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Optimum design of multi-span composite box girder bridges using Cuckoo Search algorithm

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Abstract. Composite steel-concrete box girders are frequently used in bridge construction for their economic and structural advantages. An integrated metaheuristic based optimization procedure is proposed for discrete size optimization of straight multi-span steel box girders with the objective of minimizing the self-weight of girder. The metaheuristic algorithm of choice is the Cuckoo Search (CS) algorithm. The optimum design of a box girder is characterized by geometry, serviceability and ultimate limit states specified by the American Association of State Highway and Transportation Officials (AASHTO). Size optimization of a practical design example investigates the efficiency of this optimization approach and leads to around 15% of saving in material.

Keywords: composite box girder; size-optimization; optimal design; cuckoo search algorithm

1. Introduction

For every product designed to satisfy human needs, the creator tries to achieve the best solution for the task in hand (safety and serviceability) and therefore performs optimization. The contribution of this study is concerned with discrete size optimization of straight multi-span steel box girders with the objective of minimizing the self-weight of girder. Composite steel box girders in the form of built-up steel-box sections and concrete deck slab have become very prevailed due to some positive structural features such as high torsional and wrapping rigidity, aesthetically pleasing in terms of their long span with shallow depth, and highly economical in fabrication and in maintenance (Chen and Yen 1980). Developments in computer hardware and software, advances in computer based analysis and design tools, and advances in numerical optimization methods make it possible to formulate design of complicated discrete engineering problems as an optimization problem and solve them by one of the optimization methods (Rana *et al*. 2013). Further developments on box girders can be found in the works of (Ding *et al*. 2013, Ko *et al*. 2013).

Many of optimization methods have been developed during last decades and at the pioneer are the traditional mathematical based methods which use the gradient information to search the optimal solutions with drawbacks such as complex derivatives, sensitivity to initial values,

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applicable in continuous search spaces and the large amount of enumeration memory required (Lee and Geem 2004). Although some mathematical programming based methods have been developed for discrete optimum design problems they are not very efficient for obtaining the optimum solution of the large size practical design problems (Saka 2009). In recent years, the other class of optimization techniques, stochastic optimization algorithms inspired by natural mechanisms, has been produced for overcoming these disadvantages which makes it possible to optimize complicated discrete engineering optimization problems (Kaveh 2014).

Due to the presence of large number of design variables, discrete values of variables, large size of search space, difficulties of modeling and analyzing methods, and many constraints including stress, deflection and geometry limitations under various load types, size optimization of multi-span steel-box girders have not been attempted. In practice several techniques with various degrees of consistency are available for analysis. These range from the elementary or engineer's beam theory to complex-shell finite element analyses (Razaqpur and Li 1991). One of the most prevalent analysis and design tools, the SAP2000, is employed in this study and also took advantage of Its Open Application Programming Interface (OAPI) feature to model as practical and detailed as possible. To take full advantage of the enhancements offered by the new multi-core hardware era, the MATLAB software with its Parallel Computing Toolbox is used in this research (Luszczek 2009). A population based algorithm entitled Cuckoo Search (CS), inspired by the behavior of some cuckoo species in combination with Lévy flight behavior (Yang 2008, Yang and Deb 2009), is selected to optimize straight multi-span composite steel box girders under self-weight. This population based algorithm like other ones can benefit the features of parallel computing and have been used successfully for discrete optimum deign of truss structures, 2D and 3D frames (Kaveh *et al*. 2012, Saka and Dogan 2012, Saka and Geem 2013, Kaveh and Bakhshpoori 2013). In order to verify the efficiency of the CS, two other algorithms are also used to determine the solution of the considered discrete optimization problem. These are the Harmony Search method (HS) (Kochenberger and Glover 2003) and Particle Swarm Optimization (PSO) (Kennedy *et al*. 2001) algorithm.

Taking into account all restrictions imposed by American Association of State Highway and Transportation Officials (AASHTO 2002), a practical design example is optimized using the proposed integrated parallel optimization procedure. The results reveal a saving of around 15% of material for the considered bridge girder.

The remaining sections of this paper are organized as follows. Section 2 states the design optimization problem. Third section outlines the details of parallel CS based optimization procedure. The penult section contains a comprehensive practical design optimized by the proposed method, to illustrate the features of the design method. At the end paper is concluded in the Section 5.

2. Design optimization problem

After the topology and support conditions are established, the girder is divided into some segments along the girder length. The process of division is based on fabrication requirements. The main design effort involves sizing the individual girder sections for the predetermined segments with the objective of minimizing the self-weight of the girder. A typical section for composite steel-concrete box girder is shown in Fig. 1. As it is depicted the design variables in each section are slab thickness (*tc*), top flange width (*bf*), top flange thickness (*tf*), web depth (*Dw*),

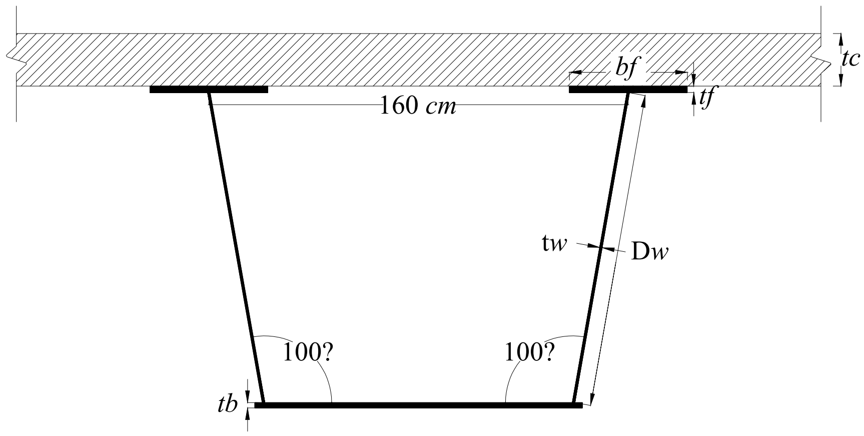


Fig. 1 A typical section of steel box girder

web thickness (*tw*) and bottom flange thickness (*tb*). The center to center distance of the top flanges and the inclination angle of web from the vertical direction are fixed to 160 cm and 100°, respectively, for the entire girder because of fabrication conditions. As a result, the width of bottom flange is a function of other variables.

The design procedure based on the AASHTO Division I (2002) provisions can be outlined as follows

2.1 Loading

Maximum compressive and tensile stresses in girders that are not provided with temporary supports during the placing of the permanent dead load is the sum of the stresses produced by the dead loads acting on the steel girders alone and the stresses produced by the superimposed loads acting on the composite girder. Therefore two different dead loads should be considered. In the first case the dead load is exerted on the non-composite section (*L*1). This load involves self-weight of the steel girder and weight of the concrete deck. The second case is applied on the composite section which includes the pavement, curb, pedestrian, and guard fence loads (*L*2). The highway live loads on the roadways of bridges or incidental structures shall consist of standard trucks or lane loads that are equivalent to truck trains. AASHTO HS loading is applied in this study. The live load for each box girder (*L*3) shall be determined by applying to the girder, the fraction W_L of a wheel load determined by the following equation

$$W_K = 0.1 + 1.7R + 0.85 / N_w, \quad R = N_w / \text{Number of girders} \tag{1}$$

in which N_w is the number of lanes. Dynamic effects of live load should be taken into account as an impact coefficient based on the Article 3.8.2 from the AASHTO (2002).

2.2 Geometric constraints

According to Section 10 of the AASHTO (2002), the following geometry limitations are imposed on the section

$$\begin{cases} g_1 \ : \ \dfrac{t_w \times 1.5}{t_f} - 1 \leq 0 \\ g_2 \ : \ \dfrac{D_w \times 0.2}{b_f} - 1 \leq 0 \\ g_3 \ : \ \dfrac{b_f}{t_f \times 23} - 1 \leq 0 \\ g_4 \ : \ \dfrac{D_w}{t_w \times 327} - 1 \leq 0 \end{cases} \tag{2}$$

2.3 Strength constraints

The flanges of section, both top and bottom, should be designed for flexural resistance as follows

$$\begin{aligned} g_5 \ &: \ \frac{\sigma_{top}}{\sigma_{all}(top)} - 1 \leq 0 \\ g_6 \ &: \ \frac{\sigma_{top}}{\sigma_{all}(bot)} - 1 \leq 0 \end{aligned} \tag{3}$$

The flexural stress of top and bottom flanges, $\sigma(top)$ and $\sigma(bot)$, are calculated under three loading conditions: the section without considering concrete slab under $L1$; the composite section under $L2$ with creep and shrinkage effects; the composite section under live loads without long term effects. Creep and shrinkage effects are took into account by dividing concrete elastic module by 3 based on 10.38.1.4 (AASHTO 2002). The allowable stress of top flange, $\sigma_{all}(top)$, and tensile allowable stress of bottom flange, $\sigma_{all}(bot)$, are equal to $0.55F_y$. The bottom flange allowable compressive stress is supplied on the 10. 39. 4. 3.

Concrete compressive stress under *L2* and *L3* loads should satisfy following constraint

$$g_7 \ : \ \frac{\sigma_{concrete}}{0.4 f'_c} - 1 \leq 0 \tag{4}$$

in which f'_c is concrete cylindrical compressive strength.

Shear stresses in the web should be bounded by allowable shear stress as follows

$$g_7 \ : \ \frac{\left(f_v = \dfrac{V}{2 D_w t_w \cos\theta} \right)}{F_v} - 1 \leq 0 \tag{5}$$

where V is the shear under dead and live loads (all three load conditions) and θ is the inclination angle of the web, f_v is shear stress and F_v is allowable shear stress which is obtained by 10.39.3.1.

2.4 Serviceability constraints

Complying section 10.6 the composite girder deflections under live load plus the live load impact (Δ_{L+I}) for each span shall not exceed 1/800 span length (S) which can be presented as follows

$$g_9 \ : \ \frac{800 \times \Delta_{L+1}}{S} - 1 \leq 0 \tag{6}$$

3. Parallel metaheuristic based optimization technique

3.1 Cuckoo search algorithm

Cuckoo Search is a metaheuristic algorithm inspired by some species of a bird family called Cuckoo because of their special lifestyle and aggressive reproduction strategy (Yang and Deb 2009). These species lay their eggs in the nests of other host birds with amazing abilities like selecting the recently spawned nests and removing existing eggs that increase hatching probability of their eggs. The host takes care of the eggs presuming that the eggs are its own. However, some of host birds are able to combat with this parasites behavior of cuckoos, and throw out the discovered alien eggs or build their new nests in new locations. The cuckoo breeding analogy is used for developing new design optimization algorithm. A generation is represented by a set of host nests. Each nest carries an egg (solution). The quality of the solutions is improved by generating a new solution from an existing solution and modifying certain characteristics. The number of solutions remains fixed in each generation. In this study the later version of the CS algorithm is used for optimum design of frames (Yang and Deb 2009). The pseudo-code of the optimum design algorithm is as it follows (Kaveh and Bakhshpoori 2013)

3.1.1 Initialize the cuckoo search algorithm parameters

The CS parameters are set in the first step. These parameters consist of the number of nests (n), the step size parameter (α), discovering probability (pa) and the maximum number of frame analyses as the stopping criterion.

3.1.2 Generate initial nests or eggs of host birds

The initial locations of the nests are determined by the set of values randomly assigned to each decision variable as

$$nest_{i,j}^{(0)} = ROUND\left(x_{j,\min} + rand.(x_{j,\max} - x_{j,\min})\right) \tag{7}$$

where $nest_{i,j}^{(0)}$ determines the initial value of the jth variable for the ith nest; $x_{j,\min}$ and $x_{j,\max}$ are the minimum and the maximum allowable values for the jth variable; *rand* is a random number in the interval [0, 1]. The rounding function is accomplished due to the discrete nature of the problem.

3.1.3 Generate new Cuckoos by Lévy flights

In this step, all the nests except for the best one are replaced based on quality by new cuckoo eggs produced with Lévy flights from their positions as

$$nest_i^{(t+1)} = nest_i^{(t)} + \alpha.S.\left(nest_i^{(t)} - nest_{best}^{(t)}\right).r \tag{8}$$

where $nest_i^t$ is the ith nest current position, α is the step size parameter; r is a random number from a standard normal distribution and $nest_{best}$ is the position of the best nest so far; and S is a random walk based on the Lévy flights. The Lévy flight essentially provides a random walk while the random step length is drawn from a Lévy distribution. In fact, Lévy flights have been observed among foraging patterns of albatrosses, fruit flies and spider monkeys. One of the most efficient and yet straightforward ways of applying Lévy flights is to use the so-called Mantegna algorithm. In Mantegnas algorithm, the step length S can be calculated by

$$S = \frac{u}{|v|^{1/\beta}} \tag{9}$$

where β is a parameter between [1, 2] interval and considered to be 1.5; u and v are drawn from normal distribution as

$$u \sim N(0,\ \sigma_u^2), \quad v \sim N(0,\ \sigma_v^2) \tag{10}$$

$$\sigma_u = \left\{ \frac{\Gamma(1+\beta)\ \sin(\pi\beta/2)}{\Gamma\left[(1+\beta)/2\right]\beta\ 2^{(\beta-1)/2}} \right\}^{1/\beta}, \quad \sigma_v = 1 \tag{11}$$

3.1.4 Alien eggs discovery

The alien eggs discovery is performed for each component of each solution in terms of probability matrix such as

$$P_{ij} = \begin{cases} 1 & if \quad rand < pa \\ 0 & if \quad rand \geq pa \end{cases} \tag{12}$$

where $rand$ is a random number in [0, 1] interval and pa is the discovering probability. Existing eggs are replaced considering quality by the newly generated ones from their current positions through random walks with step size such as

$$\begin{aligned} &S = rand.\big(nests(randperm1(n),:) - nests(randperm2(n),:)\big) \\ &nest^{t+1} = nest^{t} + S.*P \end{aligned} \tag{13}$$

where $randperm1$ and $randperm2$ are random permutation functions used for different rows permutation applied on nests matrix and P is the probability matrix.

3.1.5 Termination criterion

The generating new cuckoos and discovering alien eggs steps are alternatively performed until a termination criterion is satisfied. The maximum number of analyses is considered as termination criterion of the algorithm.

3.2 Parallel computing system

A visit to the neighborhood PC retail store provides ample proof that we are in the multi-core era. This created demand for software infrastructure to utilize mechanisms such as parallel computing to exploit such architectures. In this respect, the MathWorks introduced Parallel Computing Toolbox software and MATLAB® Distributed Computing Server (Luszczek 2009).

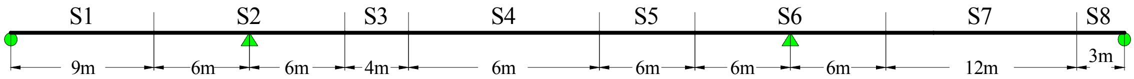
Regarding that our individual designs proposed by population based metaheuristic algorithms are evaluated independently, electing one of MATLABs most basic programming paradigms, the parallel for-loops (Luszczek 2009), makes it easy for user to handle in such optimization problem.

Since the parallel computing technique enables us to perform several actions at the same time, it is needed to adjust the analysis and design assumptions for a prime model of box girder in the SAP2000 environment. Once the optimization algorithm invokes the model, a set of sections are assigned to the predefined segments. A certain feasible number of proposed solutions get invoked for analysis and evaluating the penalized fitness value following the PARFOR conditional command, and consequently a next set of population are generated. The iteration continues until a stopping criterion is attained.

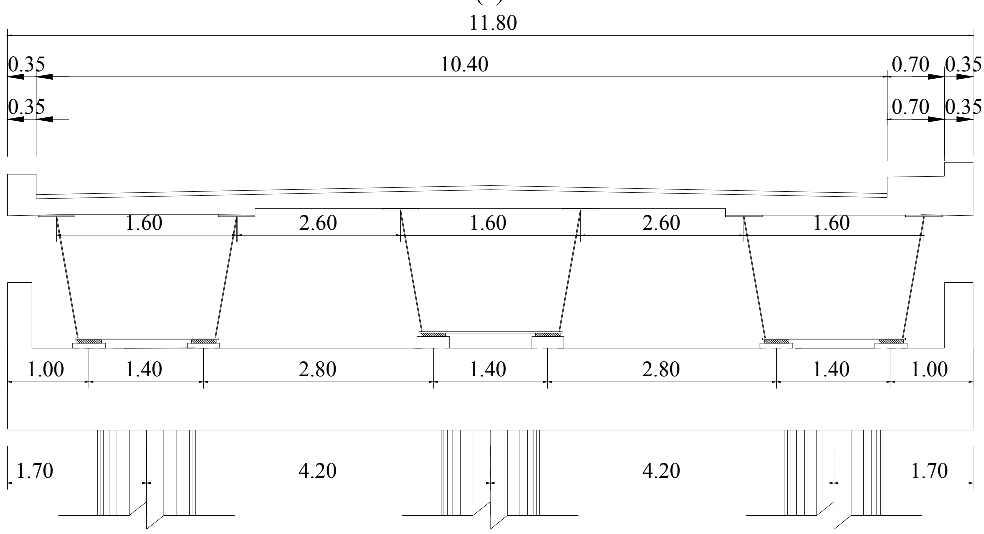
4. Design example

4.1 A three-span continuous composite bridge

In this section, a practical example is provided to investigate the application of the presented parallel integrated optimization approach. The example bridge deck is composed of three composite trapezoidal box girders which are continuous over three spans of the lengths 15, 34 and 21 meters. Figs. 2(a) and (b) show the topology, support conditions and segments of a girder, and the cross section of the bridge, respectively. The girder is divided to eight pre-built segments (S_i, i



(a)



(b)

Fig. 2 The practical design example: (a) longitudinal view; and (b) transverse view

Table 1 Segments and related variables

Segment	Section	t_c	b_f	t_f	D_w	t_w	t_b
S1	A1	t_c	b_{f1}	t_{f1}	D_{w1}	t_{w1}	t_{b1}
S2	A2	t_c	b_{f1}	t_{f2}	D_{w1}	t_{w2}	t_{b2}
	A3	t_c	b_{f1}	t_{f2}	D_{w2}	t_{w2}	t_{b2}
	A4	t_c	b_{f1}	t_{f2}	D_{w3}	t_{w2}	t_{b2}
S3	A5	t_c	b_{f1}	t_{f3}	D_{w3}	t_{w3}	t_{b3}
S4	A6	t_c	b_{f1}	t_{f4}	D_{w3}	t_{w4}	t_{b4}
S5	A7	t_c	b_{f1}	t_{f5}	D_{w3}	t_{w5}	t_{b5}
S6	A8	t_c	b_{f1}	t_{f6}	D_{w3}	t_{w6}	t_{b6}
	A9	t_c	b_{f1}	t_{f6}	D_{w4}	t_{w6}	t_{b6}
	A10	t_c	b_{f1}	t_{f6}	D_{w5}	t_{w6}	t_{b6}
S7	A11	t_c	b_{f1}	t_{f7}	D_{w5}	t_{w7}	t_{b7}
S8	A12	t_c	b_{f1}	t_{f8}	D_{w5}	$t_{w\backslash 8}$	t_{b8}

Table 2 Design variables range

Variable	Lower bound (m)	Upper bound (m)	Increment (m)
t_c	0.20	0.35	0.05
b_f	0.25	0.8	0.05
t_f, t_w and t_b	0.01	0.05	0.005
D_w	0.5	4.6	0.1

= 1, 2, …, 8) in a way to satisfy fabrication limitations and minimize material waste. Considering the concrete slab thickness as a constant value (*tc*), Table 1 presents design variables of the problem in which the second column states different cross sections for each segment. Segments on the middle supports are shaped as non-prismatic due to the presence of large negative moments. Plate thicknesses and widths are constant along each segment, also the concrete slab thickness and the top flange width are fixed for the entire girder. Altogether this problem contains 30 design variables. The range of variables is tabulated in the Table 2.

The optimum design problem can be expressed as follows

$$\begin{aligned} &\text{Considering concrete slab thickness as a constant value } (t_c): \\ &\text{find } \{X\} = \left[b_f, t_{f1}, t_{f2}, \ldots, t_{f8}, D_{w1}, D_{w2}, \ldots, t_{w1}, t_{w2}, \ldots, t_{w8}, t_{b1}, t_{b2}, \ldots, t_{b8}\right]_{1\times 30} \\ &\text{to minimize } W(\{X\}) \\ &\text{Subject to: } g_1,\ g_2,\ g_3, \ldots,\ g_9 \end{aligned} \tag{14}$$

where $\{X\}$ is the set of design variables and its components are sized from the discrete sets presented in the Table 2 and $W(\{X\})$ is the self-weight of girder obtained by SAP 2000. Optimum design of composite steel box girders is one of those issues for which the conventional objective function is not applicable. Considering concrete slab, shear connectors and reinforcement cost seems to be necessary. Cost of the shear connectors is negligible in comparison to the overall cost. Higher strength shear connectors are considered to satisfy the complete composite action. According to the articles 3.24.10.2 and 3.24.3.1 provided by AASHTO (2002) for designing the longitudinal and transverse reinforcement, the reinforcement depends only on the slab thickness and the distance of the girders. Thus reinforcement is not considered as design variables. Considering the concrete slab thickness as a design variable, the proposed objective function is not representative and needs to be modified. Instead of the total weight (concrete slab weight and steel section weight altogether), sum of the total cost of the concrete material and the total cost of the steel section material should be used. Modification can be made using unit cost coefficients for each cost frameworks. The choice of the unit cost parameters can influence the properties of the most cost-efficient design (Fragiadakis and Lagaros 2011). In addition slab thickness as a design variable has a profound effect on the model stiffness matrix and dead load. Considering t_c as a design variable simultaneously with design variables representing the steel section can lead the algorithm to unfeasible designs. In these regards, the CS is applied to find the optimum design considering the slab thickness as a constant value from a certain practical interval [0.2, 0.35] with 0.05 m increment to achieve the optimum thickness. The lower bound is considered according to the provisions of AASHTO 2002 (Table 8.9.2).

The design should be carried out in such a way that the girder satisfies the strength, displacements and geometric requirements presented in the second section. In order to handle the constraints, a penalty approach is utilized. In this method, the aim of the optimization is redefined by introducing the cost function as

$$f_{\cos t}\left(\{X\}\right) = (1+\varepsilon_1 . N)^{\varepsilon_2} \times W\left(\{X\}\right) \tag{15}$$

where N is the constraint violation function. For generating the total penalty each segment is divided to five equal parts, and all the constraints, g_1 to g_8, are checked for each part. In this way the constraint violation function can be obtained as follows

$$\begin{aligned} N &= \sum_{i=1}^{8} v_i, \quad v_i = \max(\mu_j), \quad j = 1, 2, \ldots, 5 \\ \mu_j &= \sum_{k=1}^{9} \max[g_k, 0] \end{aligned} \tag{16}$$

in which v_i is the penalty of each segment, and μ_j is the penalty value for jth part of ith segment. ε_1 and ε_2 are penalty function exponents which are selected considering the exploration and the exploitation rate of the search space. Here, ε_1 is set to unity; ε_2 is selected in a way that, in the first steps of the search process is equal to 1 and ultimately increased to 3.

In modeling, analysis and design procedures, the fundamental assumptions are made to idealize the results as follows: Material property for all sections is considered as A36 steel material with weight per unit volume of ρ =7849 kg/m^3 (0.2836 lb/in^3), modulus of elasticity of E = 199948 MPa (29000 ksi) and a yield stress of f_y = 248.2 MPa (36 ksi), and concrete material with the strength of f'_c = 24 MPa (ksi) and ρ =2500 ton/m^3 (lb/in^3); the spacing of transverse stiffeners is assumed 2 m and the bottom flange is longitudinally stiffened. As it was mentioned, the girder carries three types of loads (ton/m) as follows: $L1$ = Slab Weight + self-weight of girder; $L2$ = 1.22, and $L3$ = 1.326* (HS loading on a girder).

In order to verify the efficiency of the CS, two other algorithms are used to determine the solution of the considered discrete optimization problem, which are Harmony Search method (HS) (Kochenberger and Glover 2003) and Particle Swarm Optimization (PSO) (Kennedy *et al*. 2001) algorithm. These algorithms have been frequently used in multicriteria and constrained optimization, typically associated with practical engineering problems. For example, Erdal *et al*. (2011) has utilized these algorithms for optimum design of cellular beams. The authors have used these algorithms for discrete optimum design problem similar to the work by Erdal *et al*. (2011). Additional details can be found in (Erdal *et al*. 2011). Here the PSO, HS and CS algorithms are used for obtaining the optimum slab thickness and two adjacent depths. Considering the effect of the initial solution on the final results and the stochastic nature of the metaheuristic algorithms, each algorithm is independently solved for five times with random initial designs. Then the best run is chosen for performance evaluation of each technique. The maximum numbers of box girder evaluations is considered as 7000 for the termination criteria. The parameters of the CS algorithm are considered as n = 7, α = 0.1 and pa = 0.3. The parameters of the PSO algorithm are tuned as NPT = 50, $C_1 = C_2 = 2$, ω = 0.12, and $V_{\max} = \Delta t$ = 1.3 and the parameters of the HS algorithm are tuned as hms = 70, $hmcr$ = 0.8, and par = 0.2.

4.2 Discussions

Fig. 3 shows the obtained optimum weight for various concrete slab thicknesses by the algorithms. All three algorithms result in the optimum thickness of concrete slab as 0.2 m. It can be concluded that in this test problem considering the concrete slab thickness equal to the minimum value provided by the AASHTO (2002) provisions leads to the optimum design. The optimum feasible designs obtained by CS, PSO and HS algorithms weighted 32.77, 33.34 and 38.36 tons, respectively. For graphical comparison of algorithms, the convergence histories for the best result of five independent runs in the case of t_c = 0.2 m are shown in Fig. 4. PSO and CS act far better than the HS algorithm. PSO algorithm shows the fastest convergence rate than others and this is because of the good global search ability of PSO. It is obvious that PSO cannot perform efficiently in the local search stage of the algorithm. However PSO results in the same practical

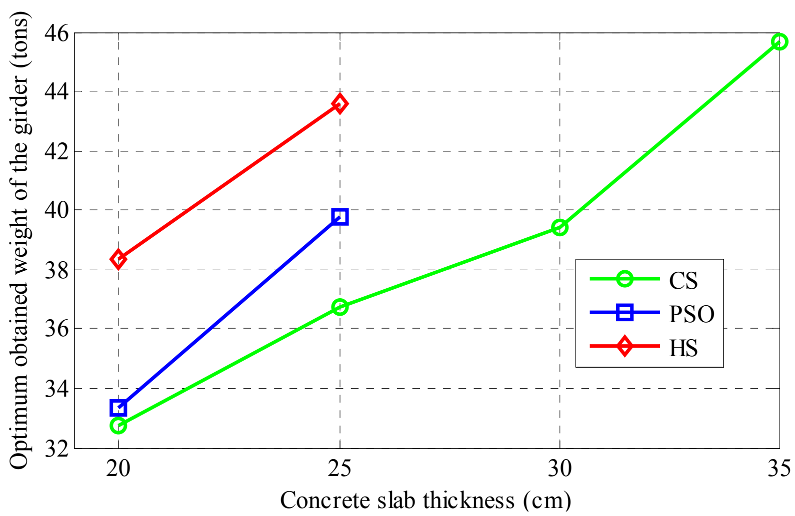


Fig. 3 Best results obtained by threee Algorithms

Table 3 Sectional designations of the best optimum design obtained by the CS

Segment	Section	b_f	t_f	D_w	t_w	t_b	Mass per length (kg/m)
S1	A1	0.3 (.45)	0.02 (0.025)	0.7 (1.5)	0.01 (0.015)	0.015 (.025)	363.83 (741.55)
S2	A2	0.3 (.45)	0.02 (0.025)	0.7 (1.5)	0.01 (0.015)	0.025 (.025)	470.33 (741.55)
	A3	0.3 (.45)	0.02 (0.03)	1.8 (2)	0.01 (0.01)	0.025 (.025)	568.05 (703.55)
	A4	0.3 (.45)	0.02 (0.02)	1.7 (1.5)	0.01 (0.01)	0.025 (.02)	559.16 (588.49)
S3	A5	0.3 (.45)	0.015 (0.02)	1.7 (1.5)	0.01 (0.01)	0.01 (.02)	416.75 (546.14)
S4	A6	0.3 (.45)	0.02 (0.02)	1.7 (1.5)	0.01 (0.01)	0.025 (.02)	559.16 (546.14)
S5	A7	0.3 (.45)	0.02 (0.02)	1.7 (1.5)	0.01 (0.01)	0.015 (.02)	479.92 (546.14)
S6	A8	0.3 (.45)	0.02 (0.02)	1.7 (1.5)	0.01 (0.01)	0.02 (.02)	519.54 (546.14)
	A9	0.3 (.45)	0.02 (0.03)	2.0 (2)	0.01 (0.01)	0.02 (.025)	550.28 (703.55)
	A10	0.3 (.45)	0.02 (0.025)	0.8 (1.5)	0.01 (.015)	0.02 (.025)	427.33 (741.55)
S7	A11	0.3 (.45)	0.015 (.025)	0.8 (1.5)	0.01 (.015)	0.015 (.025)	351.89 (741.55)
S8	A12	0.3 (.45)	0.02 (0.02)	0.8 (1.5)	0.01 (0.01)	0.01 (.02)	323.55 (546.14)

*The values in parentheses are the at hand design using the conventional design procedure

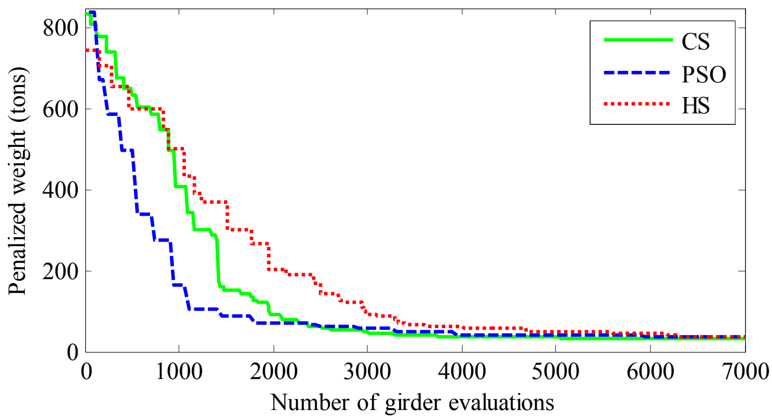


Fig. 4 Best convergence history obtained by three metaheuristic algorithms (t_c = 20 cm)

design as the CS but needs higher number of girder evaluations (6450). Continuous step like ovements of the CS algorithm demonstrates its ability in balancing the global and local search in this optimization test problem. The optimum design obtained by cuckoo search algorithm is weighted 32.77 tons which is approximately 15% lighter than the conventional design. Related sectional designations and mass per length of sections for each segment are summarized in Table 3. The sectional designations based on the conventional design, considering the concrete slab thickness equal to 0.2 cm, are also presented in this table.

Geometry constraint values of sections for each segment are listed in the Table 4. As it can be seen, the first constraint (g_1) with the aim of controlling the top flange thickness to the web thickness is the most active limitation. The last row exhibits optimum design controlling priority with respect to the geometry constraints. The serviceability and strength performance of the

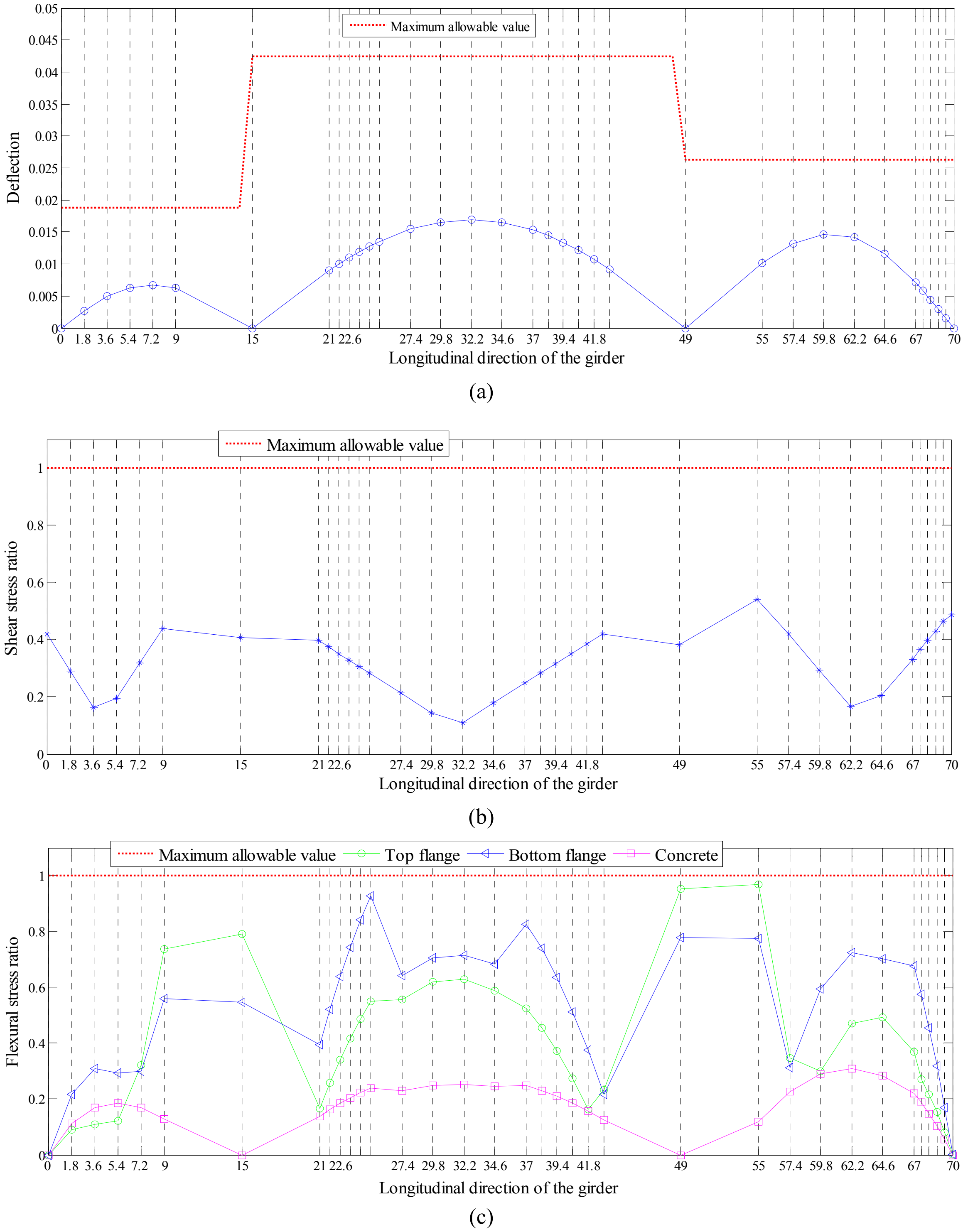


Fig. 5 Performance evaluation of the best achieved optimum design via CS. (a) Deflection; (b) Shear stress ratio; (c) Flexural stress ratios

Table 4 Geometry constraints value of each section for optimum design obtained by the CS

Segment	Section	g_1	g_2	g_3	g_4
S1	A1	0.750	0.350	0.652	0.214
S2	A2	0.750	0.350	0.652	0.214
	A3	0.750	0.900	0.652	0.550
	A4	0.750	0.850	0.652	0.520
S3	A5	1.000	0.850	0.870	0.520
S4	A6	0.750	0.850	0.652	0.520
S5	A7	0.750	0.850	0.652	0.520
S6	A8	0.750	0.850	0.652	0.520
	A9	0.750	1.000	0.652	0.612
	A10	0.750	0.400	0.652	0.245
S7	A11	1.000	0.400	0.870	0.245
S8	A12	0.750	0.400	0.652	0.245
Min		0.750	0.350	0.652	0.214
Max		1.000	1.000	0.870	0.612
Average		0.792	0.671	0.688	0.410
SD		0.097	0.261	0.085	0.159
CP		**1**	**3**	**2**	**4**

*CP: Optimum design controlling priority with respect to geometry constraints

resulted optimum girder is illustrated in the Fig. 5. Based on this figure, despite of relative long middle span, the effect of deflection constraint is not notable here. Such a performance is also observed for shear stress ratio constraint. Fig. 5(c) shows the available and allowable flexural stress ratios for the top and bottom flanges and the concrete deck. It can be observed that the stress ratio of top and bottom flanges have more effect in controlling the optimum design than the shear and concrete slab stress ratios. Also it can be interpreted that the bottom and the top flange stress ratios are dominant at the middle of spans and on the supports, respectively. This can be due to the contribution of the concrete slab in carrying the loads in a composite manner at the middle of spans.

5. Conclusions

In this study, size optimization of composite continuous multi-span steel box girders is performed based on AASHTO code of practice for loading and designing of bridges. The metaheuristic algorithm of choice is the Cuckoo Search algorithm. This algorithm optimizes the self-weight of a girder by interfacing SAP2000 and MATLAB software in the form of parallel computing. In order to verify the efficiency of the CS, two other algorithms consisting of the PSO and HS are used to determine the solution of the considered discrete optimization problem.

The results reveal that the Cuckoo Search has a good ability in finding acceptable feasible design in terms of accuracy and convergence rate. In the case of size optimization of a box girder with 30 design variables and conditions similar to practical design, the integrated parallel metaheuristic based optimization procedure resulted in around 15 % reduction of weight compared to the conventional non-optimized design. The dominance of the constraints in controlling the final optimized results is also investigated. Despite a relative long middle span, the effect of deflection constraint has not been notable here. Based on the present study it can be concluded that the geometry, top and bottom flanges flexural strength, middle span deflection, the shear and concrete slab strength constraints are effective in optimum design of a typical multi-span continuous straight steel box girders.

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