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Sensitivity analysis of design parameter of I-girder and deck system

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ABSTRACT: The objective of this study is to compare the sensitivity of deck slab thickness obtained by optimization with that of obtained from conventional method. From a real-life girder-deck design, values of 14 design parameters are obtained. And an identical girder-deck is considered for optimization. The optimization is based on a global optimization algorithm named “Evolutionary Operation (EVOP)” which is bounded by 14 explicit constraints along with 46 implicit constraints. To conduct sensitivity analysis, modified programs are developed. Then slab thickness is deviated on both the upper and lower sides of its optimum solution considering the realistic possible variation. For a small deviation from the optimum value, structural adequacy and total cost variation is observed. It is obtained that deck slab thickness obtained by the conventional method can be increased beyond 25 mm without exceeding any constraints limit whereas optimum slab thickness can be increased only up to 0.3 mm.

1 INTRODUCTION

Prestressed post-tensioned I-girder along with deck slab is the most commonly used system for bridge design. While designing this system, structural safety issue as well as economy are considered to be two significant criteria. A large number of inter-related design parameters lead to different feasible solutions. Conventional method of girder-deck design involves a number of iterations and thus is a lengthy process. Moreover, it may not be a cost effective solution. In this regard cost optimization provides a solution. Ghani (1989) developed “Evolutionary Operations based Global Optimization Algorithm (EVOP)”, which can locate the global minima. Based on this algorithm, Rana, Ahsan and Ghani (2010) developed a program to obtain the optimum values of 14 design parameter of a post tensioned prestressed I- girder bridge system.

In both the types of design method i.e. conventional and optimization, the deviation in the values of design parameters which may occur during construction are not considered. However, it is difficult to keep the values of parameters at their optimum values due to constructional ease. And deviations from optimum values can impair structural adequacy. Therefore, impact on structures due to these deviations should be examined.

Sensitivity analysis is the investigation of these deviations and their impact on structural adequacy as well as total cost. It should therefore be integrated with any of the design methodology to provide the facility for modification of design and to obtain an effective and realistic solution. Over the years, sensitivity analysis is conducted for optimization problem in various disciplines. Seferlis and Hrymak (1996) presented a parametric sensitivity analysis in chemical process. In aero-structural design, adjoint method of sensitivity analysis was presented using adjoint-coupled approach (Martins et al. 2005). Yue et al. (2008) presented a sensitivity analysis and robust experimental design of a signal transduction pathway system. Becker et al. (2011) presented a Bayesian sensitivity analysis of a model of the aortic valve. Chen and Yang (2017) conducted modeling experiments on a generic residential building in hot and humid climates. Nishat and Ahsan (2018) conducted the sensitivity analysis on a 30 m span girder bridge system. Slab thickness was found to be the most sensitive parameters in that study. Therefore, further research is imperative in order to examine the sensitivity of this parameter in different design methods.

The main objective of this study is to examine and compare the sensitivity of deck slab thickness obtained by optimization with that of obtained by conventional design method.

2 METHODOLOGY

In this study, a simply supported prestressed post-tensioned PC I-girder-deck system of a real-life bridge is considered which was designed by conventional iterative method. Values of design parameters are obtained from the existing design. Then sensitivity analysis is conducted on the slab thickness parameter keeping the remaining parameters unchanged. The sensitivity of slab thickness is measured by examining the impact on structure (i.e. variation in total cost of system and compliance with constraint limit) for deviation from its design value. Sensitivity analysis is also conducted on the slab thickness obtained by cost optimization procedure of an identical girder-deck system. Evolutionary Operation (EVOP) based algorithm is applied to obtain optimum values of design parameters which can effectively locate the global minima. A brief description of the optimization process, design parameters, constraints and constant parameters considered in the study and sensitivity analysis procedure is provided below.

2.1 *Optimization Process*

The main methodology of optimizing a system incorporating EVOP is as follows- Firstly, the optimization problem is to be identified. After selecting the objective function, the explicit and implicit constraints are to be identified. With the control parameters a feasible starting point are selected. The problem is then linked with EVOP and an optimum solution is obtained. In order to obtain the optimum values of design parameters, particular span girder-deck system is optimized based on the algorithm proposed by Rana, Ahsan and Ghani (2010).

2.2 *Design Parameters*

During optimization, for a particular girder a several design parameters are to be considered. In this study, the design parameters under consideration are- spacing of girders, cross sectional dimensions of a girder, number of strands per tendon, number of tendons per girder, location of lower most tendon, initial stage prestress, deck slab thickness and deck slab reinforcement. All the 14 parameters are listed in Table 1. A typical girder cross section along with its parameters is shown in Figure 1.

2.3 *Explicit and Implicit Constraints*

The problem is bounded by 14 explicit constraints (which are specified upper and lower limits on design parameters) and 46 implicit constraints (which represent the performance or response requirements of the bridge system). The explicit and implicit constraints are based on AASHTOO (2002) requirements. The implicit constraints are categorized into eight groups. The explicit constraints and groups of implicit constraints are shown in Table 1.

2.4 *Design Constant Parameters*

Optimum design problem is also dependent on the design constant parameters i.e. unit cost of materials (including fabrication and installation), various material properties, superimposed dead loads, AASHTO live loads, concrete strength, strand size, anchorage system etc. Cost data has been obtained from Roads and Highway Department cost schedule (RHD 2006) and then the values in BDT currency are converted to USD currency.

2.5 *Sensitivity Analysis*

Sensitivity analysis is conducted on slab thickness for both types of design solutions of the I-girder-deck system. The analysis is conducted based on the program developed by Nishat and Ahsan (2018). The procedure is described as below-

The C++ program is modified for the two types of girder-deck. The code is improvised so that the deviated value of the parameter can be introduced into the program as input value. Therefore, it can be evaluated whether the constraint limits (both explicit and implicit constraint) are satisfied for a small deviation of parameter. Variation in cost of the system can also be examined from the program. Sensitivity analysis is conducted for the same 14 design parameters considered during optimization. Therefore, 14 explicit constraints along with 46 implicit constraints remain identical to the previous code for a particular span. The material properties, design data and cost regimes used for sensitivity analyses are also similar to the previous one.

The analysis is being conducted for small deviation range from optimum value of the slab thickness which may arise during construction. Therefore, the deviation range should be determined prior to analysis. For slab thickness the range is selected as 25 mm in both the upper and lower sides from its design value. The range, based on realistic possible deviation during construction, is considered in both the upper and lower sides of optimum values. Slab thickness is gradually changed from its optimum value with 5 mm increment or decrement interval.

Table 1. Design parameters, explicit constraints and groups of implicit constraints for a girder-deck system.

Design parameters	Explicit Constraints	Implicit constraints
1. Girder spacing, S (mm)	B_W[a]$/10 \le S \le B_W$	1. Flexural working stress constraints
2. Top flange width, TF_w (mm)	$300 \le TF_w \le S$	2. Flexural ultimate strength constraints
3. Width of Bottom flange, BF_w (mm)	$300 \le BF_w \le S$	3. Deck slab design constraints
4. Thickness of Bottom flange, BF_t (mm)	a[b] $\le BF_t \le 600$	4. Shear constraints (ultimate strength)
5. Depth of girder, G_d (mm)	$1000 \le G_d \le 3500$	5. Tendons eccentricity constraints
6. Number of strands per tendon, N_s	$1 \le N_s \le 27$	6. Lateral stability constraints
7. Number of tendon per girder, N_T	$1 \le N_T \le 20$	7. Deflection constraints
8. Lowest tendon position from bottom, y_t(mm)	A_M[c] $\le y_1 \le 1000$	8. Ductility constraints
9. Prestress at initial stage, η (%)	$1\% \le \eta \le 100\%$	
10. Thickness of deck slab, t (mm)	$175 \le t \le 300$	
11. Slab main reinforcement ratio, ρ (%)	$\rho_{min} \le \rho \le \rho_{max}$	
12. Thickness of top flange, TF_t(mm)	$75 \le TF_t \le 300$	
13. Transition thickness of top flange, TFT_t (mm)	$50 \le TFT_t \le 300$	
14. Web thickness, W_w (mm)	b[d] $\le W_w \le 300$	

[a]Bridge width; [b]sum of clear cover and duct diameter; [c]Minimum vertical edge distance for anchorage;
[d]Sum of clear cover, web rebar diameter and duct diameter;

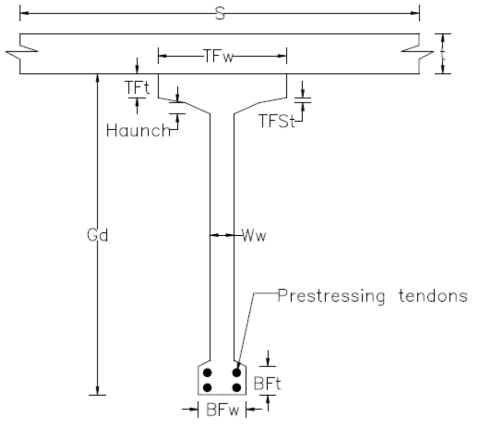

Figure 1. A girder cross section with several design parameters.

Deviation is introduced into only slab thickness to examine the impact it may produce in terms of structural adequacy or variation in total cost of the system. The constraints, of which limits are violated for the deviation from optimum, are identified. And cost variations are also enlisted. This parameter can be identified as a sensitive parameter if a small deviation from its design value causes a significant variation in total cost or make the structure inadequate.

3 SENSITIVITY ANALYSIS AND COMPARISON BETWEEN TWO DESIGN SOLUTIONS

In this section, a real life bridge project is considered which was built in northern Bangladesh. The bridge is 750 meter long and 12.11 meter wide (3 Lane). The bridge is a prestressed concrete I girder bridge of medium span (50 m) made composite with cast-in-situ deck slab (BRTC 2007). The 50 meter span (L=48.8m) girder along with its deck slab is considered as girder-deck system. 6 diaphragms are present in this system. The values 14 design parameters are obtained from existing design are enlisted in Table 10. In order to present a comparison with optimized girder-deck, an identical 50 meter span and 12 meter wide girder-deck system is considered. Three diaphragms are considered during analysis. In both types of design, the material properties and bridge design data are similar to that used for 30m span girder-deck (Nishat and Ahsan 2018). The cost data for materials, labor, fabrication and installation used are same as in RHD (2006). The girder-deck system is optimized for minimum cost and optimum values of 14 design parameters are listed in Table 2.

Table 2. Values of design parameters of optimized and existing 50 meter girder-deck.

Parameters	Optimized 50m girder-deck	50m existing girder-deck
S (mm)	3000	2400
TFw (mm)	925	1060
BFw (mm)	300	710
BFt (mm)	320	200
Gd (mm)	2625	2500
Ns	9.0 (15.2mm dia)	12.0 (12.7mm dia)
NT	6.0	7.0
yt (mm)	800	350
η (%)	44	42.8
t (mm)	220	200
ρ (%)	0.59	0.82
TFt (mm)	125	130
TFSt (mm)	100	75
Ww (mm)	150	220
Top flange haunch width (mm)	50	150
Top flange haunch thickness (mm)	50	150
Bottom flange transition thickness (mm)	37.5	250
Total cost of the system (USD)	58307	83886

The C++ code for sensitivity analysis is modified for the specifications by which this bridge was designed in conventional method. Then sensitivity analysis is conducted. The output results are shown in Table 3 and Table 4.

Table 3. Constraint parameter values due to variations in slab thickness of real life girder-deck system.

Slab Thickness, t (mm)	t	$t_{(min)}$	$t_{(max)}$	Comments
195	195	195.864	300	Not Ok
200	200	195.864	300	Ok
225	225	195.864	300	Ok

Table 4. Constraint parameter values due to variations in slab thickness of optimized girder-deck system.

Slab Thickness, t (mm)	σ_{b1}	$\sigma_{b1(min)}$	$\sigma_{b1(max)}$	$d_{required}$	d_{min}	$d_{provided}$	Comments
219.6	3.13624	-24	3.16228	162.646	89.4868	162.6	Not Ok
220	3.15101	-24	3.16228	162.658	89.493	163	Ok
220.4	3.16577	-24	3.16228	162.669	89.4993	163.4	Not Ok

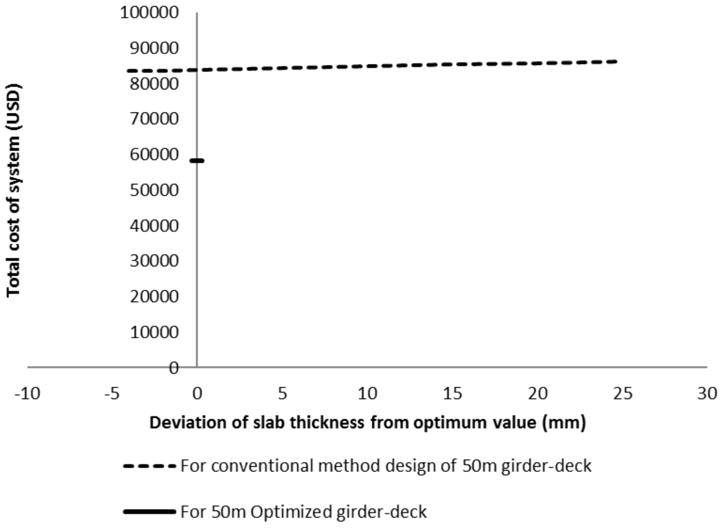

Figure 2. Comparative graph showing variations in cost due to variations in slab thickness for two design solutions.

For the existing bridge, the critical constraint that is violated by deviations in deck slab thickness is slab thickness parameter itself. It has been observed that, slab thickness exceeds its minimum permissible thickness limit if it is decreased up to 5 mm from its design thickness value. Slab thickness can be increased up to 25 mm without violating any constraint limit.

On the other side, for optimized 50m span girder-deck, the constraints that are violated by deviations in deck slab thickness are bottom fiber stress at mid-section at service load 3 and required effective depth. It is observed that, bottom fiber stress exceeds its maximum allowable stress limit if slab thickness is increased up to 0.4 mm from its optimum thickness. Furthermore, required effective depth of girder becomes less than its provided effective depth if slab thickness is decreased up to 0.4 mm from its optimum value. From this analysis it is evident that, the sensitivity of slab thickness obtained by conventional method is less sensitive than slab thickness obtained by optimum design procedure. The comparison of the sensitivity is demonstrated in Figure 2.

4 CONCLUSIONS

The paper presents an approach for sensitivity analyses on slab thickness parameter of prestressed post-tensioned I-girder and deck slab system. During construction phase, values of design parameters are subject to change and impact for these changes is to be analyzed in order to determine realistic design solution for girder design. Previous study reveals that slab thickness parameter is the most sensitive parameter in terms of structural adequacy. Hence, the study is conducted to compare the sensitivity of slab thickness obtained by conventional method with that of obtained by optimization design method.

In order to conduct sensitivity analysis code developed for optimization is modified for two types of girder. Slab thickness is deviated from its design value within its selected range of deviation. For small deviation compliance with the explicit and implicit constraints is examined. Variation of total cost due to this deviation is also identified. Finally, comparison is made between two obtained deck slab thicknesses. It is observed that:

- Slab thickness parameter obtained by conventional design procedure, can be increased up to 25 mm without exceeding any constraint limit whereas optimum slab thickness can be increased only up to 0.3 mm from optimum.
- Slab thickness obtained by conventional procedure, can be decreased up to 5 mm without exceeding any constraint limit whereas optimum slab thickness can be decreased only up to 0.3 mm from its optimum value.
- The total cost of girder-deck system designed by conventional procedure remains approximately 44% higher than that of optimum girder-deck system.

The obtained result suggests that, the conventionally obtained slab thickness is less sensitive compared to optimized slab thickness. However, it does not provide cost-effective solution. Therefore, future research is needed to reduce the sensitivity of slab thickness parameter and hence to obtain a reliable design solution. In the conclusion it is evident that slab thickness is a significant parameter while designing I-girder-deck system. And sensitivity analysis should be an integral part of any design methodology to ensure structural adequacy as well as cost efficiency.

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