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Minimum cost design of overhead crane beam with box section strengthened by CFRP laminates

György Kovács* and József Farkas

Institute of Logistics, University of Miskolc, Miskolc-Egyetemvaros, Hungary

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Abstract. An overhead travelling crane structure of two doubly symmetric welded box beams is designed for minimum cost. The rails are placed over the inner webs of box beams. 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, fatigue of CFRP (carbon fibre reinforced plastic) laminate, deflection constraint. For the formulation of constraints the relatively new standard for cranes EN 13001-3-1 (2010) is used. To fulfill the deflection constraint CFRP strengthening should be used. The application of CFRP materials in strengthening of steel and concrete structures are widely used in civil engineering applications due to their unique advantages. In our study, we wanted to show how the mechanical properties of traditional materials can be improved by the application of composite materials and how advanced materials and new production technologies can be applied. In the optimization the following cost parts are considered: material, assembly and welding of the steel structure, material and fabrication cost of CFRP strengthening. The optimization is performed by systematic search using a MathCAD program.

Keywords: FRP strengthening; crane; welded box beam; fatigue; cost calculation; optimization

1. Introduction

Fibre reinforced plastic (FRP) composites are often used in light-weight civil engineering applications due to their unique advantages. In particular, many possibilities of using FRP in the strengthening of concrete, wood and steel structures have been explored.

The aims of FRP strengthening of steel structures include (Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures, CNR-DT 202 2005):

- increasing or restoring the tensile strength,
- increasing or restoring the flexural strength,
- increasing the fatigue resistance.

The application of CFRP materials in strengthening steel and concrete structures are widely used in recent years due to its advantages, which are high strength to weight ratio, corrosion resistance and easy handling during construction.

Steel plates can also be attached by welding to strengthen existing steel structures, but the bonding of FRP laminates is superior to the welding of steel plates in the following situations (Teng *at al*. 2012):

- bonding of FRP laminates for enhanced fatigue resistance has the advantage that the strengthening process does not introduce new residual stresses;
- in certain applications (e.g., oil storage tanks and chemical plants) where fire risks must be minimized, welding needs to be avoided when strengthening a structure; bonding of FRP laminates is then a very attractive alternative;
- high strength steels suffer significant local strength reductions in heat-affected zones of welds, so bonded FRP laminates offer an ideal strength compensation method.

Benachour *et al*. (2008) analyzed the interfacial stresses in steel beams and strengthening FRP plate. They showed that there exists a high concentration of both shear and normal stresses at the ends of the laminate, which might result in premature failure.

Deng *et al*. (2004) presented an analytical solution extended to CFRP plates with tapered ends, which can significantly reduce the stress concentration at the plate ends. Finite element analysis was employed to validate the analytical results.

Haedir and Zhao (2012) have shown that the hoop CFRP reduces the effect of local buckling of steel circular hollow sections (CHS). The inclusion of the effect of strengthening in current Australian and European design rules is discussed.

Kawai (2004) has given - using a damage mechanics model-fatigue life data for unidirectional carbon/epoxy and glass/epoxy composites in function of $R=\sigma_{\min}/\sigma_{\max}$ stress ratio.

Kovács and Farkas (2015) have shown the optimization method for a new complex structural model: laminated CFRP deck plates with polystyrene foam (EPS) inner core. The structure is designed for both minimal cost and minimal weight.

Lian (2010) has used a new stiffness degradation model and finite element method to predict fatigue life of laminates. The predicted results were coincident with the

*Corresponding author, Ph.D.
E-mail: altkovac@uni-miskolc.hu

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experimental ones.

Naderi and Maligno (2012) have used a 2D finite element model to predict the progressive fatigue damage and the life of the composite laminate with different layup sequences. The predicted fatigue life was in good agreement with the experimental results.

Pellegrino *et al*. (2009) have treated the FRP strengthening of steel and steel-concrete composite structures-with any type of reinforcement geometry- taking into account the non-linear behaviour of the materials. Comparison of analytical results with the experimental data available in the literature shows good agreement.

Shokrieh and Takeri-Behrooz (2006) developed a new fatigue life model based on the energy method. They predicted the fatigue life of unidirectional composite laminates with various fibre angles. Their results are in good agreement with the experimental data of carbon/epoxy and E-glass/epoxy unidirectional plies. This agreement is shown in diagrams for number of cycles versus maximum stress for different fibre angles.

El Mahi *et al*. (2014) investigated the stress concentration caused by FRP sheets of tapered end shape. Park and Yoo (2015) have tested beams and short and long columns to determine the effect of GFRP strengthening.

Zhao and Zhang (2007) have provided a review of FRP strengthening of steel hollow section members and fatigue crack propagation in the FRP-steel system with initial crack in steel member.

FRP systems are also used for reinforcing damaged concrete structures. Naeun *et al*. (2015) investigated the behaviors of reinforced concrete beams strengthened with tapered CFRPs, Elham and Mehdi (2015) analyzed composite girders with hybrid GFRP hat-shape sections and concrete slab, and Ozgur and Ozgur (2015) used CFRPs for structural repairing of damaged reinforced concrete beam-column assemblies.

The main aim of the current study is to show a special application of CFRP strengthening systems to reduce deflection of overhead travelling crane beams.

The authors in their earlier article (Kovács *et al*. 2007) analyzed the application of FRP strengthening system in metal structures. In that study the effect of laminated FRP system on the whole structure were measured and analyzed by finite element software. The accuracy of the elaborated calculation methods was validated by measurements and finite element analysis. So the earlier applied calculation methods can be also used in this recent study.

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).

2. Problem formulation

Optimum design of an overhead travelling crane structure of two doubly symmetric welded box beams was elaborated. The rails are placed over the inner webs of box beams. The structure was designed for minimum cost.

The following design constraints are considered: local

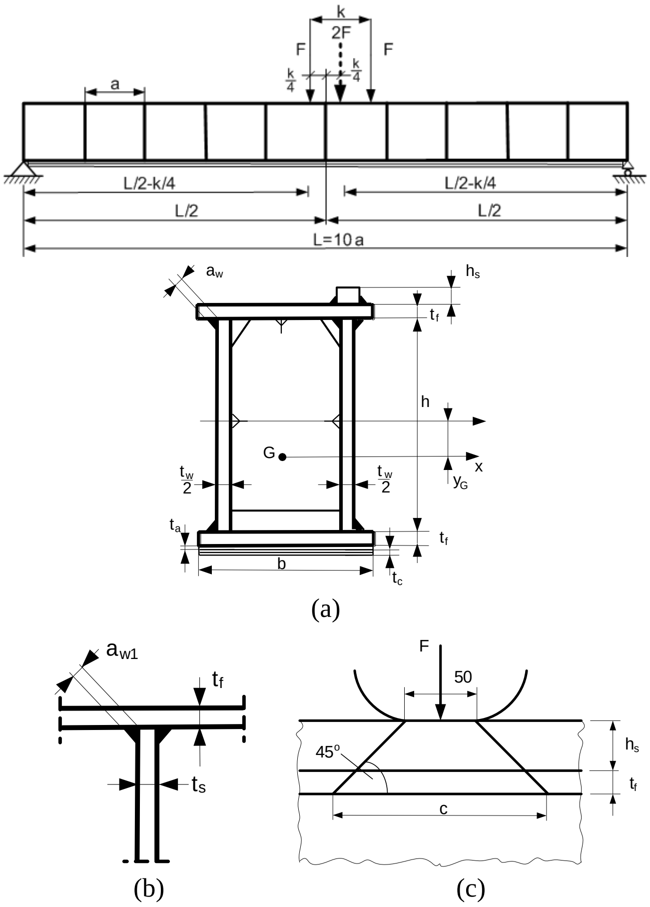

Fig. 1 Overhead crane beam section. Since the crane box beams are symmetric, the figure shows only one box beam. 11 vertical stiffeners are used. (b) shows the welds joining diaphragms to the upper flange, which should fulfill a fatigue constraint, and (c) shows the load distribution in the beam web from the crane wheel

buckling of web, local buckling of flange plates, fatigue of the butt K weld under rail and fatigue of fillet welds joining the transverse diaphragms to the box beams, deflection constraint and size constraints for design variables.

Our aim is to show that in certain realistic situations a FRP strengthening is needed to satisfy the deflection constraint.

The situation is the following: the dimensions of steel box beams [width (b), height (h)] are limited to 400 mm, because of the dimensions of the plant building. The thickness (t_f) of crane beam flange and the thickness of the web (t_w) are also limited to 30 mm because of the welding technology.

Design variable is the number of CFRP laminates (n).

The optimization has been performed by systematic search using a MathCAD standard software. MathCAD program works such a way that changing the variables the program calculates the values of formulae.

For the design the EN 13001-3-1 (2010) code is used. Since this code is not contains the dynamic factors for various crane types, the British Standard for cranes BS 2573-1 (1983) is applied. This BS gives characteristic parameters for crane groups. We select a workshop crane with a dynamic factor of ψ_d=1.1, the governing number of cycles is N=5×10^5, the coefficient of spectrum is according to EN 13001-3-1 (2010) s_3=0.125. The safety factor for fatigue is γ_f=1.25. Yield stress f_y=355 MPa, according to EN 13001-3-1 (2010) the maximum design stress for plate thicknesses t<16 mm is 323 MPa, for 16<t<40 mm 314 MPa.

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_s=70 mm, specific mass of the service-walkway and rail p=1900 N/m, steel density ρ=7.85×10^{-6} kg/mm^3 or ρ_0=7.85×10^{-5} N/mm^3, Young's modulus of steel E_S=2.1×10^5 MPa, distance of transverse diaphragms a=L/10=1650 mm. The box beams are doubly symmetric.

The reinforcing CFRP (Carbon Fibre Reinforced Plastic) plates are constructed from laminated layers. All of the carbon fibres of a layer and laminate are arranged in the longitudinal direction.

The material parameters of a CFRP layer are given as follows: the thickness of a layer t*=1 mm (t_c=$n{\cdot}t$*, where n is the number of CFRP layers), the longitudinal Young's modulus E_c=234 GPa, the tensile strength σ_{Bc}=3450 MPa.

Adhesive is used to bond CFRP laminated system to the steel beam. The material parameters of adhesive are given as follows: the thickness of a layer t_a=2 mm, the Young's modulus E_a=3.8 GPa, shear strength $\tau_{a\,adm}$=18 MPa.

3. Buckling constraints of the web under the rail

3.1 Bending

Stress from the bending about the axis x calculating as an anisotropic cross section (Research study, Chapter 6, http://ocw.nthu.edu.tw)

$$\sigma_x = \frac{M_x}{EI_x} y_a E_s \quad (1)$$

$$EI_x = E_s(I_s + A_s y_G^2) + E_a A_a \left(\frac{h}{2} + t_f + \frac{t_a}{2} - y_G\right)^2 + E_c A_c \left(\frac{h}{2} + t_f + t_a + \frac{t_c}{2} - y_G\right)^2 \quad (2)$$

indices: s - steel, a - adhesive, c - CFRP, G - gravity centre

$$I_s = \frac{h^3 t_{w0}}{12} + \frac{bh^2 t_{f0}}{2} \quad (3)$$

t_{w0} and t_{f0} are rounded up values of t_w (web thickness) and t_f (flange thickness), resp.

$$y_a = \frac{h}{2} - y_G + \frac{t_f}{2} \quad (4)$$

$$y_G = \frac{1}{EA}\left[A_a E_a \left(\frac{h}{2} + t_f + \frac{t_a}{2}\right) + A_c E_c \left(\frac{h}{2} + t_a + t_f + \frac{t_c}{2}\right)\right] \quad (5)$$

$$EA = E_s A_s + E_a A_a + E_c A_c \quad (6)$$

$$A_s = ht_{w0} + 2bt_{f0}, \quad A_a = b_a t_a, \quad A_c = b_c t_c$$

$$\sigma_C = \frac{M_x}{EI_x}\left(\frac{h}{2} + t_f + t_a + t_c - y_G\right) E_c \quad (7)$$

For the maximum bending moment (M_x) the governing position of the trolley is the following: the distance of the wheel and the resultant from the middle of the span is k/4, as it is shown in Fig. 1(a).

$$M_x = (1.05\rho_0 A_s + p)\frac{L^2}{8} + \frac{F}{2L}\left(L - \frac{k}{2}\right)^2, \quad F = \frac{\psi_d P + G_k}{4} \quad (8)$$

Bending moment from the horizontal bending

$$M_y = 0.3x0.5\left[(1.05\rho_0 A_s + p) + \frac{G_k}{8L}\left(L - \frac{k}{2}\right)^2\right] \quad (9)$$

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

$$\sigma_y = \frac{M_y}{W_y}, \quad W_y = \frac{b^2 t_{f0}}{3} + \frac{ht_{w0} b}{2} \quad (10)$$

In W_y the strengthening CFRP laminae are neglected.

It is not necessary to calculate with effective width, when

$$\sigma_x \le k_x f_y, k_x = 1 \quad (11)$$

$$\lambda_x = \sqrt{\frac{f_y}{k_{\sigma x}\sigma_e}} \le 0.673, \quad k_{\sigma x} = 7.81 - 6.29\psi_x + 9.78\psi_x^2, \quad \psi_x = -\frac{\sigma_x - \sigma_y}{\sigma_x + \sigma_y} \quad (12)$$

$$\sigma_e = \frac{\pi^2 E_s}{12(1-\nu^2)}\left(\frac{2t_{w0}}{h}\right)^2, \ \nu=0.3 \quad (13)$$

The required plate thickness

$$t_{w.req} = \frac{2h}{0.673x28.42\varepsilon\sqrt{k_{\sigma x}}}, \quad \varepsilon = \sqrt{\frac{235}{f_y}} \quad (14)$$

3.2 Shear and torsion

Shear stress (approximately)

$$\tau_V = \frac{V}{ht_{w0}}, \quad V = (1.05\rho_0 A_s + p) + \frac{F}{2L}\left(L - \frac{k}{2}\right) \quad (15)$$

$$\tau_a = \frac{VS_x}{EI_x t_a} E_a, \quad S_x = A_a\left(\frac{h}{2} + t_f + \frac{t_a}{2}\right) \quad (16)$$

Torsional shear stress

$$\tau_t = \frac{2M_t}{2bht_{w0}}, \quad M_t = \frac{F}{2L}\left(L - \frac{k}{2}\right)\frac{b}{2} + \frac{pLb}{4} \quad (17)$$

The constraint on shear buckling

$$\text{if} \quad \tau = \tau_V + \tau_t \le k_{\tau 0} f_y / \sqrt{3} \quad \text{then} \quad k_{\tau 0} = 1 \quad (18)$$

$$\lambda_\tau = \sqrt{\frac{f_y}{k_\tau \sigma_e \sqrt{3}}} \le 0.84, \quad k_\tau = 5.34 + \frac{4}{\alpha^2}, \tag{19}$$

$$\alpha = \frac{a}{h} = \frac{L}{10h}$$

i.e., $$t_{w.req} = \frac{2h}{31\varepsilon\sqrt{k_\tau}} \tag{20}$$

3.3 Compression from a wheel

According to Fig. 1(c)

$$\sigma_{y1} = \frac{2F}{ct_{w0}}, \tag{21}$$

$$c = 50 + 2\left(h_s + t_{f0}\right) = 50 + 2x100 = 250 \quad \text{mm}$$

if $\sigma_{y1} \le k_y f_y$ then $k_y = 1$ (22)

$$\lambda_y = \sqrt{\frac{f_y}{k_{\sigma y}\sigma_e \frac{a}{c}}} \le 0.831 \tag{23}$$

From the Fig. 11 of EN13001-3-1 c/a=250/1650=0.15 and $\alpha = a/h$=1650/620 = 2.7, $k_{\sigma y}$=1

$$t_{w.req} = \frac{2h}{60.97\varepsilon} \tag{24}$$

The complex check according to equations (60-64) of (EN 13001-3-1 2010)

$$\left(\frac{|\sigma_x|}{f_{bx}}\right)^{e_1} + \left(\frac{|\sigma_y|}{f_{by}}\right)^{e_2} - V_0\left(\frac{|\sigma_x \sigma_y|}{f_{bx} f_{by}}\right) + \left(\frac{\tau}{f_{b\tau}}\right)^{e_3} \le 1, \tag{25}$$

$$e_1 = 1 + k_x^4, e_2 = 1 + k_y^4, e_3 = 1 + k_x k_y k_{\tau 0}^2$$

$$V_0 = \left(k_x k_y\right)^6 \text{ if } \sigma_x \sigma_y \ge 0, \quad V_0 = -1 \text{ if } \sigma_x \sigma_y \le 0 \tag{26}$$

In our case

$$k_x = k_y = k_{\tau 0} = 1 \tag{27}$$

$$\sigma_{red} = \sqrt{(\sigma_x + \sigma_y)^2 + \sigma_{y1}^2 - (\sigma_x + \sigma_y)\sigma_{y1} + 3\tau^2} \le f_y \tag{28}$$

4. Buckling constraints of the upper flange

4.1 Vertical and horizontal bending

Similarly to the constraint on web buckling

$$t_{f.req} = \frac{b}{0.673x28.42\varepsilon\sqrt{k_{\sigma y}}}, \quad k_{\sigma y} = \frac{8.2}{1.05 + \psi_y}, \tag{29}$$

$$\psi_y = \frac{\sigma_x - \sigma_y}{\sigma_x + \sigma_y}$$

4.2 Torsion

Similarly to the web

$$t_{f.req} = \frac{b}{31\varepsilon\sqrt{k_{\tau b}}}, \quad k_{\tau b} = 5.34 + \frac{4}{\alpha_b^2}, \quad \alpha_b = \frac{a}{b} \tag{30}$$

5. Fatigue constraint for the weld under the rail

According to the EN 13001-3-1 (2010) the fatigue strength of a K butt weld for the number of cycles N=5×10^5 is $\Delta\sigma_C$=112 MPa, the allowed stress for the spectrum factor s_3=0.125

$$\Delta\sigma_{Rd} = \frac{\Delta\sigma_C}{\gamma_f \sqrt[3]{s_3}} = 179.2 \quad \text{MPa} \tag{31}$$

and for shear

$$\Delta\tau_{Rd} = \frac{\Delta\tau_C}{\gamma_f \sqrt[3]{s_3}} = \frac{80}{1.25x0.5} = 128 \quad \text{MPa} \tag{32}$$

The complex constraint on fatigue is expressed (according to Eq. (41) of (EN 13001-3-1 2010)) as

$$\eta = \left(\frac{\sigma_x + \sigma_y}{\Delta\sigma_{Rd}}\right)^3 + \left(\frac{\sigma_{y1}}{\Delta\sigma_{Rd}}\right)^3 + \left(\frac{\tau_V + \tau_t}{\Delta\tau_{Rd}}\right)^5 \le 1 \tag{33}$$

6. Fatigue constraint for fillet welds joining the transverse diaphragms (Fig. 1(b))

The fatigue strength according to (EN 13001-3-1 2010)

$$\Delta\sigma_C = 63 \quad \text{MPa} \tag{34}$$

The allowed stress

$$\Delta\sigma_{f.adm2} = \frac{\Delta\sigma_C}{\gamma_f \sqrt[3]{2}} = 100.8 \quad \text{MPa} \tag{35}$$

The constraint is given by

$$\sigma_{x1} = \frac{M_x}{EI_x} y_b E_s \le \Delta\sigma_{f.adm2}, \quad y_b = \frac{h}{2} + y_G, \tag{36}$$

$$\Delta\sigma_{f.adm2} = \frac{\Delta\sigma_C}{\gamma_f \sqrt[3]{2}} = 100.8$$

$\Delta\sigma_{f.adm2}$ is 100.8 MPa without PWT (post welding treatment), 131.04 MPa using PWT with hammer peening.

7. Fatigue constraint for CFRP laminate

According to the data of Kawai (Kawai 2004) and (Guide CNR-DT 202 2005)

$$\sigma_c \le \Delta\sigma_{f.adm3} = \frac{0.2\sigma_{Bc}}{1.25} = 552 \quad \text{MPa} \tag{37}$$

8. Deflection constraint

The maximum deflection is calculated with forces without dynamic factor and neglecting the effect of trolley

$$w_{\max} = \frac{P(L-k)}{4 \cdot 48EI_x}\left[3L^2 - (L-k)^2\right] \le w_{adm} = \frac{L}{500} = 33 \text{ mm} \quad (38)$$

9. Size constraint for design variable

$h_{\max}$ = 400 [mm] is prescribed from the steel structure of the workshop,

b = 400 [mm],

t_{f0} = 30 [mm], (39)

t_{w0} = 30 [mm],

$1 \le n \le 12$ [pieces].

These constraints represent physical limitations for the design variables, taking economical and manufacturing aspects into consideration.

10. The cost function

The cost function of steel structures is formulated according to the fabrication sequence (Farkas and Jármai 2003, 2008, 2013, 2015).

(1) Welding of the upper flange, webs and transverse diaphragms.

The structural volume for this fabrication phase is

$$V_1 = L(ht_{w0} + bt_{f0}) + 11bht_s,\ t_s = 6 \text{ mm} \quad (40)$$

The number of the assembled structural elements is κ_1=14, the factor of the complexity of assembly is Θ_1=3. The welding cost consists of three parts: GMAW-C welding of butt K welds under the rail (K_{w11}), GMAW-C welding of the fillet welds joining the other web and welding of the diaphragms (K_{w12})

$$K_{w1} = k_w(\Theta_1\sqrt{\kappa_1\rho V_1} + 1.3x0.3394x10^{-3}a_w^2L + K_{w11}),\quad k_w = 1.0 \text{ \$/min} \quad (41)$$

$$K_{w11} = k_w 1.3x0.1520x10^{-3}a_{w1}^{1.94}L,\quad a_{w1} = t_{w0}/2 \quad (42)$$

$$K_{w12} = k_w 1.3x0.7889x10^{-3}a_w^2L_w,\quad L_w = 2[11(b+2h)] \quad (43)$$

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

$$K_{w2} = k_w\left(\Theta_2\sqrt{\kappa_2\rho V_2} + 1.3x0.3394x10^{-3}a_w^2 2L\right),\quad \Theta_2 = 2,\quad V_2 = V_1 + bt_{f0}L,\quad \kappa_2 = 2 \quad (44)$$

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

$$K_{w3} = k_w\left(\Theta_2\sqrt{11\rho V_3} + 1.3x0.152x10^{-3}x10h\left(\frac{t_{w0}}{2}\right)^{1.94}\right) \quad (45)$$

$$V_3 = Lht_{w0}/2$$

Welding of the two flanges from 11×1500 mm parts with GMAW-C butt K-welds

$$K_{w4} = k_w\left(\Theta_2\sqrt{11\rho V_4} + 1.3x0.152x10^{-3}x10bt_{f0}^{1.94}\right),\quad V_4 = Lbt_{f0} \quad (46)$$

Material cost of steel structure

$$K_{ms} = k_m\rho V_2,\ k_m = 1.0 \text{ \$/kg} \quad (47)$$

Total cost of steel structure

$$K_s = K_{ms} + K_{w1} + K_{w11} + K_{w12} + K_{w2} + 2K_{w3} + 2K_{w4} \quad (48)$$

Material cost of CFRP strengthening

$$K_{mc} = nbLk_{CFRP} + bLV_ak_a \quad (49)$$

k_{CFRP}=42 \$/m^2, k_a=18.7 \$/kg, V_a=1.2 +(n-1)0.7 kg/m^2, 1.2 kg/m^2 adhesive required for the bonding of CFRP system to steel beam and further 0.7 kg/m^2 volume for the bonding of CFRP laminae.

Fabrication cost of CFRP strengthening

$$K_{fc} = nbLk_{fc},\ k_{fc} = 20 \text{ \$/m}^2 \quad (50)$$

Total cost of CFRP system

$$K_c = K_{mc} + K_{fc} \quad (51)$$

Total cost of a double box beam structure strengthened by CFRP system

$$K_{Total} = K_s + K_c \quad (52)$$

11. Results of optimization

The optimization has been performed by systematic search using a MathCAD program.

Minimal cost can be a prime design aim during the optimization of structures including FRP materials, because the composite materials are very expensive. Table 1 shows the result of cost optimization of the analyzed structure based on the cost objective function (Eq. (52)) and 6 design constraints.

The active constraint is deflection limitation of the total structure.

The results of a search for optimum dimensions of box beams and CFRP system are given in Table 1.

It can be seen that the deflection constraint ($\boldsymbol{w}_{\mathbf{adm}}$=33 mm) can be fulfilled by using a CFRP strengthening system. Without CFRP strengthening the maximal deflection of the structure is 39 mm, which is higher than the limitation. Since σ_{x1}=103.8 MPa, PWT of hammer peening is needed.

It can be summarized that the total cost of the structure is increasing by the increasing of the number of CFRP

Table 1 Dimensions and deflection in mm, layer numbers in pieces, costs in $.
Minima are marked by bold letters.

	With CFRP strengthening	Without CFRP strengthening
h	400	
b	400	
t_{w0}	30	
t_{f0}	30	
n	10	0
$w_{\max}$	**32.539**	39.029
K_s	$1.098 \cdot 10^4$	$1.098 \cdot 10^4$
K_c	$4.093 \cdot 10^3$	0
K_{Total}	$1.508 \cdot 10^4$	$1.098 \cdot 10^4$

laminate. The material cost of CFRP strengthening is significant compared to the material cost of steel structure, so the total structural cost is highly depending on the layer number of composite laminate.

12. Conclusions

Optimum design of an overhead travelling crane structure of two doubly symmetric welded box beams was elaborated. The rails are placed over the inner webs of box beams. The structure was designed for minimum cost. For the formulation of constraints the EN 13001-3-1 standard for cranes was used. To fulfill the deflection constraint we had to strengthen the structure. Instead of steel strengthening we applied CFRP strengthening.

The application of fibre reinforce plastic materials in strengthening of steel structures are widely used in civil engineering applications due to their special advantages. The advantages of FRP strengthening of steel structures include increasing or restoring the tensile strength, increasing or restoring the flexural strength and increasing the fatigue resistance. In our study we wanted to utilize these unique properties of laminated composite materials.

The structural optimization was performed by systematic search using a MathCAD program.

The following design constraints were 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, deflection constraint and size constraints for design variables.

It can be summarized that the deflection constraint can be fulfilled only by using CFRP strengthening, which resulted in an increase of the total cost of the structure.

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References

Benachour, A., Benyoucef, S., Tounsi, A. and Adda bedia, E.E. (2008), "Interfacial stress analysis of steel beams reinforced with bonded prestressed FRP plate", *Eng. Struct.*, **30**, 3305-3315.

BS 2573-1 (1983), Rules for the design of cranes. Part 1. Specification for classification, stress calculations and design criteria for structures.

Deng, J., Lee, M.M.K. and Moy, S.S.J. (2004), "Stress analysis of steel beams reinforced with a bonded CFRP plate", *Compos. Struct.*, **65**, 205-215.

El Mahi, B., Benrahou, K.H., Amziane, S., Belakhdar, K., Tounsi, A. and Bedia, E.A.A. (2014), "Effect of tapered end shape of FRP sheets on stress concentration in strengthened beams under thermal load", *Steel Compos. Struct.*, **17**(5), 601-521.

Elham, A. and Mehdi, D. (2015), "Analysis of composite girders with hybrid GFRP hat-shape sections and concrete slab", *Struct. Eng. Mech*, **54**(6), 1135-1152.

EN 13001-3-1 (2010), .Cranes-General design-Part 3-1: Limit states and proof competence of steel structure.

Farkas, J. and Jármai, K. (2003), *Economic Design of Metal Structures*, Millpress, Rotterdam.

Farkas, J. and Jármai, K. (2008), *Design and optimization of metal structures*, Chichester, Horwood Publishing, UK.

Farkas, J. and Jármai, K. (2013), *Optimum Design of Steel Structures*, Springer, Heidelberg.

Farkas, J. and Jármai, K. (2015), *Fémszerkezetek innovatív tervezése*, Miskolc, Gazdász-Elasztik Kiadó és Nyomda, (Innovative design of metal structures). (in Hungarian)

Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures: Metallic structures, National Research Council, CNR-DT 202/2005, 53.

Haider, J. and Zhao, X.L. (2012), "Design of CFRP-strengthened steel CHS tubular beams", *J. Constr. Steel Res.*, **72**, 203-218.

Kawai, M. (2004), "A phenomenological model for off-axis fatigue behavior of unidirectional polymer matrix composites under different stress ratios", *Compos. Part A*, **35**, 955-963.

Kovács, G.Y. and Farkas, J. (2015), "Optimal design of a composite sandwich structure", *Sci. Eng. Compos. Mater.*, **23**(2), 237-243.

Kovács, G.Y., Farkas, J. and Jármai, K. (2007), "Analysis of a new sandwich-like structure", *Proceedings of the 17th International Conference on Computer Methods in Mechanics*, Lódz, Poland, June.

Lian, W. and Taheri-Behrooz, F. (2010), "Fatigue life prediction of composite laminates by FEA simulation method", *Int. J. Fatig.*, **32**, 123-133.

Naderi, M. and Maligno, A. R. (2012), "Finite element simulation of fatigue life prediction in carbon/epoxy laminates", *J. Compos. Mater.*, **47,** 475-484.

Naeun, K., Young, H.K. and Hee, S.K. (2015), "Experimental and analytical investigations for behaviors of RC beams strengthened with tapered CFRPs", *Struct. Eng. Mech.*, **53**(6), 1067-1081.

Ozgur, Y. and Ozgur A. (2015), "Structural repairing of damaged reinforced concrete beam- column assemblies with CFRPs", *Struct. Eng. Mech.*, **54**(3), 521-543.

Park, J.W. and Yoo, J.H. (2015), "Flexural and compression behaviour for steel structures strengthened with GFRP sheet", *Steel Compos. Struct.*, **19**(2), 441-465.

Pellegrino, C., Maiorana, E. and Modena, C. (2009), "FRP strengthening of steel and steel-concrete composite structures: an analytical approach", *Mater. Struct.*, **42**, 353-363.

Research study, Chapter 6, http://ocw.nthu.edu.tw/ocw/upload/8/255/Chapter_6-98.pdf

Shokrieh, M.M. and Taheri-Behrooz, F. (2006), "A unified fatigue

life model based on energy method", *Compos. Struct.*, **75**, 444-450.
Teng, J.G., Yu, T. and Fernando, D. (2012), "Strengthening of steel structures with fiber-reinforced polymer composites", *J. Constr. Steel Res.*, **78**, 131-143.
Zhao, X.L. and Zhang, L. (2007), "State-of-art review on FRP strengthened steel structures", *Eng. Struct.*, **29**, 1808-1823.

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