DOUBLE MAIN GIRDER DESIGN OF AN OVERHEAD TRAVELLING CRANE FOR MINIMUM COST

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Abstract: A crane structure of two doubly symmetric welded box beams is designed for an overhead travelling crane for minimum cost. The following design constraints are considered: local buckling of web and flange plates, fatigue of the butt K weld under rail and fatigue of fillet welds joining the transverse diaphragms to the box beams. The rails are placed over the inner webs of box beams. To increase the fatigue strength of the last mentioned welds, an efficient post welding treatment (PWT) is considered. For the formulation of constraints the relatively new standard for cranes EN 13001-3-1 [1] is used. The cost function consists of cost of material, assembly, welding and PWT. PWT is economic, since it is used only for diaphragms near the span centre of box beams, where the bending stresses are high. The optimization is performed by systematic search using a MathCAD program.

Keywords: crane girder, fatigue, post welding treatment, optimum design

1. INTRODUCTION

The main girder of overhead travelling cranes can be designed as a single or double box beam. The rail can be placed in the middle of the upper flange or over the inner web of the box beams. In our case we designed a double box beam with rails over the inner webs (Fig. 1). The research of post-welding treatments (PWT) does not give any data for these welds. PWT can cause a significant increase of fatigue strength for welds joining the transverse diaphragms to the upper flange, so we use these data. Our research shows that PWT can result in significant cost savings using them in welds joining the transverse diaphragms to the box or I-beams (Jármai et al. [2]).

2. DATA OF THE TREATED CRANE

The British Standard for cranes BS 2573-1 [3] is valid at present also. This BS gives characteristic parameters for crane groups. We select a workshop crane with a dynamic factor of \( \gamma_d = 1.3 \), the governing number of cycles is \( N = 4 \times 10^6 \), the coefficient of spectrum is according to EN 13001-3-1 [1] \( s_s = 2 \). The safety factor for fatigue is \( \gamma_f = 1.25 \).

Yield stress \( f_y = 355 \) MPa, according to EN 13001-3-1 the maximum design stress for plate thicknesses \( t < 16 \) mm is \( 323 \) MPa, for \( 16 < t < 40 \) mm \( 314 \) MPa. We do not treat hybrid beams constructed with steels of two different yield stresses.

Span length is \( L = 16.5 \) m, hook load \( P = 200 \) kN, mass of the trolley \( G_k = 42.25 \) kN, distance of wheels \( k = 1.9 \) m, height of rail \( h_r = 70 \) mm, specific mass of the service-walkway and rail \( p = 1900 \) N/m, steel density \( \rho = 7.85 \times 10^3 \) kg/mm\(^3\) or \( \rho_0 = 7.85 \times 10^3 \) N/mm\(^3\), distance of transverse diaphragms \( a = L/10 = 1650 \) mm. The box beams are doubly symmetric.

2.1. BUCKLING CONSTRAINTS OF THE WEB UNDER THE RAIL

2.1.1. Bending
Stress from the vertical bending

\[ \sigma_v = \frac{M_v}{W_v} \]

(1)

Figure 1: Data and cross-sections of the crane beams. Diaphragms (a) are used in the middle of beams for high bending stresses, PWT is used for the welds joining the diaphragms, diaphragms (b) are used near the beam ends, (c) shows the welds with PWT, (d) shows the load distribution in the beam web from the crane wheel.

Maximum bending moment in the case of the load position of two concentric forces

\[ M_v = (0.05 + p) \frac{L^2}{8} + F \left( L - \frac{k}{2} \right)^2 \quad F = \frac{\rho \cdot \gamma + G_s}{4} \]

(2)

\[ A = h \tau_{cw} + 2h \tau_{po} \]

(3)

\[ W_v = \frac{h^2 \tau_{cw}}{6} + bh \tau_{po} \]

(4)

\( \tau_{cw} \) and \( \tau_{po} \) are the rounded plate thicknesses.

Bending moment from the horizontal bending
\[ M_y = 0.3x0.5 \left[ (1.05 \rho_e A + p) + \frac{G_1}{8L} \left( L - \frac{k}{2} \right) \right] \]  

The multiplier 0.5 expresses that two wheels are driven from four, 0.3 is the coefficient of mass force.

\[ \sigma_y = \frac{M_y}{W_y}, \quad W_y = \frac{b^4 t_y}{3} + \frac{h t_y b}{2} \]  

It is not necessary to calculate with effective width, when

\[ \sigma_y \leq k_0 f_y, k_0 = 1 \]  

\[ \lambda_y = \sqrt{\frac{f_y}{k_0 \sigma_y}} \leq 0.673, \quad k_0 = 7.81 - 6.29 \psi_s + 9.78 \psi_s^2, \quad \psi_s = \frac{\sigma_y - \sigma_y'}{\sigma_y + \sigma_y'} \]  

\[ \sigma_y = \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{2t_y^3}{h} \right), \quad E = 2.1 \times 10^5 \text{MPa}, \quad \nu = 0.3 \]  

The required plate thickness

\[ t_{req} = \frac{2h}{0.673x28.42 \sqrt{k_0}}, \quad e = \frac{235}{\sqrt{f_y}} \]  

2.1.2. Shear and torsion

From shear (approximately)

\[ \tau_y = \frac{V}{h t_y}, \quad V = (1.05 \rho_e A + p) + \frac{E}{2L} \left( L - \frac{k}{2} \right) \]  

From torsion

\[ \tau_t = \frac{2M_t}{2h t_y}, \quad M_t = \frac{E}{2L} \left( L - \frac{k}{2} \right) + \frac{P L h}{4} \]  

The constraint on shear buckling

\[ \sigma_y + \sigma_t \leq k_0 f_y / \sqrt{3}, k_0 = 1 \]  

\[ \lambda_y = \sqrt{\frac{f_y}{k_0 \sigma_y \sqrt{3}}} \leq 0.84, \quad k_0 = 5.34 + \frac{4}{\alpha^2}, \quad \alpha = \frac{a}{h} = \frac{L}{10h} \]  

i.e. \[ t_{req} = \frac{2h}{31.6 \sqrt{k_0}} \]  

2.1.3. Compression from a wheel

According to Figure 1d

\[ \sigma_a = \frac{2E}{c t_y}, \quad c = 50 + 2(h + t_y) = 50 + 2 \times 100 = 250 \text{mm} \]  

If \[ \sigma_a \leq k_0 f_y, k_0 = 1 \]  

\[ \lambda_a = \sqrt{\frac{f_y}{k_0 \sigma_a \sqrt{3}}} \leq 0.831 \]  

From the diagram of EN13001-3-1 [1] \[ c/a = 250/1650 = 0.15 \] and \[ \alpha = a/h = 1650/620 = 2.7 \quad k_0 = 1 \]

\[ t_{req} = \frac{2h}{60.97e} \]  

The complex check

\[ \left( \begin{array}{c} \sigma_y \\ f_y \end{array} \right) + \left( \begin{array}{c} \sigma_y \\ f_y \end{array} \right) - V_0 \left( \begin{array}{c} \sigma_y, \sigma_y \\ f_y, f_y \end{array} \right) + \left( \begin{array}{c} \tau \\ \tau \end{array} \right) \leq 1, \quad e_1 + k_s^2, e_2 = 1 + k_s^2, e_3 = 1 + k_k, k_0^2 \]

\[ V_0 = \left( k, k, \right) \]  \[ \text{if } \sigma, \sigma_y \geq 0, \quad V_0 = -1 \text{ if } \sigma, \sigma_y \leq 0 \]
In our case, \( k_s = k_y = k_{\alpha} = 1 \)  
\[
\sigma_{\text{ref}} = \sqrt{\left(\sigma_s + \sigma_y\right)^2 + \sigma_{\text{ref}}^2 - (\sigma_s + \sigma_y)\sigma_{\text{ref}} + 3\tau^2} \leq \sigma_f
\]  
\[\sigma_{\text{ref}} = \sqrt{\frac{a - a_y}{a + a_y}} \]  
\[\sigma_f = \frac{a_y - a}{a_y + a} \]  
\[\Psi = \frac{\sigma_s - \sigma_y}{\sigma_s + \sigma_y} \]  
(22)
(23)

3. BUCKLING CONSTRAINTS OF THE UPPER FLANGE

3.1. Vertical and horizontal bending

Similarly to the constraint on web buckling
\[
t_{f,\text{req}} = \frac{b}{0.673 \times 28.42 \varepsilon \sqrt{k_n}} \quad k_n = \frac{8.2}{1.05 + \psi} \quad \Psi = \frac{\sigma_s - \sigma_y}{\sigma_s + \sigma_y}
\]  
(24)

3.2. Torsion

Similarly to the web
\[
t_{f,\text{req}} = \frac{b}{3 \varepsilon \sqrt{k_n}} \quad k_n = 5.34 + \frac{4}{\alpha_s} \quad \alpha_s = \frac{a}{b}
\]  
(25)

4. FATIGUE CONSTRAINT FOR THE WELD UNDER THE RAIL

According to the EN 13001-3-1 [1] the fatigue strength of a K butt weld for the number of cycles \( N = 4 \times 10^6 \) is \( \Delta \sigma_e = 112 \text{ MPa} \), the allowed stress for the spectrum factor \( s_5 = 2 \)
\[
\Delta \sigma_{\text{fat}} = \frac{\Delta \sigma_e}{\gamma_f} \quad = 71.1 \text{ MPa}
\]  
(26)

and for shear
\[
\Delta \tau_{\text{fat}} = \frac{\Delta \tau_e}{\gamma_f} \quad = 50.8 \text{ MPa}
\]  
(27)

The complex constraint on fatigue is expressed as
\[
\eta = \left(\frac{\sigma_s + \sigma_y}{\Delta \sigma_{\text{fat}}}\right)^2 + \left(\frac{\tau_s + \tau_y}{\Delta \tau_{\text{fat}}}\right)^2 \leq 1
\]  
(28)

5. FATIGUE CONSTRAINT FOR FIELT WELDS JOINING THE TRANSVERSE DIAPHRAGMS

The fatigue strength [4]
\[
\Delta \sigma_e = \alpha_f \cdot 63 \text{ MPa}
\]  
(29)

\( \alpha_f \) is the coefficient of the effect of PWT, for ultrasonic treatment 1.3, for HiFIT high frequency impact treatment 1.6.

The allowed stress
\[
\Delta \sigma_{f,\text{req}} = \frac{\Delta \sigma_e}{\gamma_f \sqrt{2}}
\]  
(30)

The constraint is given by
\[
\sigma_s \leq \Delta \sigma_{f,\text{req}}
\]  
(31)

6. THE COST FUNCTION

The cost function is formulated according to the fabrication sequence (Farkas & Jármári books [5,6,7,8]).
(1) Welding of the upper flange, webs and transverse diaphragms, PWT of the welds joining the diaphragms. Two forms of diaphragms are used: the 5 diaphragms near the span centre are cut according to the Figure 1a, the other 6 diaphragms are constructed according to Figure 1b.

The structural volume for this fabrication phase is

\[ V_i = \frac{L}{(ht_{w0} + bt_{f0}) + 6bht_i + 2.5bh} \left( 1 + \frac{1}{\alpha_p} \right), \quad t_s = 6 \text{ mm}, \quad \alpha_p = 1.6 \]  

(32)

The number of the assembled structural elements is \( k_1 = 14 \), the factor of the complexity of assembly is \( \Theta_1 = 3 \). The welding cost consists of four parts: GMAW-C welding of Butt K welds under the rail \( (K_{w1}) \), GMAW-C welding of the fillet welds joining the other web, welding of the diaphragms \( (K_{w2}) \) and PWT of the welds of 5 diaphragms \( (K) \).

\[ K_{w1} = k_w(\Theta_1 \sqrt{K_r \rho V_i + 1.3 \times 0.3394 \times 10^{-3} a_0^2 L + K_{w1}}) \quad k_w = 1.0 \text{ $/min} \]  

(33)

\[ K_{w2} = k_w 1.3 \times 0.1520 \times 10^{-3} a_0^2 L, \quad a_0 = t_{w0} / 2 \]  

(34)

\[ K_{w2} = k_w 1.3 \times 0.7889 \times 10^{-3} a_0^2 L, \quad a_0 = t_{w0} / 2, \quad L = 2 \left( \frac{b + h}{2} \right) \left( b + \frac{h}{\alpha_p} \right) \]  

(35)

\[ K = k_w L \times t_{w0}, \quad L = 10b, \quad t_{w0} = 0.0033 \text{ min/mm} \]  

(36)

(2) Welding of the lower flange with two GMAW-C fillet welds

\[ K_{w2} = k_w(\Theta_2 \sqrt{11 \rho V_i + 1.3 \times 0.3394 \times 10^{-3} a_0^2 L}), \quad \Theta_2 = 2, \quad V_i = V_i + bt_{w0} L, \quad k_2 = 2 \]  

(37)

Welding of the two webs from 11x1500 mm parts with GMAW-C butt K-welds

\[ K_{w3} = k_w(\Theta_2 \sqrt{11 \rho V_i + 1.3 \times 0.1520 \times 10^{-3} \times 10b(t_{w0})^2}), \quad V_i = \frac{Lht_{w0}}{2} \]  

(38)

Welding of the two flanges from 11x1500 mm parts with GMAW-C butt K-welds

\[ K_{w4} = k_w(\Theta_2 \sqrt{11 \rho V_i + 1.3 \times 0.1520 \times 10^{-3} \times 10bt_{w0}}), \quad V_i = Lbt_{w0} \]  

(39)

Material cost

\[ K = k_w \rho V_i, \quad k_w = 1.0 \text{ $/kg} \]  

(40)

Total cost

\[ K = K_w + K_{w1} + K_{w2} + K_{w3} + K_{w4} + 2K_{w5} + 2K_{w6} \]  

(41)

7. RESULTS OF OPTIMIZATION

The results are given in Table 1.

| Table 1: Dimensions and deflection in mm, stresses in MPa, volume in mm³, costs in $. Minima are marked by bold letters. |
|-----------------|---------|---------|---------|---------|
| \( h \)         | 710     | 660     | 620     | 600     |
| \( b \)         | 340     | 380     | 420     | 440     |
| \( t_{w0} \)    | 30      | 28      | 26      | 26      |
| \( t_{f0} \)    | 40      | 40      | 40      | 40      |
| \( \sigma_x \)  | 61.95   | 62.6    | 62.7    | 62.8    |
| Equation (19)   | 26.9    | 25.0    | 23.5    | 22.7    |
| Equation (10)   | 20.0    | 18.4    | 17.2    | 16.6    |
| \( \nu_{max} \) | 9.3     | 10.0    | 10.5    | 10.7    |
| Equation (28)   | 0.978   | 0.995   | 0.992   | 0.983   |
| \( V_{x10^8} \) | \textbf{8.153} | 8.222 | 8.367   | 8.547   |
| \( K_f \)       | 11.2    | 12.5    | 13.9    | 14.5    |
| \( K \)         | 14230   | 13890   | \textbf{13690} | 13930   |

8. CONCLUSIONS

The optimization has been performed by using a MathCAD program. Since the welding cost depends on the web thickness, the cost can be decreased by decrease of web thickness or web height. This decrease is stopped by the
increase of cost caused by the increase of flange width. The web thickness is determined by the constraint on the maximal stress from the wheel load. In the systematic search we select a $b$ and for this value $h$ is searched, which fulfills the constraints. The web thickness is determined by the quality of the weld under the rail. Therefore, it is necessary to use high quality butt K weld. The governing constraints are the constraint on the compressive stress under rail and those on the fatigue. \( \eta \) should be smaller than 1 and \( \sigma_r \) should be smaller than \( \Delta \sigma_{f,other} = 64.0 \). The constraint of Equation 15 is passive.

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