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Cost optimum design of post-tensioned concrete bridges using a modified colliding bodies optimization algorithm

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ABSTRACT

The Colliding Bodies Optimization (CBO) algorithm is a metaheuristic algorithm inspired by the physics laws of collision in which each candidate solution is modeled as an agent with mass body in proportion to the fitness of the solution. In this paper a modified version of CBO, denoted by MCBO, is utilized to optimize the cost of bridge superstructures. The problem consists of 17 variables and 101 implicit constraints based on AASHTO standard specifications and construction limitations. The optimization is performed for bridges with different span lengths and deck widths, and with various unit costs of concrete. A comparison among the PSO, CBO, and MCBO algorithms is conducted which shows the efficiency and robustness of the MCBO algorithm.

1. Introduction

Over the last few decades, a large number of metaheuristic algorithms have been utilized to solve various optimization problems. These algorithms, with no need for gradient information and a good starting point, provide acceptable solutions in affordable time for complex optimization problems. By imitating natural phenomena, different metahiuristic algorithms are proposed, such as: Genetic Algorithm (GA) [1], Particle Swarm Optimization (PSO) [2], Harmony Search (HS) [3], Big Bang-Big Crunch (BB-BC) [4], Charged System Search (CSS) [5], Teaching-learning-based optimization (TLBO) [6], Multi-class TLBO [7] Ray Optimization (RO) [8], Dolphin Echolocation Optimization (DEO) [9], Colliding Bodies Optimization (CBO) [10], Enhanced Colliding Bodies Optimization (ECBO) [11], Ant Lion Optimizer (ALO) [12], Search group algorithm (SGA) [13].

While considerable research has been conducted on the structural optimization, the great majority deal with academic or small problems. In the past decade or so, there have been notable efforts to bring the structural optimization technology to the structural engineering practice. This technology can be of great value especially for design of large and complex structures. Because of the presence of many design variables and constraints which lead to some complexities in formulating the problem, optimization of bridge structures has not been attempted extensively. Optimum design of multi-span composite box girder bridges using Cuckoo Search algorithm is due to Kaveh et al. [14].

Prestressed concrete bridges, particularly post-tensioned concrete box girders, are very common because of their durability and economy of construction [15]. As several variables are involved in designing of these types of bridges, a wide variety of designs are possible for a certain span length and deck width such that using conventional design methods are not appropriate for finding the best solution. Therefore, optimization techniques are required for these problems. As one of the first attempt to optimize bridges, Torres et al. [16] optimized the cost of prestressed concrete highway bridges by using a linear programming method, and using general geometric programming; Yu et al. [17] presented the cost optimum design of a prestressed concrete box girder bridge; this procedure was also used by Barr et al. [18] to optimize the cost of a continuous three-span bridge RC slab; Lounis and Cohn [19] studied the cost minimization of highway bridges consisting of RC slabs on precast, post-tensioned concrete I-girders using a three-level optimization approach; Fereig [20] presented the minimum cost preliminary design of single span bridges consisting of cast-in-place RC deck and girders, the author linearized the nonlinear problem and solved it by the Simplex method; Aydin and Ayvaz [21] minimized the cost of a pretensioned PC I-girder bridge using a genetic algorithm considering 9 different variables and a total of 28 constraints. In another work [22], they also considered

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Table 1
Design variables and explicit constraints.

No.	Variable	Symbol	Type	Constraints
1	Concrete strength (MPa)	f_c'	Integer	$35 \le f_c' \le 50$
2	Girder depth (m)	h	Continuous	$1.5 \le h \le 4$
3	Top slab thickness (cm)	T_t	Continuous	$17.5 \le T_t \le 35$
4	Bottom slab thickness (cm)	T_b	Continuous	$17.5 \le T_b \le 30$
5	Web thickness (cm)	T_w	Continuous	$25 \le T_w \le 50$
6	Length of cantilever (m)	L_c	Continuous	$1 \le L_c \le 1/4W$
7	End thickness of cantilever (cm)	T_c	Continuous	$17.5 \le T_c \le 30$
8	Initial thickness of cantilever (cm)	T_s	Continuous	$20 \le T_s \le 50$
9	Length of haunch (cm)	L_x	Continuous	$50 \le L_x \le 200$
10	Width of haunch (cm)	L_y	Continuous	$25 \le L_y \le 50$
11	Number of strands per tendon	N_s	Integer	$5 \le N_s \le 25$
12	Number of tendons in each web	$N_t/2$	Integer	$1 \le N_t/2 \le 10$
13	Number of anchorages in each row	N_A	Integer	1 or 2
14	Lowest anchorage position (cm)	y_1	Continuous	$y_{min} \le y_1 \le 100$
15	Prestressing force (% of f_y*)	η	Continuous	$0.75\% \le \eta \le 0.90\%$
16	Top slab reinforcement ratio	ρ_s	Continuous	$\rho_{min} \le \rho_s \le \rho_{max}$
17	Cantilever slab reinforcement ratio	ρ_c	Continuous	$\rho_{min} \le \rho_c \le \rho_{max}$

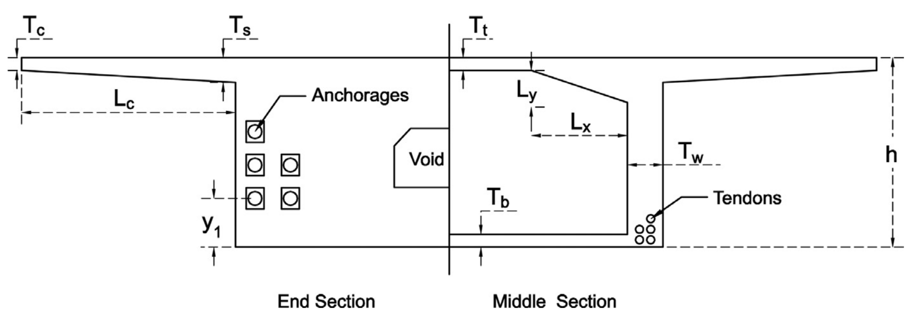

Fig. 1. Box girder cross-section.

the number of piers as a variable and used a modified hybrid GA to minimize the overall cost. Ahsan et al. [23] presented the cost optimum design of post-tensioned I-girder bridges by considering 14 different variables, 28 explicit constraints, and 46 implicit constraints using an evolutionary operation (EVOP), they also developed their previous work for two span continuous bridges with 51 implicit constraints [24].

In this paper, for the first time, the Colliding Bodies Optimization (CBO) algorithm and its modified version (MCBO) have been applied to a bridge optimization problem. The assumed bridge is a post-tensioned concrete box girder which is constructed cast-in-place (CIP) with span-by-span method. The bridge is also single-span simply-supported. The optimization is carried out for different span lengths, deck widths, and unit costs of concrete utilizing CBO and MCBO algorithms. A comparison among the PSO, CBO, and MCBO algorithms is conducted to investigate the performance of the proposed algorithm.

The remainder of this paper is structured as follows: In Section 2, the cost optimization problem with its variables, objective function, and constrains are stated. In Section 3 the optimization algorithm is introduced, and the result of optimization is presented in Section 4. Finally, in Section 5 some conclusions are provided.

2. Optimization problem statement

2.1. Design variables and constant parameters

The considered variables in this study are concrete strength, cross-sectional dimensions of a box girder, number of strands per tendon, number of tendons in each web, arrangement of tendons, prestressing force, and reinforcements of slabs. Since concrete strength is a design variable, modulus of elasticity of concrete is considered a function of concrete strength. Design variables are tabulated in Table 1, and a typical cross-section of the assumed bridge with some of the variables is shown in Fig. 1.

The constant design parameters considered in this study are span length, deck width, post-tensioning anchorage system, AASHTO live loads [25], superimposed dead loads, and properties of the materials except concrete strength. 15 mm diameter seven-wire low relaxation strands are used for tendons, and the Freyssinet C-range anchorage system is used for post-tensioning the tendons [26]. The constant design parameters are shown in Table 2.

In this study, AASHTO HS20-44 live load [25] (both truck load and lane load) is considered, as shown in Fig. 2. These loads are placed in 12-foot (3.65-m) design traffic lanes. Number of traffic lanes are calculated by the following formula for the roadway width greater than 24 ft (7.32 m) or less than 20 ft (6.10 m). Roadway widths from 20 ft to 24 ft will have two design lanes each being equal to one-half the roadway width.

$$\text{Number of design traffic lanes} = \left[\frac{\text{Roadway}}{3.65}\right] = \left[\frac{W - 2\text{BarrierWidth}}{3.65}\right] \tag{1}$$

where W is deck width in meter.

The impact factor is applied to the live load to allow for dynamic and impact effects. This factor is determined by the following formula:

$$\text{Impact Factor} = 1 + \frac{50}{3.28L + 125} \le 1.3 \tag{2}$$

where L is the length of the span in meter.