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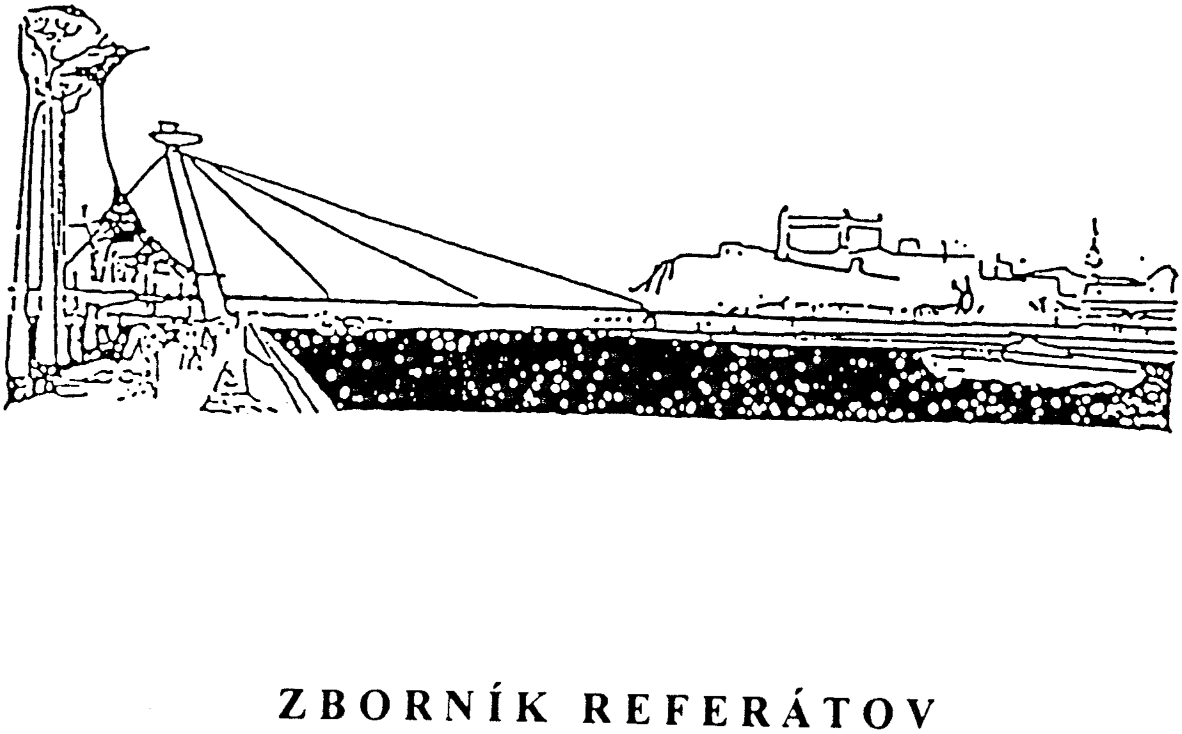
DESIGN AND RECONSTRUCTION OF STEEL STRUCTURES



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József Farkas and Károly Jármai

OPTIMUM DESIGN OF A WELDED BEAM CONSIDERING THE CONSTRAINT ON RESIDUAL WELDING DEFORMATION

Abstract

In order to meet the fabrication requirements in design process of welded structures, a cost function is used in optimum design, which contains the material and fabrication costs. A relatively simple method has been developed for the calculation of residual welding stresses and distortions. To fulfil the fabrication tolerances a distortion constraint is incorporated in the optimum design process. These two main aspects are illustrated by a numerical example of a simple welded structure constructed from a deck plate stiffened by longitudinal ribs of rectangular hollow section. The ribs are connected to the deck plate by eccentric longitudinal fillet welds the shrinkage of which causes residual deflection of the beam. The limitation of this deflection affects the deck plate thickness and the cost of the structure.

1. Introduction

Structural optimization has been developed in recent decades in a great measure. Besides the new mathematical methods the optimum design has been applied for many types of structures e.g. frames, trusses, stiffened plates, tubular structures, etc. During our research we have concentrated our efforts to contribute to this great development by some specialities. Our aim is to bridge the gap between theory and design and fabrication practice. Importance of this trend has been internationally emphasized by organizing a new subcommission in the International Institute of Welding (IIW) XV-F "Interaction of design and fabrication".

Firstly, we have developed and applied a cost function containing the material and fabrication costs. Secondly, we have formulated special design constraints relating to fabrication. Some studies in this relation can be mentioned as follows. In an article (Farkas 1991) the cost of post-welding treatment has been considered in the optimum

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Prof.József Farkas, DSc.and Prof.Károly Jármai, DSc. Department of Materials Handling and Logistics, University of Miskolc, Hungary, H-3515 Miskolc. Tel. 36-46-565-111,
Fax: 36-46-367-828, e-mail: altfar@gold.uni-miskolc.hu, altjar@gold.uni-miskolc.hu

design of box beams loaded by pulsating forces. The economy of toe grinding of fillet welds joining diaphragms to the box section has been shown. A special constraint on thickness limitation is taken into account in the study on optimum design of press frames constructed from welded box sections (Farkas 1974). The cost function based on the COSTCOMP software (COSTCOMP 1990, Bodt 1990) has been applied to the optimization of welded silos (Farkas and Jármai 1996a), stiffened plates (Farkas and Jármai 1995), Vierendeel trusses (Farkas and Jármai 1996b) and highway bridge decks (Jármai et al. 1997). Our research results have been published in the book of Farkas and Jármai (1997a).

A new aspect is to incorporate the fabrication tolerances in the design process to assure the good quality of welded structures. We have formulated distortion constraints applying our calculation method for residual welding stresses and distortions (Farkas and Jármai 1997b). Residual welding stresses and distortions have unfavourable effects on the behaviour of welded structures. Residual stresses can cause brittle fracture, they increase the fatigue crack propagation rate and decrease the overall and local buckling strength. Initial imperfections caused by residual distortions decrease also the buckling strength and affect the fabrication quality and the assembly.

These unfavourable effects should be eliminated or decreased. The importance of this problem led to the organization of a IIW joint working group X/XV-RSDP (residual stresses and distortion prevention) in frame of which a lot of documents have been presented and discussed during the IIW Annual Assembly in San Francisco in 1997. Our document (Farkas and Jármai 1997b) has been recommended for publication in the journal "Welding in the World". Using our calculation method a design constraint can be incorporated in the optimum design process to guarantee the good quality of welded structures.

The aim of the present study is to show these specialties in the miminum cost design of a simple stiffened plate structure. The investigated structure consists of a deck plate stiffened by longitudinal ribs of rectangular hollow section (RHS) connected to the deck plate by longitudinal fillet welds (Fig.1). The simply supported stiffened plate is subjected to uniform normal load. In the optimization procedure the dimensions of RHS ribs and the thickness of the deck plate are sought, which minimize the cost and fulfil the design constraints. The cost function contains the material and fabrication costs. The design constraints relate to the maximum stress due to bending of the whole structure and the local bending of deck plate strips as well as to the limitation of residual welding deflection due to shrinkage of eccentric welds.

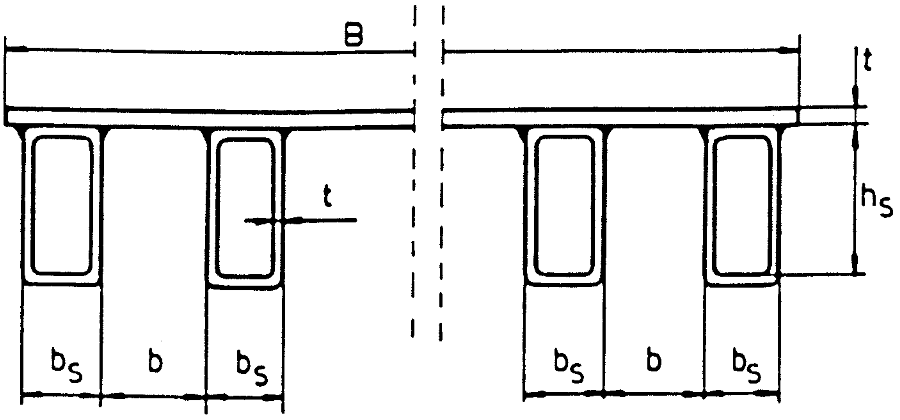

Fig.1. The investigated welded structure

2. The cost function

As mentioned in the introduction we have developed on the basis of COSTCOMP software a cost function containing the material and fabrication cost

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left[C_1\Theta_d\left(\kappa\rho V\right)^{0.5} + 1.3T_2\right] \qquad (1)$$

where ρ is the material density, k_f and k_m are the fabrication and material cost factors, respectively, κ is the number of structural elements to be assembled, $V = AL$ is the volume of the structure, Θ_d is the difficulty factor, C_1 = 1.0 min/kg$^{0.5}$. The welding time is given by

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

For submerged arc welding (SAW) it is $C_2 a_w^n = 0.2349 * 10^{-3} a_w^2$ (3)

and the weld length is $L_W = 2nL$ (L in mm), n is the number of longitudinal ribs, A is the cross-sectional area $A = nA_{RHS} + Bt$ (4)

where A_{RHS} is the cross-sectional area of a RHS.

RHS are used according to prEN 10219-2 (1992). We select RHS with $b_S = h_S/2$ only. The corner radius is taken as $2t_S$. For the calculation of cross-sectional area and moment of inertia the approximate formulae proposed by DASt Richtlinie 016 (1986) are used as follows:

$$A_{RHS} = 2t_S(1.5h_S - 2t_S)\left(1 - 0.43\frac{4t_S}{1.5h_S - 2t_S}\right) \tag{5a}$$

$$I_{RHS} = \left[\frac{(h_S - t_S)^3 t_S}{6} + \frac{t_S}{2}\left(\frac{h_S}{2} - t_S\right)(h_S - t_S)^2\right]\left(1 - 0.86\frac{4t_S}{1.5h_S - 2t_S}\right) \tag{5b}$$

3. Calculation of residual welding stresses and distortions

The derivation of calculation formulae worked out on the basis of the Okerblom's method (Okerblom et al. 1963) is described in our book (Farkas and Jármai 1997a). For the calculation of distortion of beam-like structures due to shrinkage of longitudinal welds the following formulae can be used.

The specific strain in the gravity center G of a cross-section is given by

$$\varepsilon_G = \frac{0.3355\alpha_0 Q_T}{c_0 \rho A} \tag{6}$$

where A is the cross-sectional area, c_0 is the specific heat, α_0 is the coefficient of thermal expansion, ρ is the material density. For steels it is

$$\varepsilon_G = 0.844 * 10^{-3} Q_T / A \tag{7}$$

where the specific heat input is

$$Q_T = \eta UI / v_w = 3600\eta U\rho A_w / \alpha_N \tag{8}$$

η is the coefficient of heat efficiency, U is arc voltage, I is arc current, v_W is speed of welding, A_W is the cross-sectional area of weld, α_N is coefficient of penetration.

For hand welding $\qquad Q_T(joule/mm) = 78.8a_w^2 \qquad (9)$

and for automatic welding (SAW) $\qquad Q_T = 59.5a_w^2 \qquad (10)$

where a_W (mm) is the weld dimension.

The curvature due to the weld eccentricity is given by

$$C = 0.844 * 10^{-3} Q_T y_T / I_x \tag{11}$$

y_T is the weld eccentricity, I_X is the moment of inertia of the cross-section.

The shrinkage of a weld causes a shortening of a bar $\Delta L = \varepsilon_G L$ where L is the length of the bar, the deformations caused by the curvature C can be calculated as an effect of a bending moment $M = CEI_X$.

4. The design constraints

Constraint on maximum stress due to bending of the whole structure with n ribs of RHS can be formulated as $\qquad \sigma_{max} = M_{max} / W_x \le f_{y1} = f_y / \gamma_{M1} \qquad (12)$

where f_y is the yield stress, $\gamma_{M1} = 1.1$ is a partial safety factor according to Eurocode 3 (EC3) (1992), $M_{max} = pL^2/8$, $p = Bp_0$, p_0 is the factored intensity of the uniform normal load, the section modulus and the moment of inertia are given by

$$W_x = I_x / (h_S - y_G) \tag{13}$$

$$I_x = nI_{RHS} + nA_{RHS}\left(\frac{h_S}{2} - y_G\right)^2 + Bty_G^2 \qquad y_G = \frac{nA_{RHS}h_S}{2\left(nA_{RHS} + Bt\right)} \quad (14)$$

Constraint on reduced stress due to bending of the whole structure and local bending of deck plate strips between ribs can be formulated as follows:

stress in deck plate due to bending of the whole structure is

$$\sigma_L = \sigma_{\max} y_G / \left(h_S - y_G\right) \quad (15)$$

and the stress in deck plate due to local bending is

$$\sigma_t = \frac{pb^2}{2t^2} \qquad b = \frac{B - 50 - nb_S}{n - 1} \quad (16)$$

the reduced stress is $\left(\sigma_L^2 + \sigma_t^2 + \sigma_L\sigma_t\right)^{1/2} \le f_{y1}$ (17)

Local buckling constraint of the deck plate strips can be formulated according to EC3 as follows: $b/t \le 42\left(235/\sigma_L\right)^{1/2}$ (18)

Constraint on maximum deflection due to shrinkage of longitudinal welds is given by

$$w_{\max} = CL^2/8 \le w_{allow} = L/\theta \quad (19)$$

According to (11) $C = 0.844 * 10^{-3} * 2nQ_T y_T / I_x$ (20)

where $a_W = 0.5t_S$ and $y_T = y_G - t/2$, Q_T is given by (10).

5. Optimization of a numerical example

Data: $n = 6$, $p_0 = 500$ N/m^2 = $0.5*10^{-3}$ N/mm^2, $B = 2000$, $L = 12000$ mm, $f_y = 355$ MPa.

$k_f/k_m = 2$ kg/min; $\Theta_d = 3, \kappa = n + 1, \rho = 7.85 * 10^{-6}$ kg/mm^3, $b_S = h_S/2$.

Variables: h_S, t_S, t. The optimum design is performed using the Rosenbrock's Hillclimb mathematical programming method complemented by a search for discrete values. Optimum values of variables are calculated for various values of θ to show the effect of distortion limitation. The computational results are given in Table 1.

Table 1. Optimum dimensions in mm, K/k_m values for cost in kg and checks of fulfilling the design constraints (17) and (19)

θ	h_S	t_S	t	K/k_m	(17)(MPa)	(19)(mm)
400	200	5	11	5025	303<323	13.6<30
600	200	5	11	5025	303<323	13.6<20
800	200	5	11	5025	303<323	13.6<15
900	200	5	12	5234	255<323	12.4<13.3
1000	200	5	13	5442	217<323	11.8<12

It can be seen that the deflection constraint is active for θ >800 and the reduced stress constraint is active for θ <800.

6. Conclusions

It is shown how to incorporate the constraint on residual deformation due to shrinkage of welds into the minimum cost design process. To assure the prescribed maximum distortion the structural dimensions should be increased which increases the cost. For the objective function a special cost function is used containing the material and fabrication costs.

References

Bodt.H.J.M. 1990. The global approach to welding costs. The Netherlands Institute of Welding.

COSTCOMP. 1990. Programm zur Berechnung der Schweisskosten. Deutscher Verlag für Schweisstechnik, Düsseldorf.

DASt (Deutscher Ausschuss für Stahlbau) Richtlinie 016. 1986. Bemessung und konstruktive Gestaltung von Tragwerken aus dünnwandigen kaltgeformten Bauteilen. Köln.

Eurocode 3. 1992. Design of steel structures. Part 1.1. CEN European Committee for Standardization, Brussels.

Farkas,J. 1974. Structural synthesis of press frames having columns and cross beams of welded box cross-section. Acta Techn.Hung. 79. No.1-2. 191-201.

Farkas,J. 1991. Techno-economic considerations in the optimum design of welded structures. Welding in the World 29: No.9-10. 295-300.

Farkas,J., Jármai,K. 1995. Fabrication cost calculations and minimum cost design of welded structural parts. Welding in the World 35: 400-406.

Farkas,J., Jármai,K. 1996a. Fabrication cost calculation and optimum design of welded steel silos. Welding in the World 37: No.5. 225-232.

Farkas,J., Jármai,K. 1996b. Minimum cost design of SHS Vierendeel trusses. Tubular Structures VII. Proc. 7th Int. Symposium on Tubular Structures, Miskolc, 1996. Eds Farkas,J. and Jármai,K. Balkema, Rotterdam-Brookfield. 463-468.

Farkas,J., Jármai,K. 1997a. Analysis and optimum design of metal structures. Balkema. Rotterdam-Brookfield.

Farkas,J., Jármai,K. 1997b. Analysis of some methods for reducing beam curvatures due to weld shrinkage. IIW-Doc. XV-944-97, X-1370-97, X/XV-RSDP-11-97. San Francisco.

Jármai,K., Horikawa,K., Farkas,J. 1997. Economic design of steel bridge decks. IIW-Doc. XV-F-52-97, XV-951-97. San Francisco.

Okerblom, N.O., Demyantsevich,V.P., Baikova,I.P. 1963. Design of fabrication technology of welded structures. Leningrad, Sudpromgiz (in Russian).

prEN 1029-2: 1992. Cold formed structural hollow sections of non-alloy and fine grain structural steels. Part 2. European Committee for Standardization, Brussels.

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