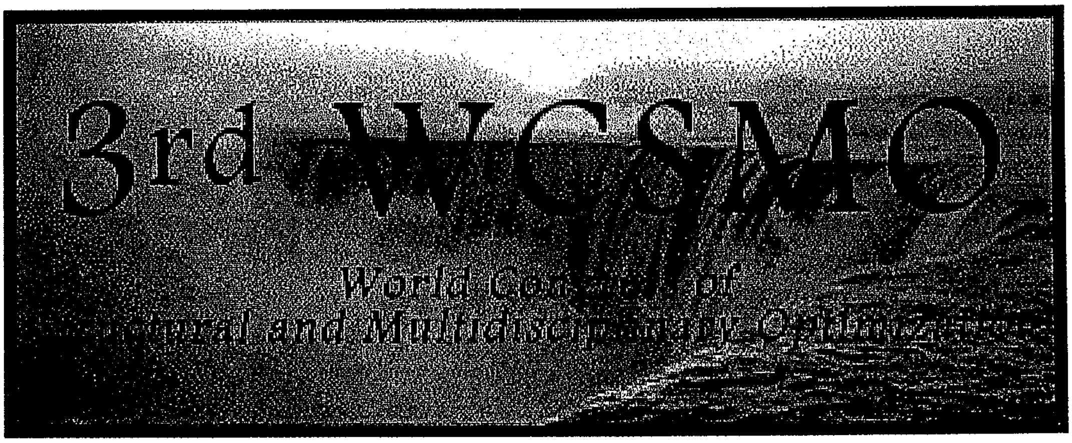

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Optimum cost design of welded box beams with longitudinal stiffeners using advanced backtrack method

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1. Abstract
The use of longitudinal stiffeners in box girders loaded in bending results in savings in weight and cost. To study these savings the optimized box beams without and with stiffeners are compared to each other. A cost function is defined containing material and fabrication (welding) costs. This function is nonlinear in the structural dimensions to be optimized, therefore an advanced backtrack method is worked out and applied. An illustrative numerical example shows the savings.

2. Keywords
Box beams, weight and cost minimization, welded structures, backtrack method

3. Introduction
Box beams are widely used in load-carrying structures because of their large bending and torsional stiffness. The minimum cross-sectional-area design of a simple welded box beam [1] shows that, to decrease this area, the web plate slenderness should be increased. This can be achieved using longitudinal stiffeners placed in 1/5 distance of web height. We have developed a cost function for welded structures using the COSTCOMP database [2,3]. This cost function contains nonlinear expressions for unknowns. The cross-sectional area minimization can be solved analytically, but, for the minimum cost design, a computerized mathematical constrained function minimization method should be used, since the cost function is nonlinear.
The backtrack discrete programming method is suitable for problems with few unknowns, but, till now, we have used it only for linear objective functions. For nonlinear objective functions we have worked out a new advanced version.

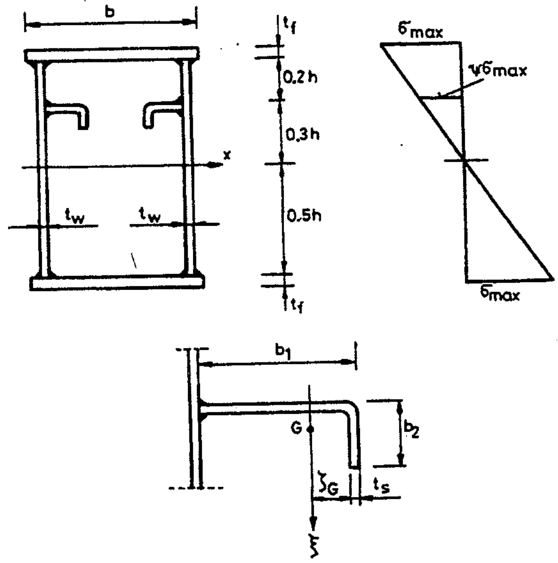

Figure 1. Stiffened box beam and the detail of a stiffener

4. Minimum cost design of longitudinally stiffened box beams
4.1 The cost function
In the cost function the material and fabrication costs are included

$$K = K_m + K_f = k_m \rho V + k_f \Sigma T_i \tag{1}$$

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 (1) can be written in the form of

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

Time for preparation, assembly and tacking can be expressed as

$$T_1 = C_1 \Theta_d (\kappa \rho V)^{1/2} \tag{3}$$

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), κ is number of structural elements to be assembled.
Welding time is

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

where a_W is the weld size, L_W is the weld length. Formulae for $C_2 a_W^n$ are developed using the COSTCOMP database for different welding technologies and weld types [4].
The additional time for electrode changing, deslagging and chipping can be calculated as

$$T_3 = 0.3 T_2 \quad (5)$$

The final form of the cost function is

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left(\Theta_d \sqrt{\kappa \rho V} + 1.3(T_1 + T_2 + T_3)\right) \quad (6)$$

It can be seen that this function contains nonlinear members of the unknown structural dimensions, therefore an advanced backtrack method should be used for the minimization.
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 are considered, the value of 0 means minimum weight design.
The cost function of a longitudinally stiffened box beam (Fig.1) can be formulated as follows.
A simply supported beam of span length L = 20 m 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 $V = AL + 11bht_D/4 + 2A_SL$ (7)

where $A = 2ht_W + 2bt_f$ (8)

The thickness of diaphragms is $t_D = 0.7t_W$, but rounded to 4, 5, 6.
The cross-sectional area of a stiffener is $A_S = (b_1 + b_2)t_S$ (9)
b_1 and b_2 can be calculated according to equation (16).
The number of structural elements to be assembled is κ = 4+11+20=35. The difficulty factor is taken as $\Theta_d = 3$.

4.2 Design constraints

Stress constraint due to bending $M/W_x = pL^2/(8W_x) \le f_y$ (10)

where the static moment and the moment of inertia are $W_x = 2I_x/(h+t_f)$; $I_x = h^3 t_W/6 + bt_f(h+t_f)^2/2$ (11)

Note that the moment of inertia of stiffeners is neglected.
The local buckling constraint for the compression flange according to Eurocode 3 [5] can be expressed as

$$b/t_f \le 1/\delta = 42\varepsilon; \qquad \varepsilon = \sqrt{235/f_y} \quad (12)$$

The local buckling constraint for the upper part of webs is $0.2h/t_w \le 42\varepsilon/(0.67+0.33\psi)$ (13)

$$h/t_w \le 242\varepsilon = 1/\beta \quad (14)$$

For the lower part of webs it is $\psi = -5/3 = -1.667$ and $0.8h/t_w \le 62\varepsilon(1-\psi)\sqrt{-\psi}$ or $h/t_w \le 267\varepsilon$ (15)

thus, the limiting slenderness defined by (14) is governing.
The local buckling constraints for the cold-formed stiffeners according to DASt Richtlinie 016 [6]

$$b_1/t_s \le 1.33\sqrt{E/f_y} \quad \text{and} \quad b_2/t_s \le 0.43\sqrt{E/f_y}$$

or in another form $b_1/t_s \le 30\varepsilon = \delta_1$ and $b_2/t_s \le 12.5\varepsilon = \delta_2$ (16)

The overall buckling constraint for compressed stiffeners according to API design rules [7]

$$I_\xi \ge 4at_W^3 \quad (17)$$

where a is the distance of diaphragms. The location of the center of gravity for a stiffener (Fig.1), calculating with

$$b_1 = \delta_1 t_s \quad \text{and} \quad b_2 = \delta_2 t_s \quad \text{is} \quad \zeta_G = \frac{t_s \delta_1^2}{2(\delta_1 + \delta_2)} \quad (18)$$

and the moment of inertia is given by $I_\xi = C_s t_s^4$; $C_S = \frac{1}{12}\left(\delta_1^3 + \frac{3\delta_1^2\delta_2^2}{\delta_1 + \delta_2}\right)$ (19)

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

4.3 The advanced backtrack method

Backtrack method is a combinatorial programming technique, solves nonlinear constrained function minimization problems by a systematic search procedure. The general description of backtrack can be found in the works of Walker [8] and Golomb & Baumert [9].An efficient and suitable built in search method is the interval halving procedure. We assume that the objective function is monotonously decreasing, if the variables are decreasing. All variables are calculated by the halving procedure, except the last variable, which is calculated from the objective function. The original version of backtrack was modified by rebuilding the algorithm so, that it is independent from the number of variables. Another development is, that the Van Wijngaarden-Dekker-Brent method [10] 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, 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. While the false position and secant methods assume approximately linear behaviour between two prior root estimates, inverse quadratic interpolation uses three prior points to fit an inverse quadratic function. This method combines the sureness of bisection with the speed of a high-order method when appropriate.

5. Optimization and results

The optimization of the box beam is performed by Hillclimb and backtrack methods. In the case of longitudinally stiffened box beam the cost function (6) should be minimized considering the constraints (14,16,18,21). 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 1 and 2.

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

Table 1. Optimum dimensions in mm of the box beam without longitudinal stiffeners obtained by Hillclimb method

method	k_f/k_m	h	t_W	b	t_f	t_S	K/k_m (kg)
	0	1450	6	440	18	5	5610
Hillcllimb	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

Table 2. Optimum dimensions in mm of the box beam with longitudinal stiffeners obtained by Hillclimb and backtrack method

It can be seen that the results obtained by Hillclimb and backtrack methods are near the same, so the new version of backtrack is suitable for nonlinear objective functions. The comparison of results obtained for unstiffened and stiffened box beams shows cost savings of 18-21%, so the application of longitudinal stiffeners is economic.

6. Conclusions

Comparisons of the optimized cross-sectional 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. The cost function contains material and welding costs, considering also the welds necessary for transverse diaphragms. Since this cost function is nonlinear, a new version of the backtrack discrete programming method is developed and used. This version contains a subroutine for the computation of the roots of a nonlinear function with one variable.

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8. References

[1] Farkas,J. (1984) Optimum design of metal structures. Budapest, Akadémiai Kiadó, Chichester, Ellis Horwood.

[2] COSTCOMP (1990) Programm zur Berechnung der Schweisskosten. Düsseldorf, Deutscher Verlag für Schweisstechnik.

[3] Bodt,H.J.M. (1990). The global approach to welding costs. The Hague, The Netherlands Welding Institute.

[4] Farkas,J., Jármai,K. (1997) Analysis and optimum design of metal structures. Rotterdam-Brookfield, Balkema.

[5] Eurocode 3. (1992) Design of steel structures. Part 1.1. General rules and rules for buildings. European Prestandard ENV 1993-1-1.CEN European Committee for Standardisation, Brussels.

[6] DASt Richtlinie 016. Entwurf (1986) Bemessung un konstruktive Gestaltung von Tragwerken aus dünnwandigen kaltgeformten Bauteilen. Deutscher Ausschuss für Stahlbau.

[7] Americal Petroleum Institute (API) (1987) Bul.2V. Bulletin on design of flat plate structures. Washington, D.C.

[8] Walker,R.J. (1960) An enumerative technique for a class of combinatorial problems. In Proc. of Symposia in Appl. Math Amer. Math. Soc. Providence, R.I. 10, 91-94.

[9] Golomb,S.W. and Baumert,L.D. (1965) Backtrack programming. J.Assoc.Computing Machinery 12, 516-524.

[10] Brent,R.P. (1973) Algorithms for minimization without derivatives. Englewood Cliffs NJ. Prentice Hall.