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Effect of Concrete Cost on Optimum Design of I-Steel Girder Bridges

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ABSTRACT

Composite Reinforced Concrete (RC) Slab on steel I-girder bridges are widely used in the world and the optimum design of these bridges is always raised as a big question. There are many factors effect on the cost of optimum design like length, width of the bridge and else. This paper presents the effect of varying concrete cost, with keeping the steel cost constant, on the optimum design of steel I-girder bridges. The orthotropic plate theory for RC deck slab analysis was used in this study, considering span as simply supported. The problem of optimum cost of steel bridges is formulated as that of minimization of initial cost (IC) for all the bridge, which consists of substructure cost and superstructure cost. The performance constraints in the forms of flexural failure, deflection failure are based on the American Association of State Highway and Transportation Officials (AASHTO) 1989 [14th Edition]. The Sequential Unconstrained Minimization Technique (SUMT) is used to produce required optimizations for costs.
A factor called Cost Ratio* which is representing the relation between concrete cost and steel cost was introduced, to show the varying concrete cost comparing with steel cost.
The computer program called CPSAO is written with FORTRAN has been built to carry out computation, consisting of the analysis, design and optimization subroutines based on the feasible direction method. It has been considered that the RC deck slab and steel girders as an equivalent orthotropic plate, to find the optimum design for a bridge.
To demonstrate the effect of concrete cost on the optimum design of steel I-girder bridges, different lengths of bridges and different values of cost ratio were used. The effect of these parameters on the total cost and others parameters has been presented in graphical forms. It is found that increasing concrete cost (i.e. decreasing cost ratio) leads to increase bridge cost, but meantime makes cost of superstructure and substructure closer.

KEYWORDS Optimum design, steel bridges, I-girder, Initial Cost.

Introduction

The objective of structural design is to select member sizes with the optimal proportioning of the overall structural geometry so as to achieve minimum initial cost design that meets the performance objectives specified in the conventional design specification (Cho 2001). A number of researchers have made their efforts to develop the optimization algorithms that are applicable to the infrastructures like bridges. (Sahin, 1985; Ito and Honorary, 1993; Cohn and Lounis, 1994; Yousef and Ghulam, 1994; Al-Shaleh, 1994; Farkas, 1996; Shin et al., 1998; Jarmai et al., 1998; Cho, 1998, 1999; Cho et al., 2001; WeldeHawariat, 2002; Salman. 2004; Hashim, 2005; Al-Osta, 2009 and Salman and Said, 2013).

The scope of this study is showing the effect of varying concrete cost (with keeping stable cost for steel sections) on optimum bridge design by writing a numerical computer program, which computes the optimum number of girders, diaphragms, piers, depth of girders and depth of diaphragms required for optimum design of steel I-girder bridges based on initial cost.

Formulation of Optimum Design Problem

The bridge consists of RC deck slab, main girders, diaphragms, and RC piers. The piers are supported by foundations consist of piles and piles cap. The optimization problem is formulated with two variables, the depth of main girders and the depth of diaphragms. Thus, the optimization problem is formulated by considering the initial total cost for the bridge system; SUMT can be also introduced to make these optimizations.

Design Variables

In this study, the design variables are two, as mentioned earlier. The first variable (X1) represents the depth of main girders and the second variable (X2) represents the depth of diaphragms. Many relations among the two variables and the dimensions of the steel sections were derived.

One of the important assumption used in this study was Schilling (1974) for I-section beams, Schilling found that the optimum ratio of Web Area to Cross Section Area (Aw/A) to be 0.5 for elastic stress and 0.75 for optimum stiffness for deflection control. Also he found that for a beam with (Aw/A) ratio of 0.39 and 0.62, the elastic bending strength is within 98% of the maximum possible strength as shown in Fig.1. At (Aw/A) ratio of 0.63 the elastic strength and stiffness are both about 97.5% of their maximum possible values.

The other dependent variables are: web depth (h), web thickness (tw), flange width (bf) and flange thickness (tf) for both girder and diaphragm sections.

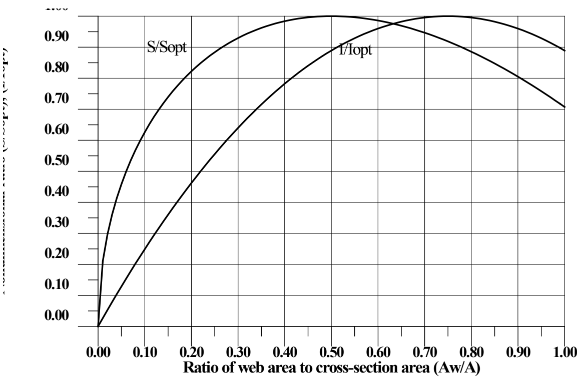

FIG. 1 OPTIMUM RELATIONSHIPS FOR MOMENT OF INERTIA AND SECTION MODULUS

From FIG. 1 above, we can derive the following equations:

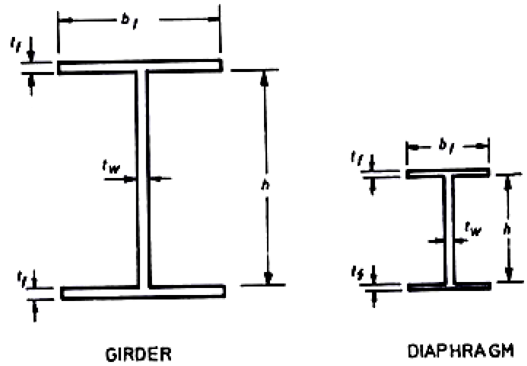

FIG. 2 TYPICAL SYMBOLS FOR STEEL SECTIONS OF GIRDERS AND DIAPHRAGMS.

$A_w/A = 0.63$ (1)
Thus, $h_w X t_w / (h_w X t_w + b_f x h_f) = 0.63$, (2)
$h_w X t_w = 0.63X(h_w X t_w)+ 0.63 (b_f X h_f)$, (3)
$0.37X (h_w X t_w) = 0.63X (b_f X h_f)$, (4)
Finally, $h_w X t_w =1.703 Xb_f X h_f$ (5)

From that we can consider for both girder and diaphragm sections the following equation which is reducing number of variables for any section from four to one variable, which is the section's depth only:

$h_w X t_w =1.703 Xb_f X h_f$ (5)

These independent variables in this study were listed as follows: -

X_1= depth of girder's section (h_G).
X_2= depth of diaphragm's section (h_D).

Other variables will be dependent variables, and they can be calculated from X_1 and X_2.

Objective Function
As mentioned previously, it is shown in this paper that the design goal is to minimize the total expected initial cost that can be divided into substructure and superstructure cost.

This cost can be formulated as follows:

Total Cost = Substructure Cost+ Superstructure Cost.

Ctotal = Csub + Csuper (6)

FIG. 3 and FIG. 4 show various sections in a composite RC deck on I-girder Bridge. The bridge is simply supported above two piers or more. The main girders and diaphragms are I-steel built-up sections.

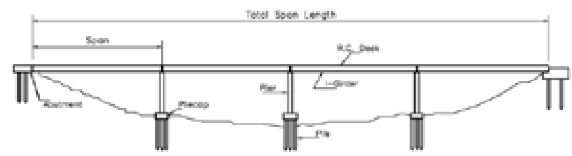

FIG. 3 LONGITUDINAL SECTION FOR SIMPLY SUPPORTED BRIDGE

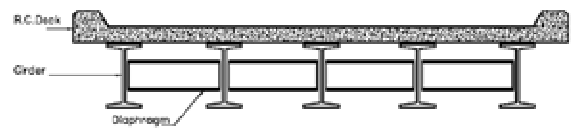

FIG. 4 TYPICAL CROSS-SECTION IN COMPOSITE STEEL I-GIRDRD BRIDGE

Constant Relations in the Bridge System
The bridge consists of concrete deck slabs, build-up I-section for main girders and for diaphragms, and concrete piles and piers.

In this study, American Association of State Highway and Transportation Officials (AASHTO), 1989 is used for bridge loads and constraints. The designed live loading has been assumed to give the worst effect of HS20 and Equivalent Load for both directions of the deck.

The following assumptions have been used to prepare this study:

- Deck concrete Strength Grade is 25 MPa.
- Superimposed dead load is 50 mm of asphalt, uncontrolled with load factor.
- Deflection under HS20 loading with spacing between rear axles equals to 4.27 m is limited to Span/800.
- Girders are composite for all loads.
- Bearing capacity of piles are 240 tons.
- Cost of steel is fixed as 2000 US $/ton, including transportation and fabrication costs.
- Cost of concrete is taken from 50 to 200 US$/M3, including reinforcement and formwork cost.
- Deck slab thicknesses, as shown in table 1 below:

TABLE 1 THICKNESS OF REINFORCED CONCRETE DECK SLAB

Girder Spacing (mm)	Deck Slab Thickness (mm)
1700 -2200	180
2800	200
3500	220

Results were studied to investigate the influences of steel grade, cost ratio of materials, bearing capacity for piles, width and length of the bridge.

The constant relations used in this study are: -

(a) Span length = Total Length / (Number of Piers – 1) (7)

(b) Spacing between girders (SPG),

$$SPG = \frac{\text{Width of bridge}}{(\text{No. of girders} - 1)} \quad (8)$$

(c) Spacing between diaphragms (SPD),

$$SPD = \frac{\text{Total Length}}{(\text{No. of diaphragms} - \text{No. of piers} + 1)} \quad (9)$$

(d) According to AASHTO [Clause 1.7.21]

And, for each span, Minimum number of diaphragms = 3

Max. spacing between 2 diaphragms ≥ 7.55 m (25 ft) (10)

$$\text{NODES} = \frac{\text{Total No.of diaphargms for bridge (NOD)}}{(\text{No.of piers} - 1)} \quad (11)$$

$$\text{No. of diaphragms for each span} - 3.0 > 0 \quad (12)$$

(e) For each bridge, minimum number of piers = 2 (13)

(f) Minimum Number of Main Member = 2, AASHTO [Clause1.7.22] (14)

(g) According to AASHTO [Clause 1.5.27], slab thickness (t_s) must be not less than 0.165 m (0.542 ft) for continuous span; and that for simple span should have about 10% greater thickness, in which (t_s) is not less than 0.180 m, thus:

ts ³ 0.180 (15)

The Constraints
1) Behaviour Constraints
(i) Deflection:
Maximum deflection occurring at mid-span of the girder must be less than or equal to the maximum allowable deflection. According to AASHTO [Clause 1.7.12], the deflection due to live load plus impact shall not exceed 1/800. All bridges in this study are simply supported, thus:

$$\Delta_{all} > \Delta_{\max} \Rightarrow \Delta_{all} - \Delta_{\max} > 0 \quad (16)$$

$$\Delta_{all}(\boldsymbol{m}\ ) = \frac{span \times 1000}{800} \quad (17)$$

(ii) Stresses
$F_b > \frac{M_x}{S_x}$ Girders subjected to bending stresses shall be proportioned to satisfy the following requirements.

where Fb = 0.60 Fy (18)

(iii) Local Buckling of Flanges
$\frac{b_f}{t_f} > \frac{3250}{\sqrt{f_b}}$The local buckling constraint for the compressed flanges of I-structural sections of uniform thickness subjected to bending or compression is given by AASHTO [Clause 1.7.6]:

for girders (19)

2) Side Constraints
(i) Ratio of Depth to Length
AASHTO [1.7.10] stated that for girders the ratio of depth to length of span, preferably shall not be less than 1/25, and for composite girders the ratio of depth of steel girder alone to length of span shall not be less than 1/30.

$$\frac{Length\ span}{Depth} < 25 \qquad \text{if non- composite} \quad (20)$$

$$\frac{Length\ span}{Depth} < 30 \qquad \text{if composite} \quad (21)$$

(ii) Depth of Diaphragm

AASHTO [clause 1.7.21] stated that diaphragms shall be at least 1/3 and preferably 1/2 the girder depth.

$$\frac{Diaphragm\ \ depth}{Girder\ \ depth} > \frac{1}{3} \quad (22)$$

(iii) Minimum Thickness of Web

AASHTO [1.7.13] indicated that the thickness of web shall be not less than 8 mm (5/16 in). Here in this study, minimum thickness of web plate (t_{WG}) used = 10 mm.

AASHTO [Clause 1.7.70] stated that the web plate thickness of plate girders without longitudinal stiffeners shall not be less than that determined by:

$$\frac{X_1\sqrt{0.145 f_{b1}}}{23000} \quad (23)$$

Where X_1= Depth of Main Girder, and f_{b1} in kPa.

Thus the thickness shall not be less than the depth of main girder divided by specified value, (*Coef*2); and this value is found according to yield strength for the girder F_y. This is shown in Equation (19):

$$Coef\,2 = \frac{23000}{\sqrt{0.145 * 0.6 * Fy}} \quad (24)$$

$$t_{WG} = \frac{\text{Depth of Girder}}{Coef\ 2} \quad (25)$$

By the same way, and if the diaphragm has same F_y the thickness of web plate for it equals:

$$t_{WD} = \frac{\text{Depth of diaphragm}}{Coef\ 2} \quad (26)$$

(iv) Minimum Thickness of Slab

According to AASHTO [Clause 1.5.27], minimum thickness of slab equals:

$$D\min_{(m)} = 0.1 + \frac{Spacing\ between\ girders}{30}$$

But not less than 0.165 m (27)

Where Spacing in meters.

Computer Program for Structural Analysis and Optimization (CPSAO)
A computer program is written using FORTRAN 77. In addition to the main computer program, several subroutines have been written and one subroutine has been developed to satisfy constraints that may control the design process.

The program has been tested; and Microsoft Developer Studio-Fortran Power Station 4.0 Compiler was used in compilation, linking and creating an execution file for computer program for structural analysis and optimization (CPSAO). The linking process has been made for the main program and subroutines. Figure 5 shows the detailed flow chart for the main computer program.

A computer program for the analysis of structural systems was built by using orthotropic plate theory and for the optimum design by using SUMT. The main objective of the program is to analyse and find the optimum design of I-girder steel bridges with minimum cost. With this objective the program was developed in such a way that a routine can be added for any type of bridges without disturbing the main program.

The program is organized to analyse bridges using different span, width and cost ratio by using three loops. The various routines that constitute the core of the program CPSAO, only deck analysis subroutine ORTHO flow chart is shown in the following sections.

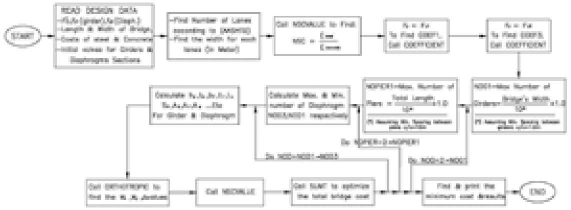

FIG. 5 DETAILED FLOW CHART FOR MAIN PROGRAM.

Applications and Discussion of Results

The optimum design of two-dimensional bridge is studied by using three applications for cost ratios of steel I-girder bridges. The cost ratios used were 10, 25 and 40 respectively. The effect of cost ratio on the cost and on other parameters was studied.

A sample of results was given in this paper for bearing capacity of piles 240 tons, yielding strength for steel used in girders and diaphragms = 248 MPa and bridge's width = 10 m.

Discussion of Results

Structural optimization means producing a design with structural section minimum size or weight (based on the objective function prepared for each case) can be formulated in certain mathematical models. The acceptance of an optimum solution from a practical viewpoint is different from what a mathematician would consider ideal. However, the optimum design solution given in this, or any other study, considers the cost as an objective function and it can only suggest a best possible design that may be accepted, or modified after further analysis. This fact arises mainly from a reason that requirements and constraints of practical engineering are so complicated even if a good mathematical model is used.

Effect of Cost Ratio on Bridge Optimization

To study the effect of cost ratio on the optimum design, reinforced concrete; comparisons between the results are made. The compared results are shown in Figure 6 through Figure 16, for a bridge width = 10m and F_y = 248 MPa.

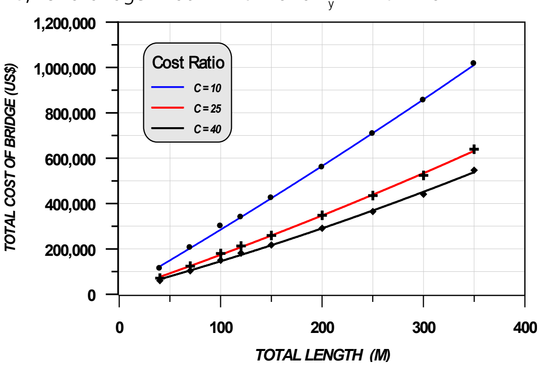

FIG. 6 Relation between total length and total cost for F_y=248 for steel and Bridge's Width =10 m.

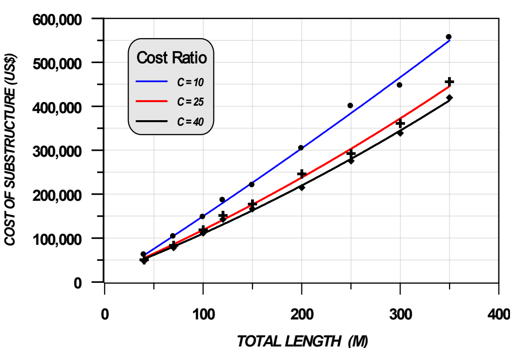

FIG. 7 Relation between total length and substructure cost for F_y=248 for steel and Bridge's Width =10 m.

Figure 6 through 8 show that as the cost ratio increases, the cost of total bridge decreases proportionally, that means that the saving in concrete volume (i.e. concrete cost) more than the additional cost coming from increasing the steel section and cost.

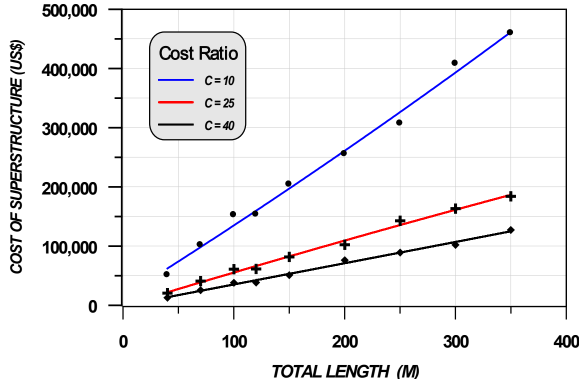

FIG. 8 Relation between total length and superstructure cost for F_y=248 for steel and Bridge's Width =10 m.

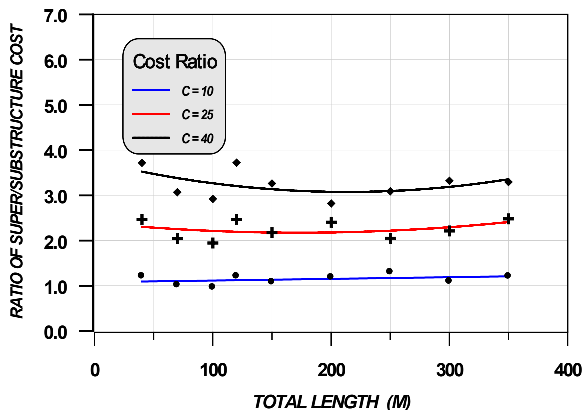

FIG. 9 Relation between total length and super/ substructure cost for F_y=248 for steel and Bridge's Width =10 m.

From Figure 9, one can observe that the ratios of substructure cost to superstructure are oppositely proportioned with the cost ratio. Sub/ Super ratio is in its optimum value (approximately = 1) for any bridge length when cost ratio = 10, while it is ranging around 2 and 3, when cost ratio = 25 and 40 respectively. Also the curvature of the curves increase positively with cost ratio; when cost ratio = 10, curve is approximately straight; when cost ratio = 40, curvature is clearly increase.

Changes in cost ratio value will not effect on the required number of girders and diaphragms for optimum design of a bridge, this can be observed in Figure 10and 11.

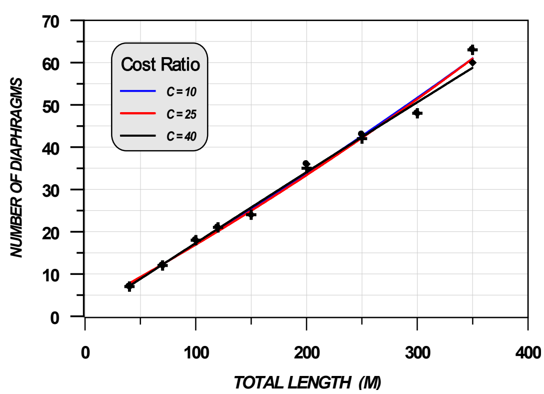

FIG. 10 Relation between total length and number of diaphragms for F_y=248 for steel and Bridge's Width =10 m.

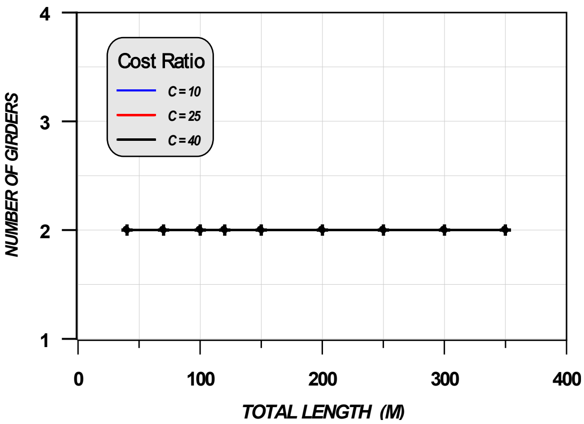

FIG. 11 Relation between total length and number of girders for F_y=248 for steel and Bridge's Width =10 m.

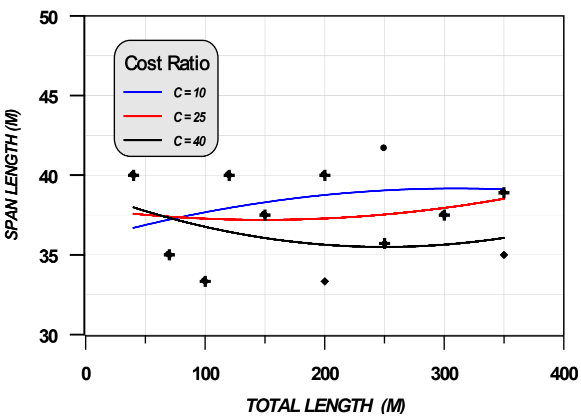

FIG. 12 Relation between total length and span length for F_y=248 for steel and Bridge's Width =10 m.

From this study, no clear effect of cost ratio on the relation between total bridge length and span length; but it can be observed that there is certain bridge length, (75 m for present study), the span length is constant for all cost ratios (37.5 m) and there is no effect of cost ratio on it. Length of bridge less than 75 m, cost ratio will effect positively on span length, while when total length is more than 75 m, cost ratio will effect negatively on span length, as shown in Figure 12.

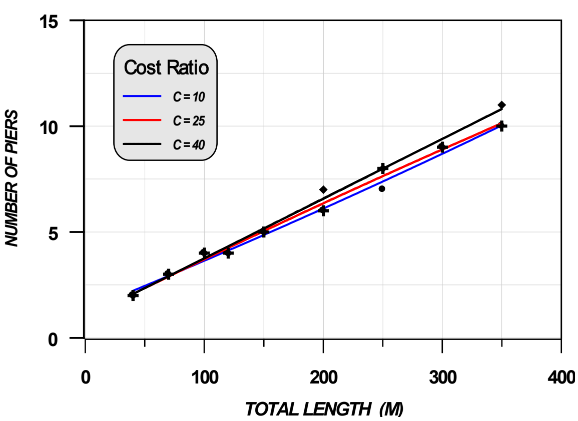

FIG. 13 Relation between total length and number of piers for F_y=248 for steel and Bridge's Width =10 m.

The number of piers positively behaves with the cost ratio; which it has small influence on it, as shown in Figure 13.

Figure 14 and 15 showing small effect of cost ratio on steel sections used in bridges; but it behaves negatively with main girder's depth. Also there is approximately linear relation between the span length and the depth of girder, resulting from the limitations and the constraint shown above, which keeps the girder size with certain limit to give minimum cost.

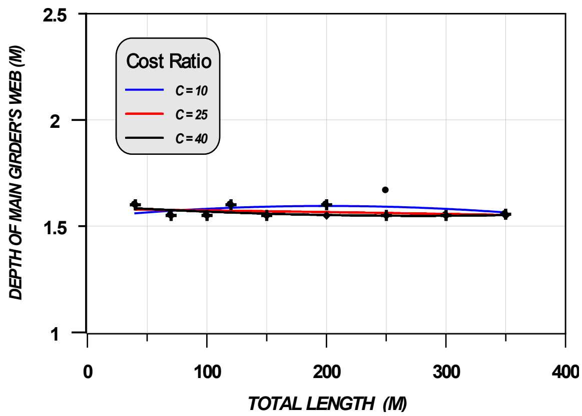

FIG. 14 Relation between total length and depth of main girder's web for F_y=248 for steel and Bridge's Width =10 m.

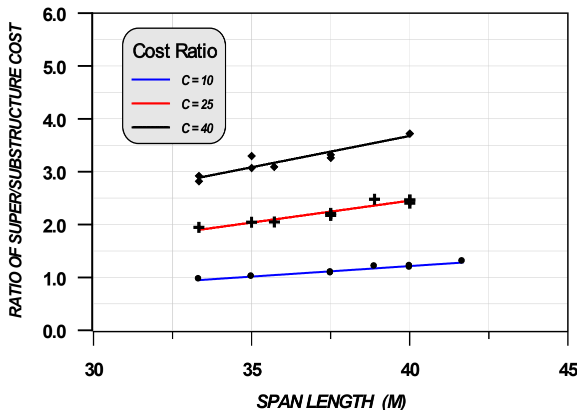

FIG. 15 Relation between span length and depth of main girder's web for F_y=248 for steel and Bridge's Width =10 m.

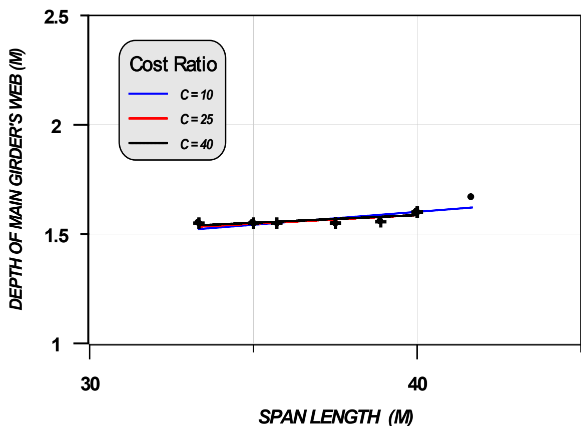

FIG. 16 Relation between span length and super/substructure cost for F_y=248 for steel and Bridge's Width =10 m.

It is very clear to find from Figure 16 that span from 33 to 37 m length with cost ratio = 10, give the equilibrium ratio when superstructure = sub structure cost which is ranging from 0.95 to 1.05.

Conclusion

Based on the formulations and discussions presented in previous paragraphs, the following conclusions can be drawn:

1- It is found that the SUMT is a proper technique that can be

used for optimum designs of steel I-girder bridges for various values of total length of bridges and cost ratios.
2- Decreasing of cost ratio leads to decrease the super/substructure ratio making it reach to 1.0, i.e. the cost of superstructure will be equal to substructure.
3- Optimum cost not necessary to be obtained when super/substructure value = 1.0.
4- There is no effect for cost ratio on the number of diaphragms used in a bridge.
5- According to this study, 2 girders for bridges with width = 10 m or less always give optimum design without any effect from cost ratio value.
6- From this study, increasing concrete cost with keeping steel cost constant (i.e. increasing Cost Ratio) leads to reducing the total cost of the bridges.

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He has graduated from University of Technology (Baghdad) in 1990 earning B.Sc. degree in Civil Engineering, and M.Sc. degree in Structural Engineering from Baghdad University in 2004. Now he is Ph.D. student in Structural Engineering in School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia. He has worked in different contracting and consultant companies as a civil and Sr. structural engineer in Iraq and UAE from 1992 till now. | | Dr. Abdul Muttalib I. Said was born in Baghdad, Iraq in 1969. He has graduated from University of Mosul (Mosul, Iraq) in 1991 earning B.Sc. degree in Civil Engineering, Master of Science (M.Sc.) in Civil Engineering (Structures), and from Nahrian (Saddam) University (Baghdad-Iraq) in 1995, and Ph.D. degree in Civil Engineering (Structures) from University of Baghdad (Baghdad–Iraq) in 2000. Now he is Assistant Professor in Civil Engineering Dept., College of Engineering, University of Baghdad. He has worked as Manager of the Consulting Engineering Bureau, College of Engineering, University of Baghdad. He has Academic Activities in teaching different subjects (under-graduate courses) since 1995, Teaching post graduate studies since 2001, in addition, he has published (16) scientific papers, and supervised M. Sc. Research students (10 Students) as well as Ph.D. Research students (6 Students). He has worked as Structural designer, consultant and direction and management of the projects from 1995 till now. | | Norazura Muhamad Bunnori (PhD) has been involved in Acoustic Emission (AE) technique since 2004 while she was pursuing her PhD study at Cardiff University, Wales, UK. She was graduated from Cardiff University in 2008 and continues with the AE research area in Universiti Sains Malaysia (USM), Malaysia. Currently she is working as a Senior Lecturer at School of Civil Engineering, Universiti Sains Malaysia (USM) since 2009. The research covered several topics of AE applications and analysis (quantitative and qualitive). The aim is to continue the AE study especially in Structural Health Monitoring (SHM) research area and to discover more in this potential area. The passion towards AE is deep and she believes that there are a great number of information can be studied and discovered with this tools. | | Dr. Izwan Bin Johari has been involved in Building Materials since 2005 while he was pursuing his Master and PhD study at Universiti Sains Malaysia, Penang, Malaysia. After he was graduated from USM in 2004, his work in research is more toward masonry (material and testing). Currently he is working as a Senior Lecturer, teaching undergraduate and postgraduate student at School of Civil Engineering, Universiti Sains Malaysia (USM) since 2010. |