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

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Abstract: 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. 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.

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

Introduction

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.

During the 1998 IIW Annual Assembly in Hamburg a great number of participants interested in the Commission XIII Workshop on Improvement Methods and a lot of reports have been discussed.

For designers it is important to know the measure of savings in structural weight and cost, which can be achieved by using these treatments. Optimum design is suitable for this task, since the additional cost of PWT can be included in the cost function and the improved fatigue stress range can be considered in the fatigue strength constraint. Thus, our aim is to illustrate this saving by means of a simple numerical example of a welded I-beam.

In this case the transverse fillet welds used for vertical stiffeners decrease the fatigue stress range, thus the effect of PWT can be illustrated minimizing the cost function, which contains also the additional cost of PWT and the increased fatigue stress range can be included in the fatigue stress constraint. Note that Farkas [1] has treated this problem in a recent article for a welded box beam using only a few experimental data given by Woodley [2].

Improvement of fatigue strength using various PWT-s

Haagensen et al [3] have summarized the results of investigations relating to the measure of improvement in a table, from which we cite some basic data in Table 1. Note that the data are obtained for high strength steel of yield stress 780 MPa.

Table 1. Some improvement data according to [3]

	Stress range (MPa) at $2x10^6$	Improvement % at $2x10^6$
as welded	86	--
UIT	190	121
TIG dressing	132	53
TIG+UIT	202	135

A wide overview of results is given by Braid et al [4]. This article gives a hammer-peening speed of 25 mm/s and uses 6 passes, i.e. 6x1000/(25x60) = 4 min/m.

Maddox et al [5] have given the improvement citing the UK standard fatigue classes stating that the fatigue limit for weld toe burr grinding or hammer peening equals to the UK class C at $2x10^6$ cycles. According to the BS 5400 Part 10 (1980) [6] for transverse fillet welds in as welded state the fatigue limit is given by Class F of 40 MPa at 10^7 cycles, and for Class C of 78 MPa. Calculation for $2x10^6$ cycles gives 68 and 123 MPa, respectively, thus, the improvement is 123/78 = 1.8 (80%).

Lobanov and Garf [7] have treated the effect of UIT in connections of tubular structures.

According to Gregor [8] the TIG-dressing results in 40% improvement. Woodley [2] gives also 40% improvement for toe burr grinding and the necessary time for grinding 60 min/m.

According to Janosch et al [9] the ultrasonic peening of fillet welded T-joints results in a fatigue stress range at $2x10^6$ cycles of 290 MPa, which is 70-80% improvement compared with the as-welded value of 168 MPa. For a treatment of 3 passes 15 min/m specific time has been necessary.

Huther et al [10] worked out a summary of improvement methods and results using data of 51 references. For fillet welded T- or cruciform joints the following final design fatigue stress ranges at $2x10^6$ cycles can be used: for TIG dressing 124 MPa (70% improvement as compared to EC3 data); for hammer peening 209 MPa (190% improvement). These data are valid for steels of yield stress less than 400 MPa.

For our purpose that publications are suitable, in which data are given not only for the measure of improvement (α), but also for the time required for treatment (T_0). These data are summarized in Table 2.

Table 2. Measure of improvement and specific treatment time for various treatments according to the published data

Method	Reference	T_0 (min/m)	Improvement %	α	Remark
Grinding	[2]	60	40	1.4	
TIG dressing	[11]	18	40	1.4	can be 70-100%
Hammer peening	[4]	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.

Minimum cost design of a welded I-beam considering the improved fatigue stress range and the additional PWT cost

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.1). For this reason two types of stiffeners are used as it can be seen in Fig.1.

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}.

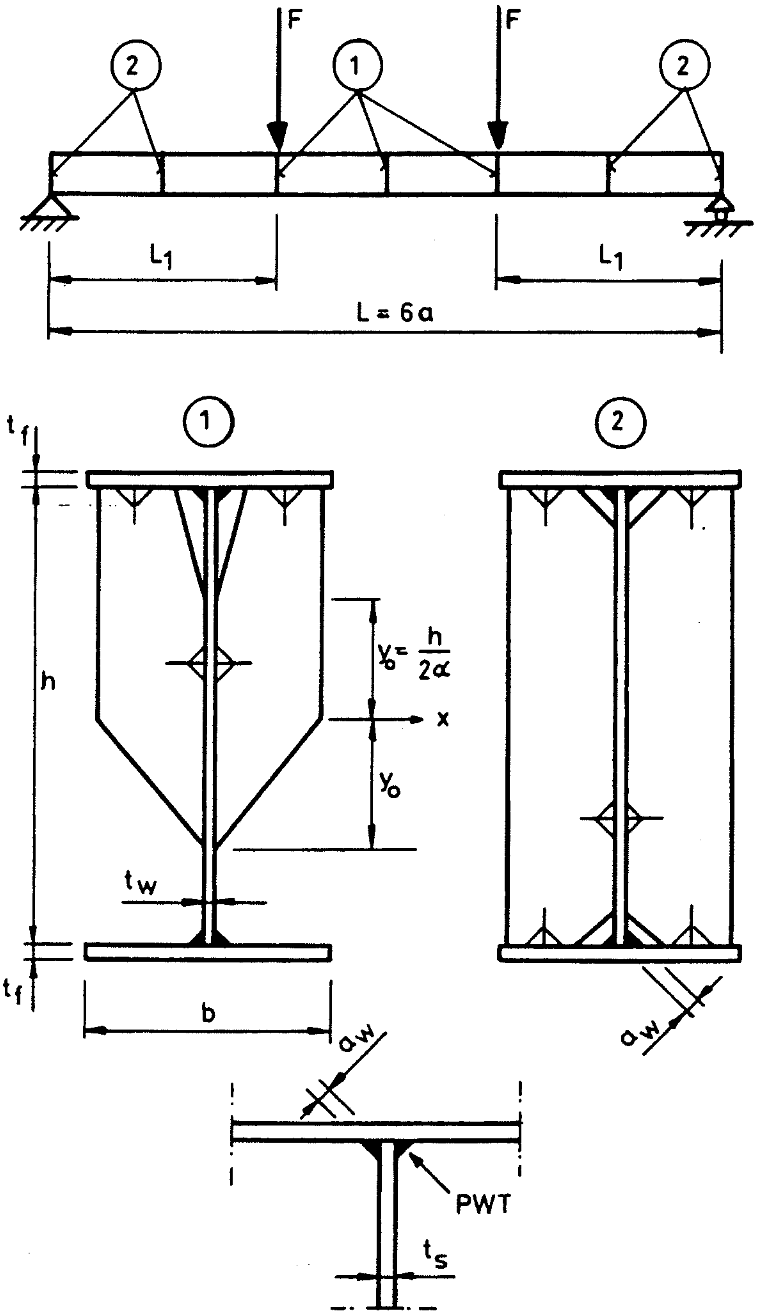

Fig. 1. Welded I-beam with vertical stiffeners. Double fillet welds with (1) and without (2) PWT

3.1 The cost function

In our previous studies (e.g. [12,13]) we have used a cost function containing the material and fabrication costs as follows:

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

where ρ is the material density, V is the volume of the structure, k_m and k_f are the corresponding cost factors, T_i are the fabrication times. Eq.1 can be written in the form of

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m} \sum T_i \tag{2}$$

We use the following cost factors: $k_m = 0.5 - 1$ \$/kg, $k_{f\,max} = 60$ \$/h = 1 \$/min, thus the ratio of k_f/k_m can be varied in a wide range of 0 - 2 kg/min. $k_f/k_m = 0$ means that K/k_m is a weight (mass) function, $k_f/k_m = 2$ kg/min can be used for developed countries.

The fabrication times can be calculated as follows:

$$\sum T_i = T_1 + T_2 + T_3 + T_4 \tag{3}$$

Time for preparation, assembly and tacking is

$$T_1 = C_1 \Theta_d \sqrt{\kappa \rho V} \tag{4}$$

where $C_1 = 1$ min/kg$^{0.5}$, Θ_d is a difficulty factor expressing the complexity of a structure (planar or spatial, consisting of plates or tubes etc.), κ is the number of elements to be assembled.

Time for welding is

$$T_2 = \sum C_{2i} a_{wi}^n L_{wi} \tag{5}$$

where $C_{2i} a_{wi}^n$ is given for different welding technologies and weld shapes according to COSTCOMP software [14]and [13], a_w is the weld size, L_w is the weld length.

Time for additional works as deslagging, chipping and electrode changing is

$$T_3 = 0.3 T_2 \tag{6}$$

Time for PWT is

$$T_4 = T_0 L_t \tag{7}$$

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

The final form of the cost function is

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m} \left(\Theta_d \sqrt{\kappa \rho V} + 1.3 \sum C_{2i} a_{wi}^n L_{wi} + T_0 L_t \right) \tag{8}$$

3.2 Design constraints

The constraint on fatigue stress range can be formulated as

$$\frac{F_{\max} L_1}{W_x} \le \frac{\alpha \Delta \sigma_C}{\gamma_{Mf}} \tag{9}$$

where

$$W_x = \frac{I_x}{\dfrac{h}{2}+\dfrac{t_f}{2}}; \qquad I_x = \frac{h^3 t_w}{12} + 2bt_f\left(\frac{h}{2}+\frac{t_f}{2}\right)^2 \tag{10}$$

According to Eurocode 3 (EC3) [15] 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

$$\alpha = \frac{\Delta\sigma_{Cimproved}}{\Delta\sigma_{Caswelded}}.$$

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

$$\frac{h}{t_w} \le 69\varepsilon; \qquad \varepsilon = \sqrt{\frac{235}{\alpha\Delta\sigma_C / \gamma_{Mf}}} \tag{11}$$

Note that we calculate in the denominator of ε with the maximum compressive stress instead of yield stress [16].

The constraint on local buckling of the compression flange is

$$\frac{b}{t_f} \le 28\varepsilon \tag{12}$$

3.3 Numerical example

Data: F_{max}= 138 kN, L = 12 m, L_1 = 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

$$V = (ht_w + 2bt_f)L + 4bht_S + 1.5bht_S\left(1+\frac{1}{\alpha}\right); \qquad t_s = 6 \text{ mm} \tag{13}$$

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

$$C_2 a_w^n L_w = 0.3394x10^{-3} x4^2 x4L = 260 \text{ min}, \tag{14}$$

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

$$C_2 a_w^n L_w = 0.7889x10^{-3} x4^2 \left[6\left(b+\frac{2h}{\alpha}\right) + 16(b+h)\right] \tag{15}$$

For the constrained minimization of the nonlinear cost function the Rosenbrock Hillclimb 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 3.

Table 3. 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

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

Conclusions

I 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.

Acknowledgements

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