585

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