Economic Design of Steel Bridge Decks

by

JÁRMAI, Károly *
HORIKAWA, Kohsuke **
FARKAS, József *

* Prof., University of Miskolc, Hungary

** Prof., Joining and Welding Research Institute
Osaka University, Japan

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Abstract

In the structural synthesis the cost function is minimized considering design constraints on fatigue stress range of welded joints, local buckling, deflection and size limitations. In the cost function the material and fabrication costs are defined. The bending moments and the torsional stiffness of trapezoidal longitudinal stiffeners are calculated according to the Pelikan-Esslinger method, neglecting the flexibility of crossbeams. In fatigue constraints the published recent experimental research results are taken into account. A computer program of the Rosenbrock mathematical programming method is used to determine the following optimum dimensions: thickness of the deck plate, thicknesses and heights of stiffeners and crossbeams as well as the distance between crossbeams. The optimization procedure is illustrated by a numerical example.

Keywords

bridge decks, fatigue of welded joint, cost calculation, structural optimization, stiffened plates
Introduction

Stiffened steel decks form are important structural parts of bridges. Their welded joints can fail due to fatigue because of heavy traffic load. The fabrication cost form the main part of total cost, therefore it affects significantly the optimum dimensions of the deck structure. Although there are many size limitations, some dimensions can be optimized. These dimensions are as follows: thickness of the deck plate, height and thickness of stiffeners and crossbeams as well as the distance between crossbeams.

For the calculation of bending moments and the torsional stiffness of stiffeners the Pelikan-Esslinger method is used. The formulae are relatively complicate, thus a computer method should be applied. The Rosenbrock Hillclimb method was efficient for this purpose. The optimization procedure is illustrated by a numerical example. It should be noted that the optimum design of bridge decks with flat stiffeners has been treated in [1]. In the present paper the case of trapezoidal stiffeners is dealt with.

Assumptions

- The deck plate is simply supported around its periphery.
- The effect of the flexibility of crossbeams on bending moments in stiffeners is neglected.
- The main bridge girder and its connections to the deck structure are excluded from the calculations.
- The self-mass is neglected, since in the governing fatigue stress range constraint it has not to be considered.
- The spectrum factor in the calculation of fatigue stress range is taken as 1, the number of load cycles is \(2 \times 10^6\).

The live load considered for highway bridges

We select for our numerical example as live load trucks shown in Fig.1. According to DIN 1072 a truck has two wheel loads of 50 kN and two wheel loads of 30 kN. The widths of wheels are 400 and 260 mm respectively.

![Diagram of trucks considered as live load](image-url)
The bending and torsional stiffness of stiffeners

The dimensions of a stiffener section are given in Fig. 2.

Fig. 2. Dimensions of a stiffener section

The specific bending stiffness is defined by

$$B_y = \frac{I_y E}{a + e}$$  \hspace{1cm} (1)

where the moment of inertia is given by

$$I_y = (a + e)t_f z_G^2 + a_1 t_s (h - z_G)^2 + I_\xi + 2a_2 t_s \left(\frac{h}{2} - z_G\right)^2$$  \hspace{1cm} (2)

with

$$I_\xi = t_s \frac{a_2^3}{12} \sin^2 \alpha$$  \hspace{1cm} (3)

and

$$z_G = \frac{h t_s}{t_s (a_1 + 2a_2) + (a + e)t_f}$$  \hspace{1cm} (4)

The specific torsional stiffness can be calculated by using the Pelikan-Esslinger formulae [2], which take into account the local deformations of trapezoidal stiffeners.

$$H = \frac{\mu GT}{2(a + e)}$$  \hspace{1cm} (5)

where

$$\frac{1}{\mu} = \frac{GT}{GT_{red}}$$  \hspace{1cm} (6)

$$\frac{1}{\mu} = 1 + \frac{GT}{E I_0} \left(\frac{a^3}{12(a + e)^2} \left(\frac{\pi}{t_2}\right)^2 \left(\frac{e}{a}\right)^3 + \left(\frac{e - a_1}{a + a_1 + \lambda}\right)^2 + \frac{\lambda^2}{\kappa_0} \left(\frac{a_1}{a}\right)^3 + \frac{2a_2}{\kappa_0 a} \left(c_1^2 + c_1 c_2 + \frac{c_2^2}{3}\right)\right)$$  \hspace{1cm} (7)

$T'$ is the torsional stiffness for a closed thin-walled section [3,4].

$$T = \frac{4A_k^2}{\sum_i \frac{b_i}{t_i}}$$  \hspace{1cm} (8)
\[ t_2 = 0.81t \]  
\[ EJ_0 = \frac{Et_0^3}{10.92} \]  
\[ A_k = h\frac{a+a_1}{2} \]  
\[ c_1 = \frac{\lambda}{2} \frac{a_1}{a} \]  
\[ c_2 = \frac{(\lambda a-a_1)}{a} - \frac{(a+e-a_1)}{(a+a_1/2a)} \]  
\[ h = \sqrt{a_2^2 - \left(\frac{a-a_1}{2}\right)^2} \]  
\[ \lambda = \frac{(2a+a_1)(a+e)a_1a_2 - \kappa_0 a^3(e-a_1)}{(a+a_1)(2a_2(a^2+aa_1+a_1^2)+a_1^3+\kappa_0 a^3)} \]  
\[ \kappa_0 = \left(\frac{t_1}{t_f}\right)^3 \]  

The moment of inertia of crossbeams

The dimensions of a crossbeam section are shown in Fig.3.

![Fig.3. Dimensions of a crossbeam section](image)

\[ I_x = t_0t_fy_G^2 + \frac{h_0^2t_w}{12} + h_0t_w\left(\frac{h_w}{2} - y_G\right)^2 + b_{f1}t_{f1}\left(h_w - y_G\right)^2 \]  
\[ y_G = \frac{b_{f1}t_{f1}h_w + h_0t_w}{t_0t_f + b_{f1}t_{f1} + h_0t_w} \]  
\[ t_0 = 0.917t \] approximately according to a Pelikan-Esslinger diagram.

Note that the torsional stiffness of crossbeams can be neglected.
The bending moment of stiffeners at midspan

The homogeneous differential equation of an orthotropic plate, neglecting the bending stiffness in transverse direction, can be written as

\[ B_y \frac{\partial^4 w}{\partial y^4} + 2H \frac{\partial^4 w}{\partial x^2 \partial y^2} = 0 \]  

(19)

the solution of which is

\[ w = \left[ C_1 \sinh(\alpha y) + C_2 \cosh(\alpha y) + C_3 \alpha y + C_4 \right] \sin \frac{n\pi x}{b} \]  

(20)

Considering the boundary conditions, the bending moment at midspan due to a concentrated force \( Q \) is given by

\[ M_{00} = \psi Q t \left\{ \frac{1}{2} \frac{\cosh \left( \alpha \left( \frac{t}{2} - e_0 \right) \right)}{\cosh \left( \alpha \frac{t}{2} \right)} \right\} + M_{01} \left\{ \frac{1}{2} \frac{\sinh \left( \alpha e_0 \right)}{\alpha e_0} \frac{1}{\cosh \left( \alpha \frac{t}{2} \right)} \right\} \]  

(21)

where \( Q = 50 \text{ kN/400 mm} \) is the specific force (wheel load reduced to the plane of a stiffener). \( M_{00} \) is the specific bending moment acting in the plane of a stiffener. The bending moment acting on a stiffener is

\[ M = M_{00} (a + e) \]  

(22)

\[ M_{01} = \frac{\kappa_m}{a_1 (1 - \kappa_m)} \frac{1}{2 \cosh \left( \alpha \frac{t}{2} \right)} \]  

(23)

\[ \kappa_m = -c + \sqrt{c^2 - 1} \]  

(24)

\[ a_1 = -a_1 B_y \alpha^2 t \]  

(25)

\[ a_{11} = -\frac{1}{B_y \alpha^2 t} \frac{\sinh(\alpha t) - \alpha t}{\sinh(\alpha t)} \]  

(26)

\[ a_{22} = -\frac{2}{B_y \alpha^2 t} \frac{\alpha t \cosh(\alpha t) - \sinh(\alpha t)}{\sinh(\alpha t)} \]  

(27)

\[ \alpha = \frac{n\pi}{b} \sqrt{\frac{2H}{B_y}} \]  

(28)

The dynamic factor can be calculated according to DIN 1072 [5] as

\[ \psi = 1.4 - 0.008 \frac{t}{1000} - 0.1 h_a \]  

(29)

\( h_a \) is the thickness of asphalt.
The bending moment of a crossbeam at midspan

The reactive force from the wheel loads, according to Fig.4, is

\[ P = 50 \text{ kN} + \frac{2 \times 30(t - 3000)}{t} \quad \text{when} \quad t > 3000 \text{ mm} \]

and

\[ P = 50 \text{ kN} \quad \text{when} \quad t < 3000 \text{ mm} \]

![Diagram of reactive force P acting on a crossbeam from wheel loads](image)

**Fig.4.** Reactive force \( P \) acting on a crossbeam from wheel loads

In our numerical example we treat a bridge deck of width \( b = 12 \text{ m} \), thus we calculate with \( 8P \) (Fig.5).

![Diagram of forces acting on a crossbeam](image)

\[ M_{\text{max}} = Pb \]

**(30)**

**Fatigue constraint for stiffeners**

For bridge decks the fatigue constraint of welded joints is governing. There are some published recent experimental research results in addition to the design categories defined by Eurocode 3 (EC3) [6,7,8]. Although the trapezoidal stiffeners can be prefabricated in workshop and need not splices welded in site, we consider a site splice with butt weld, no splice plate, with backing strip, full penetration, root gap \( >4 \text{ mm} \), for which the recommended design category according to [8] is 80 MPa. Since this important joint is difficult to access for a test, we consider a safety factor according to EC3 of \( \gamma_{mf} = 1.35 \). Spectrum factor can be taken as 1, the number of load cycles is \( 2 \times 10^6 \).

The fatigue constraint is formulated as

\[ \frac{M_{00}(a+e)}{I_y(h-z_G)} \leq \frac{\Delta \sigma}{\gamma_{mf}} = \frac{80}{1.35} \]

**(31)**
Fatigue constraint for crossbeams

\[ \sigma_{\text{max}} = \psi \frac{M_{\text{max}}}{I_x} (h_w - y_G) \leq \frac{\Delta \sigma_1}{\gamma_{M1}} \]  

(32)

The fatigue stress range is 125 MPa, according to EC3, for automatically welded continuous longitudinal fillet welds carried out from both sides with no stop/start positions. The safety factor can be taken as 1.15 for important accessible joints.

Deflection constraints

Deflection should be calculated without dynamic factor.

Stiffeners:

\[ w_{\text{max}} = \frac{P t^3}{48 E I_y} \leq w^* \]  

(33)

According to Eurocode 3 Part 2 \( w^* = 5 \) mm.

Crossbeams:

\[ \frac{5 P_{\text{red}} b^4}{384 E I_x} \leq w^* \]  

(34)

where

\[ P_{\text{red}} = \frac{8 P}{b} \]  

(35)

Local buckling constraint for stiffeners

According to Eurocode 3 Part 2

\[ a_2 \leq 38 \alpha t_s \]  

(36)

Shear buckling constraint for crossbeam web

\[ \frac{F_A}{h_w t_w} \leq \frac{\tau_{ba}}{\gamma_{M1}} \]  

(37)

where the partial safety factor for shear is

\[ \gamma_{M1} = 11 \]  

(38)

\[ \lambda_w = \frac{h_w}{37.4 \varepsilon \sqrt{\kappa}} \]  

(39)

if \( \lambda_w \leq 0.8 \) then \( \tau_{ba} = \frac{f_y}{\sqrt{3}} \)
if $0.8 \leq \lambda_w \leq 1.2$ then $\tau_{ba} = \frac{f_y}{\sqrt{3}} \left[ 1 - 0.625(\lambda_w - 0.8) \right]$

if $\lambda_w \geq 1.2$ then $\tau_{ba} = \frac{0.9 f_y}{\lambda_w \sqrt{3}}$ (40)

**Frequency constraints**

The stiffeners' first eigenfrequency is limited for according to Eurocode 3. Part 2. [7] in 2 Hz. The calculation of eigenfrequency is as follows

$$f_{u} = \frac{\pi}{2t^2} \sqrt{\frac{EI_y}{m_s}}$$ (41)

The cross section area of the stiffener and the deck plate is

$$A_s = a_1 t_s + 2a_2 t_s + (a + e)t_f$$ (42)

The mass of this part is

$$m_s = A_s \times 7.85 \times 10^{-6} (a + e)$$ (43)

The cross beam's first eigenfrequency is also limited in 2 Hz. The calculation of eigenfrequency is as follows

$$f_{nc} = \frac{\pi}{2b^2} \sqrt{\frac{EI_x}{m_c}}$$ (44)

The cross section area of the cross beam and the deck plate is

$$A_c = t_0 t_f + b_{f1} t_{f1} + h_w t_w$$ (45)

The mass of this part is

$$m_c = A_c \times 7.85 \times 10^{-6} (a + e)$$ (46)

**Size limitations**

According to Eurocode 3 Part 2

$$e \leq 25 t_f$$ (47)

$$t_s \geq 6 \text{ mm}$$

$$t_f \geq 12 \text{ mm}$$

**Formulation of a cost function according to the fabrication steps**

The cost of a structure is the sum of the material and fabrication costs. The fabrication cost elements are the welding-, cutting-, preparation-, assembly-, tacking-, painting costs etc. It is very difficult to obtain such cost factors, which are valid all over the world, because there are great differences between the cost
factors at the highly developed and developing countries. If we choose the time, as the basic data of a fabrication element we can handle this problem. The fabrication time depends on the technological level of the country and the manufacturer, but it is much closer to the real process to calculate with. After computing the necessary time for a fabrication work element one can multiply by a specific cost factor, which can represent the development level differences. Although the whole production cost depends on many parameters and it is very difficult to express their effect mathematically, a simplified cost function can serve as a suitable tool for comparisons useful for designers and manufacturers [9,10].

The cost function can be expressed as

$$K = K_m + K_f = k_m V + k_f \sum_i T_i$$

(48)

where $K_m$ and $K_f$ are the material and fabrication costs, respectively, $k_m$ and $k_f$ are the corresponding cost factors, $\rho$ is the material density, $V$ is the volume of the structure, $T_i$ are the production times.

Fabrication times for welding

Table 1. Welding times $T_2$ (min) in function of weld size $a_w$ (mm) for longitudinal fillet welds downhand position (see also Fig. 6.)

<table>
<thead>
<tr>
<th>Welding method</th>
<th>$a_w$ (mm)</th>
<th>$10^3 T_2 = 10^3 C_2 a_w^{n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>2 - 5</td>
<td>$4.0 a_w$</td>
</tr>
<tr>
<td></td>
<td>5 - 15</td>
<td>$0.7889 a_w^2$</td>
</tr>
<tr>
<td>GMAW-C</td>
<td>2 - 5</td>
<td>$1.70 a_w$</td>
</tr>
<tr>
<td></td>
<td>5 - 15</td>
<td>$0.3394 a_w^2$</td>
</tr>
<tr>
<td>SAW</td>
<td>2 - 5</td>
<td>$1.190 a_w$</td>
</tr>
<tr>
<td></td>
<td>5 - 15</td>
<td>$0.2349 a_w^2$</td>
</tr>
</tbody>
</table>

Eq.(48) can be written in the following form

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

(49)

where

$$T_1 = C_1 \Theta_d \sqrt{k \rho V}$$

(50)

is the time for preparation, assembly and tacking, $\Theta_d$ is a difficulty factor, $\kappa$ is the number of structural elements to be assembled.
Fig. 6 Welding times for fillet welds of size $a_w$

Table 2. Welding times $T_2$ (min) in function of weld size $a_w$ (mm) for longitudinal 1/2 V butt welds downhand position

<table>
<thead>
<tr>
<th>Welding method</th>
<th>$a_w$ (mm)</th>
<th>$10^3T_2 = 10^3C_2a_w^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>4 - 6</td>
<td>2.7 $a_w$</td>
</tr>
<tr>
<td></td>
<td>6 - 15</td>
<td>0.45 $a_w^2$</td>
</tr>
<tr>
<td>GMAW-C</td>
<td>4 - 15</td>
<td>0.1939 $a_w^2$</td>
</tr>
<tr>
<td>SAW</td>
<td>4 - 15</td>
<td>0.1346 $a_w^2$</td>
</tr>
</tbody>
</table>

Table 3. Welding times $T_2$ (min) in function of weld size $a_w$ (mm) for longitudinal K-butt welds downhand position

<table>
<thead>
<tr>
<th>Welding method</th>
<th>$a_w$ (mm)</th>
<th>$10^3T_2 = 10^3C_2a_w^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>5 - 16</td>
<td>1.4029 $a_w^{1.25}$</td>
</tr>
<tr>
<td>GMAW-C</td>
<td>5 - 16</td>
<td>0.129 $a_w^2$</td>
</tr>
<tr>
<td>SAW</td>
<td>5 - 16</td>
<td>0.089 $a_w^2$</td>
</tr>
</tbody>
</table>

$$T_2 = \sum_i C_{2i}a_{wi}^n L_{wi}$$  \hspace{1cm} (51)$$

is the time of welding, $a_{wi}$ is the weld size, $L_{wi}$ is the weld length in mm, $C_{2i}$ and $n$ are constants given for different welding technologies.

$$T_3 = \sum_i C_{3i}a_{wi}^n L_{wi}$$  \hspace{1cm} (52)
is the time of additional fabrication actions such as changing the electrode, deslagging and chipping.

The different welding technologies are as follows: SMAW, GMAW-C, SAW.

Ott and Hubka [10] proposed that \( C_{3i} = 0.3 \ C_{2i} \), so

\[
T_2 + T_3 = 13 \sum C_{2i} a_{wi} L_{wi}
\]  

(53)

Values of \( C_{2i} \) and \( n \) may be given according to COSTCOMP [11] as follows. It gives welding times and costs for different technologies [12]. To compare the costs of different welding methods and to show the advantages of automation, the manual SMAW, semi-automatic GMAW-C and automatic SAW methods are selected for fillet welds. The analysis of COSTCOMP data resulted in constants given in Fig. 6 and Table 1-3 for different joint types.

One can establish other fabrication components, can calculate the fabrication time to even plates, the surface preparation time, the painting time, the cutting and edge grinding times, etc, but the main problem is how to formulate the equation concerning the time. The difficulty factor \( \delta \) represents that the welding, or painting is overhead, or vertical, or horizontal and also the complexity of the structure. In our case we focused on welding costs [13,14,15,16,17,18]. The robot welding and some new technologies have different cost aspects [19,20].

![Fig. 7. The main dimensions of the bridge of our numerical example](image)

The following formulae and values are used for the fabrication steps in our numerical example.

A complete bridge deck is constructed from structural elements of transportable dimensions [21]. In our numerical example a bridge of length \( L = 60 \) m and width \( b = 12 \) m is selected, composed from elements of dimensions \( L_0 = 12 \) m and \( b_0 = 3 \) m (Fig. 7).
1) Fabrication of 12*3 m elements in workshop

a) welding of stiffeners to deck plate with SAW fillet welds

\[ C_2 = 0.2349 \, a_w^2, \quad a_w = 1.25 \, t_s, \quad L_w = 2 \Phi_s \Phi t \]

b) cutting the crossbeam webs excluding the end crossbeam

\[ C_2 = 1.1388 \, t_{w}^{0.25}, \quad t = t_{w}, \quad L_w = \Phi_s(a_1 + 2a_2)(\Phi - 1) \]

c) welding of crossbeam lower flanges to webs with SAW fillet welds

\[ C_2 = 0.2349 \, a_w^2, \quad a_w = 0.5 \, t_w, \quad L_w = 2 \Phi_s \Phi t \]

d) welding of crossbeam webs to deckplate and to stiffeners with GMAW fillet welds

\[ C_2 = 0.3394 \, a_w^2, \quad a_w = 1.25 \, t_s, \quad L_w = \left( e + 2a_2 \right) \Phi_s 2(\Phi - 0.5) \]

Table 4. The place, type, cost, size and length of the welded joint for the fabrication of the 12*3 m elements in workshop

<table>
<thead>
<tr>
<th>Place of the joint</th>
<th>Welding technology</th>
<th>Cost parameter</th>
<th>Welded joint size</th>
<th>Welded joint length</th>
</tr>
</thead>
<tbody>
<tr>
<td>stiffener-deck plate</td>
<td>SAW</td>
<td>0.2349 , a_w^2</td>
<td>( t_s )</td>
<td>2 ( \Phi_s \Phi t )</td>
</tr>
<tr>
<td>cutting</td>
<td>normal acetylene</td>
<td>1.1388 ( t_w^{0.25} )</td>
<td>( t_w )</td>
<td>( \Phi_s(a_1 + 2a_2)(\Phi - 1) )</td>
</tr>
<tr>
<td>crossbeam lower</td>
<td>SAW</td>
<td>0.2349 , a_w^2</td>
<td>0.5 ( t_w )</td>
<td>2 ( \Phi_s \Phi t )</td>
</tr>
<tr>
<td>flange-web</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>crossbeam web-deck plate</td>
<td>GMAW</td>
<td>0.3394 , a_w^2</td>
<td>1.25 ( t_w )</td>
<td>( (e + 2a_2) \Phi_s 2(\Phi - 0.5) )</td>
</tr>
</tbody>
</table>

The volume of an element in which the number of stiffeners is \( \Phi_s = \frac{b_0}{a + e} \) and the number of crossbeams is \( \Phi = \frac{L_0}{t} \)

\[ V_1 = \Phi_s(a_1 + 2a_2)t_s\Phi t + b_0\Phi t t_f + \left( h_wt_w + A_f \right)\Phi b_0 \]  \( (54) \)

The number of assembled elements is

\[ \kappa_1 = \Phi_s + \Phi + 1 \]  \( (55) \)

The cost function for an element can be written as

\[ \frac{K_1}{k_m} = \rho V_1 + \frac{k_f}{k_m} \left[ \Theta_d \, \sqrt{\kappa_1 \rho} V_1 + 13 \left[ C_{2 \text{SAW}} \left( 0.5t_w \right)^n 2b_0 \Phi + C_{2 \text{CUT}} t_w^2 \Phi_s(a_1 + 2a_2)(\Phi - 1) + \ldots \right] \right] \]

\[ \left[ \ldots + C_{2 \text{SAW}} \left( 1.25t_s \right)^n 2\Phi_s \Phi t + C_{2 \text{GMAW}} \left( 1.25t_s \right)^n \left( e + 2a_2 \right) \Phi_s 2(\Phi - 0.5) \right] \]  \( (56) \)
2) Fabrication of the whole deck structure in site

a) welding of stiffeners to end crossbeams with GMAW fillet welds

\[ C_{2GMAW} = 0.3394 \, a_w^2 \quad a_w = 1.25 \, t_s \quad L_w = \frac{b}{b_0} \frac{L}{L_0} (a_1 + 2a_2 + e) \Phi_s \]

b) welding of the longitudinal and transverse splices with SAW butt welds

\[ C_{2SAW} = 0.2349 \, a_w^2 \quad a_w = t_f \quad L_w = \left( \frac{b}{b_0} - 1 \right) b \]

c) welding of crossbeam web and lower flange splices (these splices can also be realized by using bolted connections) with GMAW butt welds

- web splices \[ C_{2GMAW} = 0.3394 \, a_w^2 \quad a_w = t_w \quad L_w = \left( \frac{b}{b_0} - 1 \right) \left( \frac{L}{L_0} + 1 \right) \]

- flange splices \[ C_{2GMAW} = 0.3394 \, a_w^2 \quad a_w = t_f \quad L_w = \left( \frac{b}{b_0} - 1 \right) \left( \frac{L}{L_0} + 1 \right) \]

Table 5. The place, type, cost, size and length of the welded joint for the fabrication of the whole deck in site

<table>
<thead>
<tr>
<th>Place of the joint</th>
<th>Welding technology</th>
<th>Welding cost parameter</th>
<th>Welded joint size</th>
<th>Welded joint length</th>
</tr>
</thead>
<tbody>
<tr>
<td>stiffeners to end crossbeams</td>
<td>GMAW</td>
<td>0.3394 (a_w^2)</td>
<td>1.25 (t_s)</td>
<td>(\frac{b}{b_0} \frac{L}{L_0} (a_1 + 2a_2 + e) \Phi_s)</td>
</tr>
<tr>
<td>longitudinal and transverse splices</td>
<td>SAW</td>
<td>0.2349 (a_w^2)</td>
<td>(t_f)</td>
<td>(\left( \frac{b}{b_0} - 1 \right) b)</td>
</tr>
<tr>
<td>web splices</td>
<td>GMAW</td>
<td>0.3394 (a_w^2)</td>
<td>(t_w)</td>
<td>(\left( \frac{b}{b_0} - 1 \right) \left( \frac{L}{L_0} + 1 \right))</td>
</tr>
<tr>
<td>flange splices</td>
<td>GMAW</td>
<td>0.3394 (a_w^2)</td>
<td>(t_f)</td>
<td>(\left( \frac{b}{b_0} - 1 \right) \left( \frac{L}{L_0} + 1 \right))</td>
</tr>
</tbody>
</table>

The volume of the whole deck structure is

\[ V_2 = \kappa_2 V_1 \quad (57) \]

\[ \kappa_2 = \frac{bL}{b_0 L_0} \quad (58) \]

The cost function of the whole deck structure is

\[ \frac{K_2}{k_m} = \frac{k_f}{k_m} \left[ \Theta_d \sqrt{\kappa_2 \rho V_2} + 1.3 \left( C_{2GMAW} (1.25 t_s)^n \frac{b}{b_0} L_0 (a_1 + 2a_2 + e) \Phi_s + C_{2SAW} t_f \left( \frac{b}{b_0} - 1 \right) b \right] + \ldots \right] \]
\[
\left[ \ldots + C_{2GM_{AW}} \left( h_w t_w^n + b_f L_f^n \right) \left( \frac{b}{b_0} - 1 \right) \left( \frac{L}{L_0} + 1 \right) \right] \]

(59)

The whole cost function to be minimized is

\[
\frac{K}{k_m} = \frac{20K_1 + K_2}{k_m}
\]

(60)

The optimization procedure for the numerical example

The cost function (Eq. 60) is to be minimized considering the following constraints: Eqs.31, 32, 33, 34, 36, 37 and 41.

Size limitations

The variables are as follows: \( t_f, h_w, t_w, A_f = b_f t_f \), which are optimized for a series of discrete values of \( t \) to obtain \( t_{opt} \) corresponding to \( K_{min} \).

- \( 12 \leq t_f \leq 28 \) mm
- \( 300 \leq h_w \leq 2000 \) mm
- \( 8 \leq t_w \leq 25 \) mm
- \( 200 \leq A_f \leq 1600 \) mm
- \( 6 \leq t_s \leq 20 \) mm

Results and conclusions

The optimization is made with the following data:

- steel yield stress is \( f_y = 235 \) MPa, the cost ratio is between \( \frac{k_f}{k_m} = 0 \div 2 \), the number of unknown variables is 5, they are as follows
  \[
  x_1 = t_f, \quad x_2 = h_w, \quad x_3 = t_w, \quad x_4 = A_f = b_f t_f, \quad x_5 = t_s
  \]
  (61)

The number of constraints for the cross beam is 5, for the stiffener is 3 according to Eqs.(31, 32, 33, 34, 36, 37, 41, 44 and 47).

The mathematical optimization technique is the Rosenbrock’s Hillclimb procedure [4].

The results for normal steel, \( f_y = 235 \) MPa, and cost ratio \( \frac{k_f}{k_m} = 0.5 \) can be seen in Table 6.
Table 6. The minimum cost of bridge deck due to different cross beam distance with normal steel and cost ratio $= 0.5$

| $t$ mm | Total cost $|$ | Material cost $|$ | Fabrication cost $|$ |
|--------|--------------|----------------|------------------|
| 1000   | 344199.8     | 261422.0       | 112381.0         |
| 1500   | 272902.0     | 215660.5       | 89674.1          |
| 2000   | 269494.5     | 217542.1       | 83933.3          |
| 2500   | 245737.0     | 179673.0       | 66064.0          |
| 3000   | 246077.6     | 177011.8       | 69065.8          |
| 3500   | 327045.2     | 202234.9       | 124810.2         |
| 4000   | 314094.2     | 199084.1       | 115010.0         |
| 4500   | 324922.8     | 186202.2       | 138720.6         |

The results for normal steel, $f_y = 235$ MPa, and cost ratio $\frac{k_f}{k_m} = 10$ can be seen in Table 7. and Fig. 8.

Fig. 8. The optimum bridge decks' cost in the function of the cross beam distance.

The results for normal steel, $f_y = 235$ MPa, and cost ratio $\frac{k_f}{k_m} = 2.0$ can be seen in Table 8.
Table 7. The minimum cost of bridge deck due to different cross beam distance with normal steel and cost ratio = 1.0

<table>
<thead>
<tr>
<th>$t$ (mm)</th>
<th>Total cost ($)</th>
<th>Material cost ($)</th>
<th>Fabrication cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>459578.3</td>
<td>323394.6</td>
<td>182805.8</td>
</tr>
<tr>
<td>1500</td>
<td>377686.3</td>
<td>285605.9</td>
<td>177337.8</td>
</tr>
<tr>
<td>2000</td>
<td>390670.2</td>
<td>269446.8</td>
<td>188773.8</td>
</tr>
<tr>
<td>2500</td>
<td>378348.4</td>
<td>228944.2</td>
<td>149404.2</td>
</tr>
<tr>
<td>3000</td>
<td>382242.1</td>
<td>222327.5</td>
<td>159884.6</td>
</tr>
<tr>
<td>3500</td>
<td>434997.3</td>
<td>217004.6</td>
<td>217992.7</td>
</tr>
<tr>
<td>4000</td>
<td>448506.2</td>
<td>241262.1</td>
<td>207244.1</td>
</tr>
<tr>
<td>4500</td>
<td>518236.9</td>
<td>239987.3</td>
<td>278249.5</td>
</tr>
</tbody>
</table>

Table 8. The minimum cost of bridge deck due to different cross beam distance with normal steel and cost ratio = 2.0

<table>
<thead>
<tr>
<th>$t$ (mm)</th>
<th>Total cost ($)</th>
<th>Material cost ($)</th>
<th>Fabrication cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>686824.3</td>
<td>500915.1</td>
<td>350528.2</td>
</tr>
<tr>
<td>1500</td>
<td>612183.4</td>
<td>405159.3</td>
<td>355136.3</td>
</tr>
<tr>
<td>2000</td>
<td>582811.4</td>
<td>389439.0</td>
<td>343595.5</td>
</tr>
<tr>
<td>2500</td>
<td>671563.8</td>
<td>336396.2</td>
<td>398456.2</td>
</tr>
<tr>
<td>3000</td>
<td>666933.8</td>
<td>311444.8</td>
<td>355488.9</td>
</tr>
<tr>
<td>3500</td>
<td>706580.4</td>
<td>296284.2</td>
<td>410296.2</td>
</tr>
<tr>
<td>4000</td>
<td>758852.9</td>
<td>339493.8</td>
<td>419359.2</td>
</tr>
<tr>
<td>4500</td>
<td>792211.7</td>
<td>323837.4</td>
<td>468374.3</td>
</tr>
</tbody>
</table>

The results show, that the optimum distance between cross beams for $\frac{k_f}{k_m} = 0.5$ is about $t_{opt} = 2600$ mm, for $\frac{k_f}{k_m} = 1.0$ is $t_{opt} = 2500$ mm, for $\frac{k_f}{k_m} = 2.0$ is $t_{opt} = 1900$ mm. The higher fabrication cost results closer cross beam, which means weaker stiffeners.

The ratio between material over fabrication costs for $\frac{k_f}{k_m} = 0.5$ ratio is about 30% - 70%, for $\frac{k_f}{k_m} = 1.0$ is 43% - 57%, for $\frac{k_f}{k_m} = 2.0$ is 46% - 54% respectively.
Using higher strength steel $f_y = 355$ MPa, for $\frac{k_f}{k_m} = 2.0$ the optimum cross beam distance is $t_{opt} = 2050$, instead of 1900 mm. It means, that higher strength steel increase the distance between cross beams. We have fixed the minimum stiffener thickness in 6 mm. If we decrease this limit to 4 mm, the distance of cross beams became smaller due to the smaller stiffener costs. The developed computer program runs on Pentium PC, under MS Fortran Power Station Developing System. The user interface is made by MS Visual Basic. One runtime is a few minutes. The calculation contains the discretization after finding the continuous values. This is very important for the fabrication. The computer calculation shows, that this program is useful for the predesign of bridge decks, taking into account fatigue, stability, deflection and frequency constraints.

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References


