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Optimization of Quickly Assembled Steel-Concrete Composite Bridge Used in Temporary

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Abstract

The temporary bridge is used to cross river, canyon, ditches and other obstacles duo to its simplicity, convenience for operation and short construction time.How to design the temporary bridge economically and install it quickly are the primary considerations to meet the load requirements and traffic considerations. Based on the structural optimization design theory, the Small Arch Bridge, which is a steel-concrete composite girder bridge and locates in Fu ling district of Chongqing city, is optimized using the linear programming method. In this method, first assume the cross-section of I-girder and the dimensions of deck as the design variables, the mechanical behavior of the whole bridge and the deformation stiffness as the constraints, and then find the minimized cost using MATLAB optimization tools. On the basis of the optimization results, this paper presented the arguments of I-girder and deck panel which meet the mechanical and economical requirements and could provide some references for bridges of like.

Keywords: temporarybridge, long-termbridge, compositebridge, transformation, optimization

1. Introduction

The temporarybridge isbuilt for constructionand transportation, for example, in thedisaster relief,the mountainsacrossthe valleygrooveorbridgelocateswhere the geological condition can’tmeet the constructionand transportationrequirements. Service time of the temporary bridge is short and it loses function as soon as the project completes, therefore, how to design the temporary bridge economically and install it quicklyarethe primaryconsiderations to meet theloadrequirements andtrafficconsiderations (Sun Z. & Hu W., 2010).

In recent years, the research about structural optimization theory and method are numerous at home and abroad, which have been exploring along different roads in engineering practice, and some have already achieved significant outcomes (André D. O. & Dan M. F., 2011). As a new field, it still has a lot of uncovered things worthy of further research and exploration. Based on modern technology and associated with the ideal design of structure, it has aroused great interest of many scientific and technical workers and attracted people for the further research on the theory and method, as well as made contribution to the application in the engineering design (Li Zh., 1982).

The designer is an optimizer (Richard B., 2006). Optimal design theory provides a shortcut to optimize the design of the temporary bridge, in this paper, the structural optimizationtheory is used to illustrate the optimization ofquicklyassembledsteel-concrete composite bridge availablefor emergency.

2. The Structural Optimization Theory (Jiang A., 1986)

Structural optimization is using structural analysis theory to describe the problem in mathematical way, namely create a mathematical model, and then select a reasonable and effective calculation method to solve the problem by computer programming. On the basis of the structure parameters, the maximum or minimum solutions of the objective function that satisfy all the constraints can be found out.

The programming method is currently used in the structural optimization, which in fact is to seek the extreme point of the objective function.

When using the programming method, specify the design variable x_i and the objective function

$$W = W(x_i) \tag{1}$$

Minimize W and make it satisfy the constraints.

$$g_j(x_i) \le 0 \quad i = 1, 2, \cdots, n \tag{2}$$

$$x_i \ge 0 \quad j = 1, 2, \cdots, m \tag{3}$$

Where *n* is the number of design variables, *m* is the number of constraints, *w* is the objective function of weight, *g* is the constraint function.

For simplicity, formula (a) can be abbreviated as:

$$\text{Solve X} \quad \min \quad W(X)$$

$$\text{S.t.} \quad G(X) \le 0$$

$$X \ge 0$$

Where X is the vector comprising of $x_1, x_2, \cdots x_n$ min represents minimization, s.t represents constraints, $G(X)$ is a vector of constraint function comprising of $g_1(X), g_2(X), \cdots g_n(X)$

3. Project Introduction

The Small Arch Bridge locates in Fu ling District of Chongqing city, which is a 1-10 meter stone arch bridge built in 1958 and cross Yuelailong River. The design load is automotive-20 and trailer-100. After the water level of the Three Gorges Dam reservoir reaches 175 meter, the bridge site was flooded, so the original bridge was reconstructed as a 20 m steel-concrete composite simply supported beam bridge connected with PCCS shear connector. The vehicle load is highway - Ⅱ, the crowd load is 3.5kN/m^2, and the bridge width is 2m (sidewalk) +2 × 3.5m (driveway) +2 m (sidewalk), the superelevation is 1.5%. C40 concrete is used for the deck and Q345 is used for the I-girder. To facilitate the fast construction and save material usage, the bridge was first built as temporary bridge, and then the deck and I-girder were connected by shear connector transforming the temporary bridge to long-term bridge. The general layout and cross-section of the Small Arch Bridge are shown in Figure 1 and Figure 2.

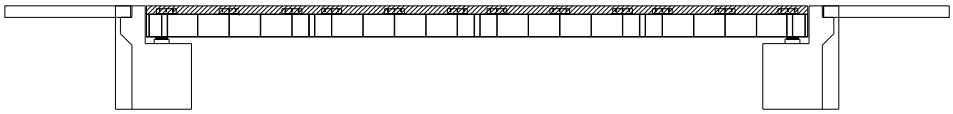

Figure 1. General layout of the Small Arch Bridge

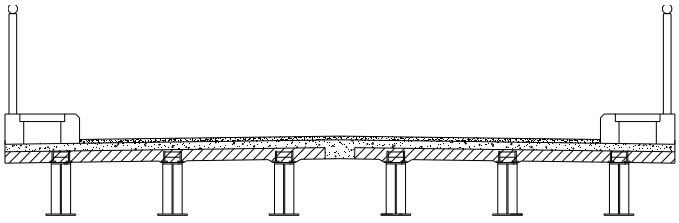

Figure 2. Cross-section of the Small Arch Bridge

4. The Optimization Process

In the optimization of the Small Arch Bridge, the least cost is assumed as the objective function, the cross-section of I-girder and the dimensions of deck are assumed as the design variables, the mechanical behavior of the whole bridge was analyzed to identify the constraints, then to find the minimized solution of cost using MATLAB programming.

4.1 Calculation of the Temporary Bridge

The concrete deck of emergency bridge is directly placed on the I-girder and no connection measures such as shear key are implemented. The deformation of the I-girder under load is shown in Figures 3 and 4.

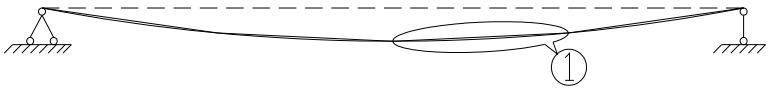

Figure 3. Deformation of I-girder

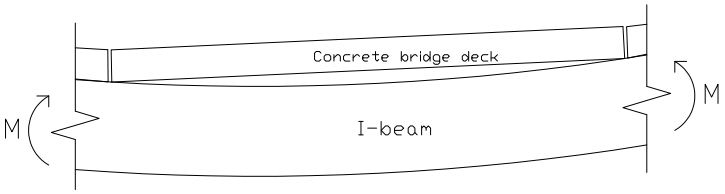

Figure 4. The detailed drawing of I-girder deformation

As is shown in Figure 4, the I-girder of the emergency bridge is subjected to self-weight, lane load and concentrate load caused by the bridge deck, the concentrate load can be simplified as uniform load in the calculation.The deck panel itself can be simplified as a simply supported beam.

4.1.1 The Mechanical Analysis of I-girder

Figure 5 is the calculation diagram of the I-girder of the emergency bridge. The design load is highway - Ⅱ.

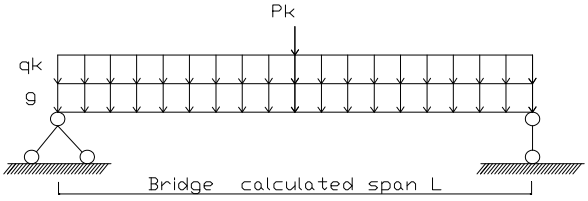

Figure 5. Calculation diagram of emergency bridge I-girder

The slandered lane uniform load and concentrate load of highway - Ⅱ is 0.75 times of the highway-Ⅰ. For highway-Ⅰ, $q_k = 10.5kN/m$, when $L \le 5m$, $p_k = 360kN$; when $L \ge 50m$, $p_k = 180kN$, when $5m < L < 50m$, p_k is determined by linear interpolation.

$$q_K = 0.75 \times 10.5 = 7.875 kN/m$$

$$P_k = 3L + 120$$

$$g = 25tl + 78.5A$$

Where *L is the* bridge span *(m)*, *g* is the self-weight of the bridge deck *(KN)*, *t* is the thickness of the bridge deck *(m)*, *l* is calculated span of deck panel *(m)*. A is the cross-section area of I-girder(JTG D60-2004).

The moment of girder at the joint action of dead load and vehicle load is given by:

$$M = \frac{L^2}{8}(25tl + 78.5A + 7.875) + \frac{L}{4}(3L + 120)$$

Lower flange controlling stress of I-girder: $\sigma = M/W \le 200Mpa$,

then:

$$\frac{L^2}{8}(25tl + 78.5A + 7.875) + \frac{L}{4}(3L + 120) - 2 \times W \times 10^5 \le 0 \quad (4)$$

$$W = I/zc \quad (5)$$

Where:

z_c—centroid coordinate of I-girder cross section

I —Moment of inertia of I-girder

Figure 6 is the cross-section of I-girder. Assuming the thickness and the moment of inertia of the upper and lower flange is negligible. The cross-section area of I-girder is $A = A_1 + A_2 + th$

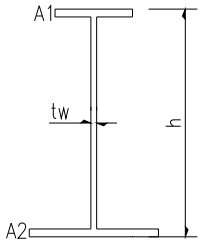

Figure 6. Cross-section of I-girder

The selected a coordinate system oyz is shown in Figure 7, C is the centroid of cross-section.

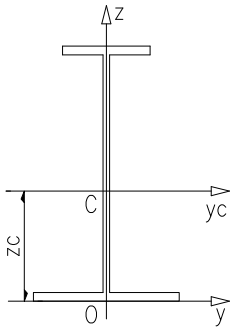

Figure 7. The selected coordinate system

The centroid coordinates of composite cross-section is given by:

$$yc = \frac{\sum_{i=1}^{n} A_i y_{ic}}{\sum_{i=1}^{n} A_i} \quad zc = \frac{\sum_{i=1}^{n} A_i z_{ic}}{\sum_{i=1}^{n} A_i},$$

then: $$zc = \frac{A_1 + 1/2 t_w h^2}{A_1 + A_2 + t_w h} \tag{6}$$

I-girder cross section can be regarded to consist of three rectangular cross sections when calculating the cross-section inertia moment, and then according to rectangular cross-section inertia moment formula $I_y = \frac{bh^3}{12}$、the parallel shift formula of inertia moment $I_y = I_{yc} + a^2 A$ and the inertia moment formula of composite cross-section: $I_y = \sum_{i=1}^{n} I_{yi}$ (Where I_{yi} is the inertia moment of each part of the composite cross-section in terms of y-axis, *n* is the number of rectangular cross-section), the moment of inertia of girder cross section is given by:

$$I = th^3/12 + th \times (h/2 - y)^2 + A_1 \times (h - zc)^2 + A_2 \times zc^2 \tag{7}$$

4.1.2 Force Analysis of the Deck Panel

1) The longitudinal force analysis

According to Figures 1, 2, the deck along the longitudinal direction can be simplified as a simply supported beam shown in Figure 8.

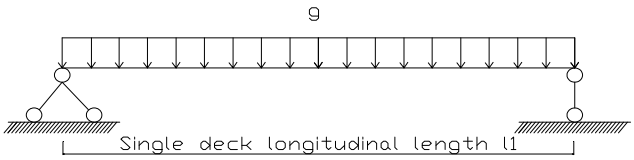

Figure 8. The longitudinal calculation diagram of deck panel

Wherein the longitudinal length of the bridge deck l_1 (m), $g = 25tl$, Bending moment: $M = gl_1^2/8 = 3.125tll_1^2$;

Sectional resistance moment: $W = lt^2/6 = 0.167lt^2$;

Controlling stress: $\sigma = M/W \le 3Mpa$

We can get:
$$3.125tll_1^2 - 501lt^2 \le 0 \tag{8}$$

2) The lateral force analysis (Yao L., 2008)

The lateral force analysis of the deck panel is in accordance with the internal forces analysis of carriageway board. The carriageway board is subjected to the wheel load directly, so $a_1 = a_2 = 0.2$, and the effective distribution width $a = 2l/3$ [4].The calculation diagram is shown in Figure 9,

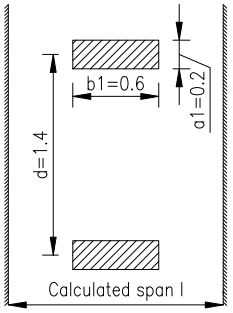

Figure 9. Wheel load calculation diagram (m)

- The internal forces of deck panel caused self-weight

The self-weight of the deck panel: $g = 25at = 16.667lt$

Bending moment: $M_{og} = 1/8\, gl^2 = 2.083l^3t$

- Internal forces caused by vehicle load:

$$M_{op} = (1+\mu)\times\left(\frac{P}{4}\times\frac{l}{2} - \frac{P}{4}\times\frac{b_1}{4}\right) = 22.75l - 6.825$$

- Load combination:

$$M_o = M_{op} + M_{og} = 22.75l - 6.825 + 2.083l^3t$$

When $t/h < 1/4$, the bending moment in mid-span is $M = +0.5M_o$; When $t/h \ge 1/4$, the bending moment in mid-span is $M_{中} = +0.7M_o$ (Fan L., 2011). Select the larger value, that is $M = +0.7M_o$, thenthe cross-section stress in the mid-span is $\sigma = M/W \le 3Mpa$, where $W = at^2/6 = 0.111lt^2$, then we can get:

$$1.458tl^3 + 15.925l - 333.33lt^2 - 4.778 \le 0 \tag{9}$$

4.2 Force Analysis of the Long-Term Bridge

The mechanism of the long-term bridge is significantly different from that of the emergency bridge. In the long-term bridge, the deck panel is connected to the I-girder through shear connector to form steel - concrete composite girder. Therefore, the external force is resisted by the joint work of steel girder and concrete panel, and the deformation of the deck panel is in accordance with the I-girder as is shown in Figure 10.

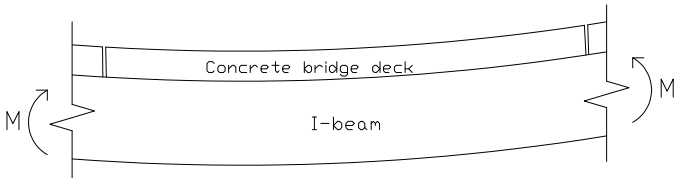

Figure 10. Deformation of the deck panel and I-girder

4.2.1 The Internal Forces and Stress Analysis of Steel - Concrete Composite Girder (JIN B. &TONG G., 2008)

The long-term bridge is a steel - concrete composite girder, in which the deck panels and the upper flange of girder are mainly in compression and the bottom flange in tension. This paper mainly calculated stress of I-girder. The main girder calculation diagram is shown in Figure 11.

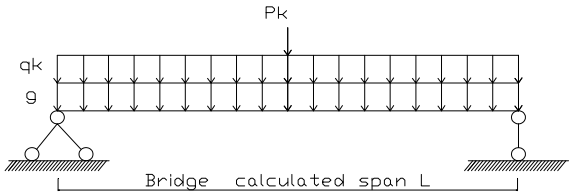

Figure 11. The calculation diagram of I-girder

$P_K = 3L + 120$

$q_K = 0.75 \times 10.5 = 7.875 kN/m$

$g = 25tl + 78.5A + 4.24l$

The bending moment of girder under self-weight, secondary load and vehicle load is given by:

$$M = \frac{L^2}{8}(25tl + 78.5A + 4.24l + 7.857) + \frac{L}{4}(3L + 120)$$

Lower flange stress of I-girder is $\sigma = M/W \le 200Mpa$.

Then we can get:

$$\frac{L^2}{8}(25tl + 78.5A + 4.24l + 7.875) + \frac{L}{4}(3L + 120) - 2 \times W \times 10^5 \le 0 \quad (10)$$

$$W = I/zc' \quad (11)$$

ZC '—centroid coordinate of composite cross-section,

I —Moment of inertia of composite cross-section

Figure 12 is the cross-section of the steel-concrete composite girder.

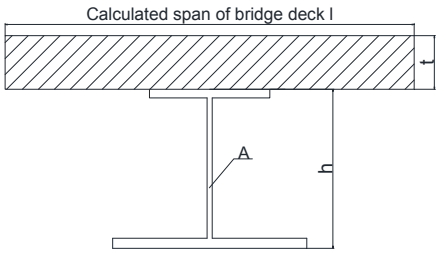

Figure 12. Cross-section of composite girder

Figure 13 shows the selected coordinate system oyz, C is centroid of composite cross-section.

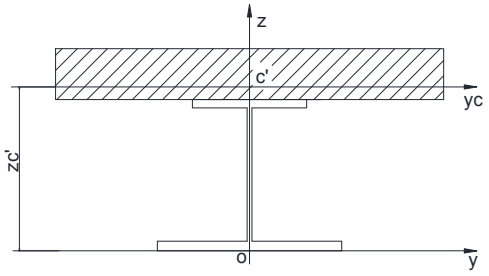

Figure 13. The selected coordinate system of composite cross-section

The centroid coordinates of composite cross-section is given by:

$$yc = \frac{\sum_{i=1}^{n} A_i y_{ic}}{\sum_{i=1}^{n} A_i}, \quad zc = \frac{\sum_{i=1}^{n} A_i z_{ic}}{\sum_{i=1}^{n} A_i}$$

Then:

$$zc' = \frac{tl \times (h + t/2) + A \times \mathrm{zc}}{tl + A} \tag{12}$$

When calculating the inertia moment of composite cross-section, the inertia moment should be first translated into a unified form. Here the inertia moment of deck panel is converted into the inertia moment that can be multiplied by steel elastic modulus, that is, $I = lt^3/12$ is converted to $I = 3.25lt^3/247.2$. Plus with the inertia moment of I-girder cross-section, the parallel shift formula of moment of inertia $I_y = I_{yc} + a^2 A$, and the moment of inertia formula of composite cross-section: $I_y = \sum_{i=1}^{n} I_{yi}$, (Where I_{yi} is the inertia moment of each part of the composite cross-section in terms of y-axis, *n* is the number of rectangular cross-section), the inertia moment I_z of composite girder cross section is given by (Chai H. Y., Kyungsik K., Kyoung C. Lee & Junsuk K., 2013):

$$I_z = 3.25lt^3/247.2 + tl \times (h + t/2 - zc')^2 + I + A \times (zc' - zc)^2 \tag{13}$$

4.2.2 Force Analysis of the Deck Panel

For long-term bridge, the deck panels are covered with pavement comprising of 10cm anti-wear concrete and 8cm asphalt concrete. According to Internal force calculation method of the carriageway board, the calculation diagram of deck panel is shown in Figure 9.

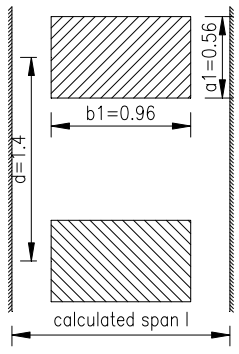

Figure 14. Wheel load calculation diagram (m)

1. The dead load and the internal force caused by dead load per meter of deck panel:

Asphalt concrete pavement g_1: 0.08×1.0×23=1.84kN/m

Anti-wear concrete g_2: 0.1×1.0×24=2.4kN/m

Deck panel g_3: t×1.0×25=25tkN/m

Bending moment caused by dead load per meter of deck panel:

$$M_{og} = 1/8\left(g_1 + g_2 + g_3\right)l^2 = 0.53l^2 + 3.125tl^2$$

2. Internal forces caused by vehicle load:

$$a_1 = a_2 + 2H = 0.2 + 2\times 0.18 = 0.56m\ ,$$

$$b_1 = b_2 + 2H = 0.6 + 2\times 0.18 = 0.96m$$

Then the effective distribution width of load is:

$$a = a_1 + d + l/3 = 0.56 + 1.4 + l/3 = 1.96 + l/3$$

The Bending moment: $M_{op} = \left(1+\mu\right)\times\frac{P}{8a}\left(l - b_1/2\right) = \frac{68.25l - 32.76}{5.88 + l}$

3. Load combination: $M_o = M_{op} + M_{og}$

When $t/h < 1/4$ the bending moment in mid-span is $M_{中} = +0.5M_o$; When $t/h \geq 1/4$ the bending moment in mid-span is $M_{中} = +0.7M_o$ .Select the larger value, that is $M_{中} = +0.7M_o$ thenthe cross-section stress in the mid-span is $\sigma = M_{中}/W \leq 3Mpa$, $W = at^2/6 = \left(5.88 + l\right)\times t^2/18$.

Then we can get:

$$1.113l^2 + 6.563tl^2 - 500lt^2 - 2940t^2 + \frac{143.325l - 68.796}{5.88 + l} \leq 0 \tag{14}$$

4.3 MATLAB-based Computing

Based on the principle of least cost, the objective function can be assumed as:

$$Q_{\min} = \mathrm{a}\times A\times L\times B/l + b\times t\times B\times L \tag{15}$$

Where: a—steel price per cubic meter

b—concrete price per cubic meter

L—bridge span

B—bridge width

t—bridge panel thickness

l —calculated span of deck panel

A—cross-section area of I-girder

As for arguments (L, B), five groups are chose, namely (7, 6), (10, 6), (10, 9), (15, 9), (20, 9). The optimization process was completed using MATLAB optimization tool. As is shown in Figure 15, equations were put into MATLAB optimization tools to calculate I-beam height, web thickness, flange area, moment of inertia; the thickness of bridge deck, computing span and the inertia moment of the composite section.

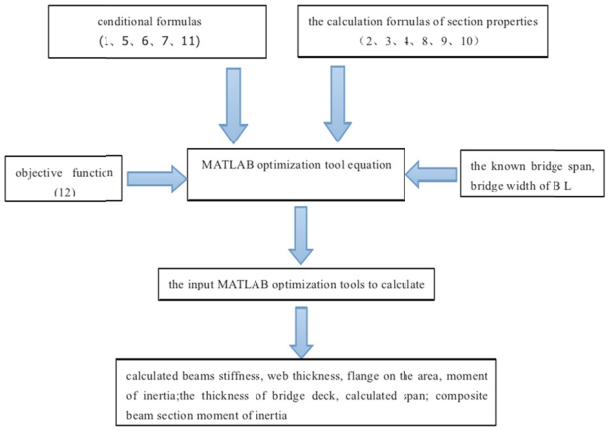

Figure 15. Diagram of optimization process

The minimum cost of the whole bridge is assumed as the objective function, due to that the price of steel is much higher than that of the concrete, calculation of the above formula will yield unexpected results of the deck thickness using the optimization toolbox in MATLAB directly, in some cases, the thickness is up to 1m or even more. Therefore, iterative method was used, first calculate the thickness and computing length of deck according to the stress controlling equation 6, and then assume that the deck thickness is 0.2m and the computing length of deck is 1.4m. The width of Small Arch Bridge is 9m, for the easy arrangement of girder, assume that the computing length of deck is 1.5m (the space of I-girder), then the deck thickness is 0.21m, and select a general thickness of 0.25m. Then the deck thickness of 0.25m, and calculating span of 1.5m were substituted into the equation 3.4 whose results proved its reasonability, thus the bridge deck thickness is 0.25m and the calculated span is 1.5m.

The fmincon function (constrained nonlinear programming) in MATLAB optimization toolbox was used. In the optimization process, if numerical level reaches10-4, the result is 0, therefore 0.001 is defined as the minimum value. The values of I-girder height h, I-beam web thickness TW are assumed as conventional integer and the calculation results are shown in Table 1.

Table 1. The results of optimization

Bridge type	A(m^2)	A_1(m^2)	A_2(m^2)	h(m)	tw(m)	I (m^4)	I_z(m^4)	t(m)	l (m)
L=7 m；B=6 m	0.0088	0.0016	0.0027	0.45	0.010	0.00028	0.00223	0.25	1.5
L=10 m；B=9 m	0.0119	0.0019	0.0034	0.55	0.012	0.00054	0.00249	0.25	1.5
L=15 m；B=9 m	0.0202	0.0041	0.0098	0.65	0.016	0.00132	0.00327	0.25	1.5
L=20 m；B=9 m	0.0271	0.0057	0.0088	0.70	0.018	0.00211	0.00406	0.25	1.5

5. Conclusions

In the design of a temporary bridge, except formeeting theloadrequirements andtrafficconsiderations, the cost economy should be taken into account. On the basis of the structural optimization design theory, the Small Arch Bridge, which is a steel-concrete composite girder bridge, is optimized by using the linear programming method and the basic theory of bridge engineering. Refereed to relevant specification,that is assuming the cross-section of I-girder and the dimensions of deck as the design variables, and the mechanical behavior of the whole bridge and the deformation stiffness as the constraints, the minimized solution of cost using optimization tool can be found out. To ensure the optimization toolbox in MATLAB yields the expected results, iterative method is proposed instead of using the toolbox directly. According to the optimization results, this paper presented the arguments of steel I-girder and deck panel that meet the mechanical and economical requirements for steel-concrete composite girder bridges within the span of 20m. The results of this paper could also provide some references for bridges of like.

This example also illustrates the structure optimal design theory in engineering application universality. The method is calculated by MATLAB software using the optimization theory of mathematics which is simple and intuitive but not so fast and convenient. It can be believed that with the development of mathematics, bridge engineering, new tools and methods can be found out to solve this kind of problems.

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