Smart Structures and Systems, *Vol. 20, No. 5 (2017) 607-618*
DOI: https://doi.org/10.12989/sss.2017.20.5.607

Design of multi-span steel box girder using lion pride optimization algorithm

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(Received May 30, 2017, Revised August 3, 2017, Accepted August 10, 2017)

Abstract. In this research, a newly developed nature-inspired optimization method, the Lion Pride Optimization algorithm (LPOA), is utilized for optimal design of composite steel box girder bridges. A composite box girder bridge is one of the common types of bridges used for medium spans due to their economic, aesthetic, and structural benefits. The aim of the present optimization procedure is to provide a feasible set of design variables in order to minimize the weight of the steel trapezoidal box girders. The solution space is delimited by different types of design constraints specified by the American Association of State Highway and Transportation Officials. Additionally, the optimal solution obtained by LPOA is compared to the results of other well-established meta-heuristic algorithms, namely Gray Wolf Optimization (GWO), Ant Lion Optimizer (ALO) and the results of former researches. By this comparison the capability of the LPOA in optimal design of composite steel box girder bridges is demonstrated.

Keywords: composite box girder; optimal design; lion pride optimization algorithm; constrained problems; meta-heuristic search

1. Introduction

In this study, a recently developed population-based metaheuristic algorithm, named as Lion Pride Optimization Algorithm (LPOA), is utilized for optimization of multi-span composite steel box girder bridges. The structural configuration of a composite steel box girder bridge system is a traffic-carrying reinforced concrete slab, on top of a single or multiple steel trapezoidal box beams. The reinforced concrete deck and the steel girders behave together as a composite section to resist the applied loads.

The metaheuristics are non-gradient stochastic optimization algorithms which attempt to obtain optimum solutions globally. Nevertheless, search agents can be trapped in local minima and there is no guarantee that a near-global optimal solution can be found. In fact, it is often the case that a well-designed metaheuristic algorithm can only find a good quality (near-optimal) solution (Redondo 2009). As such, performance enhancement of metaheuristics to obtain sufficiently good results with reasonable computational cost is always an important issue (Bureerat and Pholdee 2015).

Lately, researchers have proposed many metaheuristic algorithms. For instance: Jaya (a Sanskrit word meaning victory) (Rao 2016); Sin Cosine Algorithm (SCA) (Mirjalili 2016); JADE (Zhang and Sanderson 2009); Firefly Algorithm (FA) (Yang 2010); Salp Swarm Algorithm (SSA) (Mirjalili *et al.* 2017); Symbiotic Organisms Search (SOA) (Cheng and Prayogo 2014); Charged System Search (CSS) (Kaveh and Talatahari 2010). Overwhelming number of these techniques have been inspired by the nature. Additionally, there is a remarkable number of proposed modified or hybrid algorithms. For example: L-SHADE incorporated with eigenvector-based crossover and successful-parent-selecting framework (Guo *et al*. 2015); SHADE algorithm with linear population size reduction (Tanabe and Fukunaga 2014); hybridization of the Charged System Search and the Big Bang-Big Crunch algorithms with trap recognition capability (Kaveh and Zolghadr 2012).

In the last decades, a number of optimization techniques have been developed and used for structural optimization problems (Kaveh 2017a). These methods have been implemented for wide variety types of structural design problems such as health monitoring, size and placement optimization designs and performance-based design problems. Some applications of metaheuristic algorithms can be found in the work of (Yi *et al*. 2011, Yi *et al*. 2012, Hasançebi *et al*. 2011, Hasançebi and Azad 2013, Kaveh and Ilchi Ghazaan 2015, Kaveh 2017 a, b) among many others.

There are recent research works focused on optimization of different types of bridges: Long *et al*. (1999) presented a procedure to minimize the cost of materials of cable-stayed bridges with composite box girder. The design of a T-girder bridge deck was performed using Artificial Neural Networks (ANN) and Genetic Algorithms (GA) (Srinivas and Ramanjaneyulu, 2007); An Arch Bridge was designed using Evolutionary Operation (EVOP) (Islam *et al*. 2014); Artificial Neural Networks (NNA) was applied to a post-tensioned concrete road bridge design problem (García-

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http://www.techno-press.com/journals/sss&subpage=7
ISSN: 1738-1584 (Print), 1738-1991 (Online)

Segura *et al.*); A pre-cast road bridge was designed by the Descent Local Search (DLS) (Yepes *et al.* 2017); A precast-prestressed concrete U-beam and post-tensioned cast-in-place concrete slab road bridge design example was also solved by Simulated Annealing (SA) and Threshold accepting (TA) methods; Genetic Algorithm (GA) was applied to the design of a long-span suspension bridge (Sgambi *et al.* 2012). There are also some studies focused on key components of bridges. A tall bridge pier was designed by ant colony optimization (ACO) (Martínez *et al.* 2011); A simulated annealing (SA) based approach was used for design of reinforced concrete (RC) bridge piers (Martinez-Martin *et al*. 2012).

In this study, real-world design of a multi-girder and multi-span bridge is performed to show the potential of the LPOA in optimizing this type of bridges. The optimization goal is to find the proper set of design variables in order to obtain the minimum weight of the girders of the bridge. The Open Application Programming Interface (OAPI) feature is used as an interface tool between the Structural Analysis Program (SAP2000) (Wilson and Habibullah 2002), and the MATLAB program (MatLab 2012), the programming language software, to perform the optimization. The optimum design is characterized by three different types of code rules: four geometric constraints of the trapezoidal steel box girders; one serviceability constraint; and four strength constraints. These design constraints are specified by the standard specifications for highway bridges of the American Association of State Highway and Transportation Officials (Highway and Officials 2002). The optimal design solution obtained using the LPOA is presented and subsequently, the optimized solution is compared with the results of the conventional design and other state-of-the-art optimization approaches. Gray Wolf Optimizer (GWO) (Mirjalili *et al.* 2014), Ant Lion Optimizer (ALO) (Mirjalili 2015) in this research effort are used for further validate the research. In addition, the results are compared with the other results in literature that was found with Particle Swarm Optimization (PSO) (Kennedy and Eberhart 1995), Harmony Search (HS) (Geem *et al*. 2001), and Cuckoo Search (CS) (Gandomi *et al*. 2013). The comparisons show that the proposed algorithm obtains the best result for the design example under consideration.

The remainder of the article is organized as follows: Section 2 describes the Lion pride optimization algorithm briefly; The comprehensive practical design of a composite steel box girder bridge is outlined in Section 3; The mathematical formulation and initial setting of the optimization procedure is stated in Section 4; Section 5 describes the optimum results of LPOA. Finally, the concluding remarks are presented in Section 6.

2. Lion pride optimization algorithm

This section provides a brief introduction of the LPOA technique (Kaveh and Mahjoubi 2017) that is a population-based meta-heuristic algorithm and mimics some parts of lions' life in pride groups. Each search agent is considering as a lion or lionesses. In the following, the mathematical model of the algorithm is provided.

2.1 Generate initial lions and prides

The first step is to initialize the vector of *lion* matrices with the number of design variables, and then evaluate their associated fitness function.

$$a_{\min,i} < a_i < a_{\max,i} \tag{1}$$

$$lion_j = \left[a_{1,j}, \cdots, a_{n,j} \right] \tag{2}$$

where $lion_j$ is the initial position of the jth lion, n represents the number of design variables, a_i is vector's components of the ith design variable, and a_{min} and a_{max} are the minimum and the maximum permissible values, respectively.

Lions live together and form social groups named Pride

$$Pride_k = \begin{pmatrix} lion_{1,k} \\ \vdots \\ lion_{pk,k} \end{pmatrix} = \begin{pmatrix} a_{1,1,k} & \cdots & a_{1,n,k} \\ \vdots & \ddots & \vdots \\ a_{pk,1,k} & \cdots & a_{pk,n,k} \end{pmatrix} \tag{3}$$

where $Pride_k$ is the kth pride group and pk represents the population number of residents in the kth pride. The residents of each pride group are selected randomly.

2.2 Optimality search (main loop)

Metaphorically speaking, lions and lionesses are the search agents of the LPOA and the search space is their habitats.

2.2.1 Hunting

Resident lionesses usually go hunting as a team. Each lioness takes-over the specific role in hunting cooperation. Three different types of rules are assumed as Chaser, Cheater (refrainer) and Winger. The chaser pursues the prey directly and Winger attacks the victims in other directions. In the meantime, cheaters just run to narrow down the prey and usually never hunts in the presence of a cooperator. Therefore, individuals that do not participate in group hunts withhold effort increasing the group's success rate (Stander 1992).

The formation of the hunter groups is assumed as the following: all female lions in each pride sort as their fitness and grouped into three main groups. The best female lions are named as chasers, the second best group are considered as wingers and the third group set as cheaters. One member of each of these three general groups are selected unmethodical and form hunting groups.

The mathematical model of the chaser hunters is as follows

$$Chaser_{new} = Chaser + H_1 \times rand + (D) \times (2\,rand - 1) \tag{4}$$

$$H_1 = (Prey - Chaser) \tag{5}$$

$$D = DF \times amp \quad (6)$$

$$amp = a_{\max} - a_{\min} \quad (7)$$

where $Chaser_{new}$ and *chaser* are the new and existing positions of the chaser lion, respectively. *D* represents the diversification matrix, *DF* is the diversification factor, *rand* is a random value in the interval [0,1], and *Prey* is a randomly parameter chosen from the best positions of search agents until now.

The new position of wingers follows the following equation

$$Winger_{new} = \text{Prey} + H_2 \times |W| \times rand + (D) \times (2\,rand - 1) \quad (8)$$

$$W = Prey - Winger = [w_1 + \cdots + w_n] \quad (9)$$

$$|W| = \sqrt{w_1^{\,2} + \cdots + w_n^{\,2}} \quad (10)$$

where $Winger_{new}$ represents the new position of the Winger hunter lion and H_2 is a random unit vector perpendicular to the vector *W*.

The new position of the cheaters follows the equation below

$$Cheater_{new} = Prey + \text{H}_3 \times rand + (D) \times (2\,rand - 1) \quad (11)$$

$$H_3 = (Prey - Cheater) \quad (12)$$

where $Cheater_{new}$ is the new position of the cheaters and *Cheater* is the present position of the cheater.

2.2.2 Excursion

Each male lion in a pride move to their pride's territory to protect their home range. To simulate this behavior, males visit their territories randomly and explore around the territorial areas. The movement of male lions is formulated as the following

$$Malelion_{new} = Territory + E \times (D) \times (2\,rand - 1) \quad (13)$$

$$Territory_i = BestPositions(rand \times TR)_i \quad (14)$$

where $Malelion_{new}$ is the new position of the male lion, *Territory* is randomly selected from the best positions in the pride members, *BestPositions* is the cumulative best position of the resident lions (including both sexes) that is sorted according to the fitness values and ranked from best to worst, *E* is the excursion constant, and *TR* represents the territory ratio.

2.2.3 Mating

The basic concept of mating that is proposed by Yazdani and Jolai (2016) is used to model the mating of the lions. Female lions are sorted as their best fitness values derived until the current iteration and M% (mating probability) of female lions in each pride that have better best solution so far in the current iteration mate with one or several resident males. These males are selected randomly from the same pride as the selected females. Two offspring breed in each mating according to the following equations

$$Offspring_1 = \beta \times FemaleLion + \sum_{l=1}^{nm} \frac{1-\beta}{\sum_{l=1}^{nm} S_l} \times MaleLion_l \times S_l \quad (15)$$

$$Offspring_2 = (1-\beta) \times FemaleLion + \sum_{l=1}^{nm} \frac{1-\beta}{\sum_{l=1}^{nm} S_l} \times MaleLion_l \times S_l \quad (16)$$

where *FemaleLion* is the best position of the selected mother and *MaleLion* represents the best position of males in the pride, S_l equals to 1 if the male l is in the coalition, otherwise it is equal 0; *nm* is the number of resident males in the pride and β is a randomly generated number with a normal distribution with mean value 0.5 and standard deviation 0.1. It is assumed that the gender of these two newborns is random.

2.2.4 Intragroup interaction

Male lions grow into mature and become aggressive and fight other males in their pride. As male mature lions, any male cubs that becomes a mature are a new rival of his throne and so must be eliminated. Male lions in the same pride fight each other weaker ones beaten from the pride and become a nomad. This behavior is represented by the following: number of male lions in each pride is in equilibrium and weaker agents (according to their fitness values) must leave the pride and become a nomad.

2.2.5 Migration

To simulate this natural phenomenon of pride resident lions' migration, some female lions in each pride migrate with probability of immigration rate (I%) in every iteration. Also, surplus female lions in each pride get out of the pride and become a nomad.

2.3 Flowchart

A flowchart of the proposed algorithm is shown in Fig. 1.

3. Problem statement

A three-span continuous composite bridge design example that has been studied in (Kaveh 2014) is chosen to show the performance of the LPOA and existing results.

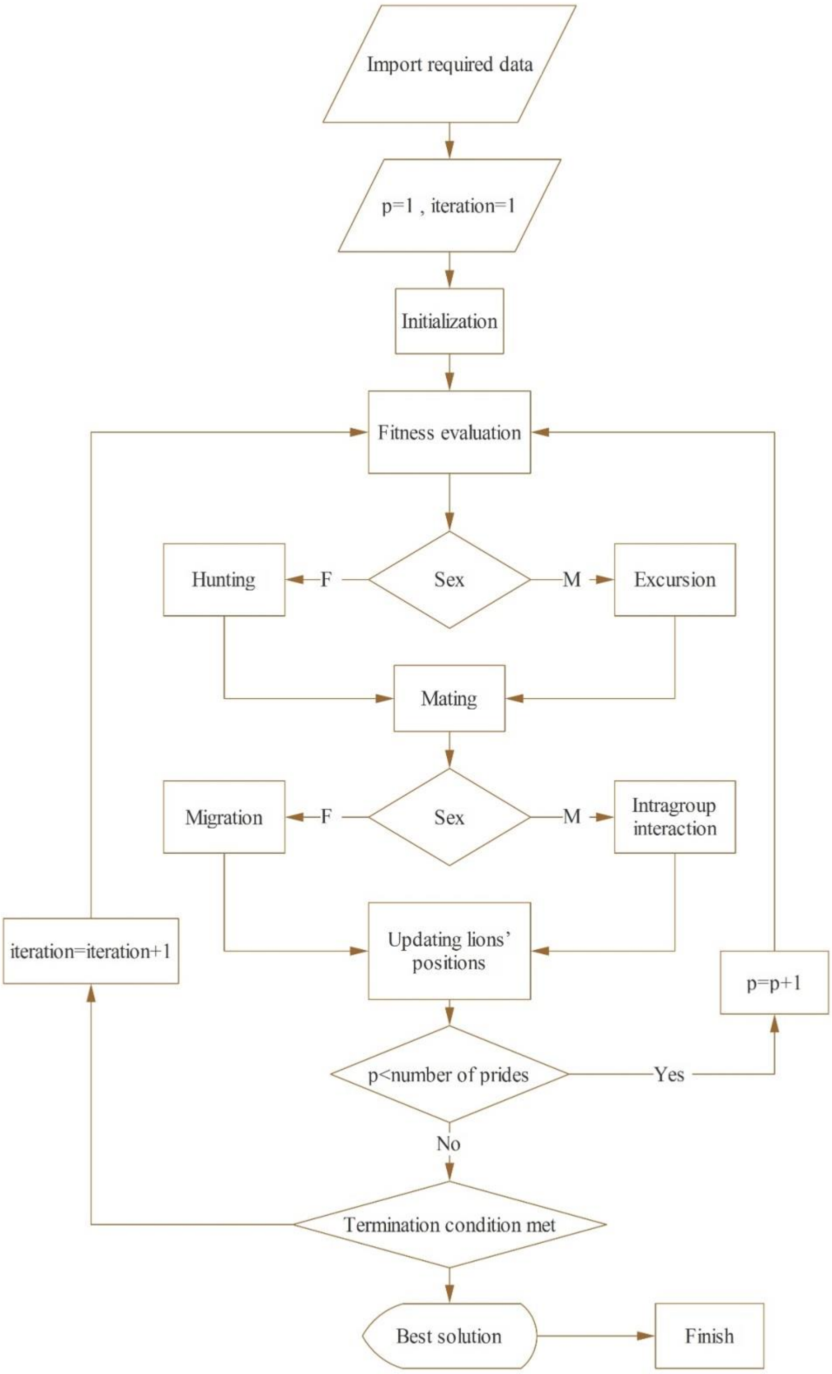


Fig. 1 Simplified flowchart of the LPOA (Kaveh and Mahjoubi 2017)

3.1 Material properties

A material property of all steel sections is considered as A36 steel material with weight per unit volume of ρ =7849 kg/m^3, modulus of elasticity of E=199948 MPa and a yield stress of f_y=248.2 MPa. In addition, concrete material that used in slab deck is assumed as the strength of f'_c=24 MPa and ρ =2500 ton/m^3.

3.2 Topology and support conditions

The bridge segment is shown in Fig. 2. Three girders are made of the same material and similarly sized. Furthermore, Fig. 3 shows the topology, support conditions and the location of eight different segments of the bridge. As shown in this figure, the multi-girder composite steel box bridge is continuous over three spans of the lengths 15, 34 and 21 meters.

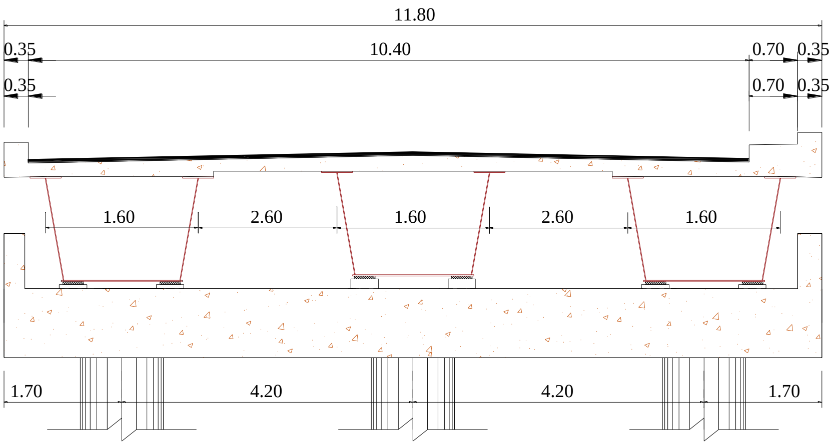


Fig. 2 A cross-sectional view of the composite steel box girder bridge

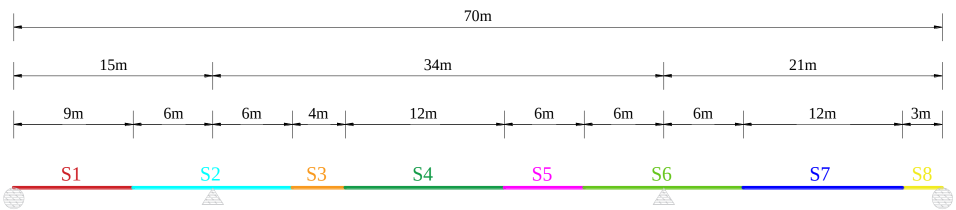


Fig. 3 Topology, support conditions and pre-built segment locations of the composite steel box girder bridge

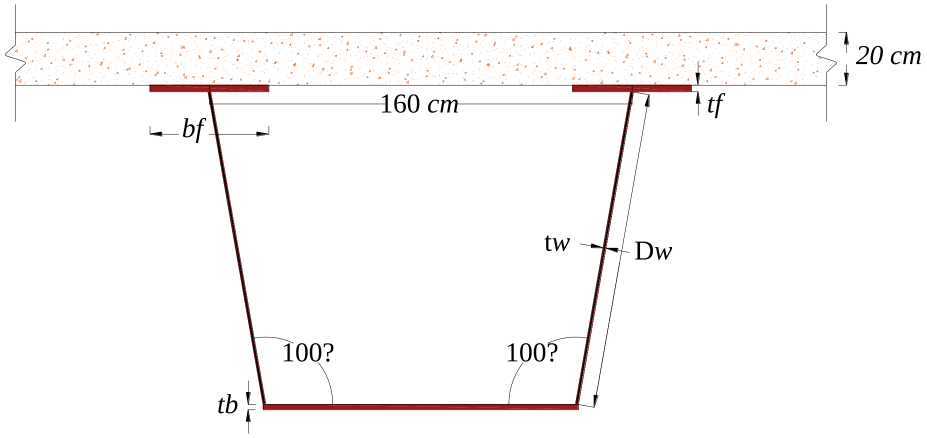


Fig. 4 A typical section of trapezoidal steel box girder

3.3 Optimization variables

All three girders are divided into eight pre-built segments. Fig. 4 shows the section of a typical girder. In addition, the design variables are depicted in this figure. As defined, the design variables in each section are top flange width (b_f), web depth (D_w), web thickness (t_w), top flange thickness (t_f), and bottom flange thickness (t_b). The center to center distance of the top flanges and the inclination angle of the web from the vertical direction are fixed to 160 cm and 100°, respectively, for the entire girder because of fabrication conditions (Kaveh 2014). Additionally, the width of the bottom length is changed as the defined independent variable is altered.

Table 1 Segments and related variables

Segment	Section	b_f	t_f	D_w	t_w	t_b
S1	A1	b_{f1}	t_{f1}	D_{w1}	t_{w1}	t_{b1}
	A2	b_{f1}	t_{f2}	D_{w1}	t_{w2}	t_{b2}
S2	A3	b_{f1}	t_{f2}	D_{w2}	t_{w2}	t_{b2}
	A4	b_{f1}	t_{f2}	D_{w3}	t_{w2}	t_{b2}
S3	A5	b_{f1}	t_{f3}	D_{w3}	t_{w3}	t_{b3}
S4	A6	b_{f1}	t_{f4}	D_{w3}	t_{w4}	t_{b4}
S5	A7	b_{f1}	t_{f5}	D_{w3}	t_{w5}	t_{b5}
	A8	b_{f1}	t_{f6}	D_{w3}	t_{w6}	t_{b6}
S6	A9	b_{f1}	t_{f6}	D_{w4}	t_{w6}	t_{b6}
	A10	b_{f1}	t_{f6}	D_{w5}	t_{w6}	t_{b6}
S7	A11	b_{f1}	t_{f7}	D_{w5}	t_{w7}	t_{b7}
S8	A12	b_{f1}	t_{f8}	D_{w5}	t_{w8}	t_{b8}

Table 2 Design variables range

Variable	Lower bound (m)	Upper bound (m)	Increment (m)
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

Table 1 shows the relation between the optimization variables and girder dimension variations in which each row represents one girder section. The segment geometry of S2 and S8 sections that are on middle supports are non-prismatic due to the presence of large negative moments. Plate thicknesses and widths are constant along each non-prismatic segment as shown in Table 1. Besides, top flange width is fixed in all sections and the concrete deck thickness is assumed to be constant for the entire girder and equal to 20 cm as the study of Kaveh et al. (Kaveh 2014). For designing the longitudinal and transverse reinforcement, the reinforcement of the slab deck is dependent on the slab thickness and the distance between the girders. Thus, reinforcement is not considered as design variables.

In addition, the lower and upper bounds of the design variables are depicted in Table 2.

3.4 The applied loads

3.4.1 Dead loads

Two dead load cases are considered. In the first case, this load named L1, involves self-weight of the steel girders and the slab deck. The second case that is applied on the bridge includes the pavement, curb, pedestrian, and guard fence loads (L2) which is considered as uniform loads of 1.22 ton/m^2. This load is applied on the bridge.

3.4.2 Moving loads

AASHTO HS standard moving loads are applied in this bridge design example. The live load for each box girder (L3) shall be determined by applying this standard to the girders. The fraction of a wheel load (both front and rear) determined by the equation of 10-70 on the Article 10.39.2.1 from the AASHTO. The live load bending moment for each box girder is carried by each steel box beam. Also, the impact factor of 1.326 is considered as the dynamic effects of moving loads.

3.4.2 Stiffeners

The spacing of transverse stiffeners is assumed as two meters and the bottom flanges are longitudinally stiffened.

3.5 Design constraints

Three different types of design limitations, geometry, serviceability and ultimate limit states that specified by the American Association of State Highway and Transportation Officials division 1 are considered in the practical design example.

3.5.1 Geometric requirements for trapezoidal steel boxes

The geometric limitations that are specified by section 10 of the standard specifications for highway bridges are imposed in the following:

$$g_1 : \frac{t_w \times 1.5}{t_f} - 1 \le 0 \tag{17}$$

$$g_2 : \frac{D_w \times 0.15}{b_f} - 1 \le 0 \tag{18}$$

$$g_3 : \frac{b_f}{t_f \times 23} - 1 \le 0 \tag{19}$$

$$g_4 : \frac{D_w}{t_w \times 327} - 1 \le 0 \tag{20}$$

where b_f is top flange width, t_f is top flange thickness, D_w is web depth, t_w is web thickness, and t_b is bottom flange thickness.

3.5.2 Flexural stress limitations of steel box flanges

The top and bottom flanges of steel box sections should be designed for flexural resistance as follows

$$g_5 : \frac{\sigma_{top}}{\sigma_{all}} - 1 \le 0 \tag{21}$$

$$g_6 : \frac{\sigma_{bot}}{\sigma_{all}} - 1 \le 0 \tag{22}$$

where σ_{top} and σ_{bottom} are the flexural stress of the top and bottom flanges respectively, and σ_{bottom} is the allowable stress and equal to 0.55 f_y. Three different load cases are considered and structural analysis is performed in order to calculate flexural stresses in flanges. These load cases are as the following: 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 taken into account by dividing concrete elastic module by 3 (Kaveh 2014).

3.5.3 Compressive stress limitation of concrete slab deck

Compressive stress in the concrete deck under *L2+L3* loads should be delimited by the following equation

$$g_7 : \frac{\sigma_{concrete}}{0.4 f'_c} - 1 \le 0 \tag{23}$$

where $\sigma_{concrete}$ is the compressive stress in concrete slab and f'_c is the concrete cylindrical compressive strength.

3.5.4 Shear stress limitation of steel box girders

Shear stresses in the web of girders should satisfy the following constraint

$$g_\delta : \frac{f}{F_v} - 1 \le 0 \tag{24}$$

Where f_v is shear stress and F_v is allowable shear stress which is obtained by 10.39.3.1. The shear stress is determined by the following

$$f_v = \frac{V}{2 D_w t_w \cos\theta} \tag{25}$$

where V is the shear under L1, L2, and L3, θ is the inclination angle of the web that is fixed as 100 degrees, D_w is web depth, and t_w is web thickness.

3.5.5 Deflection constraint

The composite girder deflections under live load plus the live load impact (Δ_{L+I}) for each span length (S) should satisfy the following constraint equation

$$\mathrm{f}_v = \frac{V}{2 D_w t_w \cos\theta} \tag{26}$$

4. Optimization procedure

The girder is divided into eight pre-built segments (S_i, i=1, 2,…, 8) and twelve different cross-sectional segments in a way to satisfy fabrication limitations and minimize the material waste. In addition, the concrete slab thickness is considered as a fixed value of 20 cm. The penalty approach is used for constraint handling as its simplicity. The design problem can be outlined as follows

$$\begin{aligned}&\text{find}\{X\} = [b_f, t_{f1}, t_{f2}, ..., t_{f8}, D_{w1}, D_{w2}, ..., D_{w5}, t_{w1}, t_{w2}, ..., t_{w8}, t_{b1}, t_{b2}, ..., t_{b8}]_{1\times 30}\\ &\text{to minimize } f\\ &\text{subjected to: } g_1, g_2, g_3, \cdots g_9\end{aligned} \tag{27}$$

where, $\{X\}$ is the vector of the optimum solution, g_1 ,…, g_9 are the optimization constraints, and f denotes the penalized weight of the girder or the objective function of the problem that are defined as

$$f = f_{penalty} \times f(\{X\}) \tag{28}$$

$$f(\{X\}) = \sum_{n=1}^{ns} \rho l_i A_i \tag{29}$$

$$f_{penalty}(x) = (1 + \varepsilon_1 \times v)^{\varepsilon_2}, v = \sum_{i=1}^{c} v_i \tag{30}$$

where $f(\{X\})$ is weight of a girder; $f_{penalty}$ represents the penalty function; and ρ, A_i, and L_i are the material density, the cross-sectional area, and the length of the *n*th girder, respectively; *ns* presents the number of segment sections; v_i is the constraint violation of *i*th constraint; *c* is the number of constraints; ε_1 and ε_2 are parameters that extremely penalize the unfeasible solutions. ε_1 is taken as unity, and $\varepsilon 1$ starts from 1.2 and linearly increases to 3 in the bridge design problems.

It should be noted that, Open Application Programming Interface (OAPI) feature of the MATLAB® program is used as an interface tool between the Structural Analysis Program (SAP2000®), and the mentioned program, the programming language software, to perform the optimization.

Table 3 The LPOA parameters

Parameter	Value
Number of Prides	3-7
Lions in each prides	4-7
Male lions in each prides	1-2
Female lions in each prides	3-6
Territory ratio	0.2
Mating probability	0.1
Immigration rate	0.2
diversification factor	0.1 to 0.0001

Table 4 Sectional designations of the best design solution obtained by LPOA

Segment	Section	b_f	t_f	D_w	t_w	t_b	Mass per length (kg/m)
S1	A1	0.3	0.015	1.2	0.01	0.01	351.89
	A2	0.3	0.015	1.2	0.01	0.015	398.33
S2	A3	0.3	0.015	1.9	0.01	0.015	479.59
	A4	0.3	0.015	1.6	0.01	0.015	444.76
S3	A5	0.3	0.015	1.6	0.01	0.01	403.78
S4	A6	0.3	0.015	1.6	0.01	0.015	444.76
S5	A7	0.3	0.02	1.6	0.01	0.01	427.33
	A8	0.3	0.025	1.6	0.01	0.02	532.84
S6	A9	0.3	0.025	1.9	0.01	0.02	563.58
	A10	0.3	0.025	0.9	0.01	0.02	461.12
S7	A11	0.3	0.015	0.9	0.01	0.01	312.97
S8	A12	0.3	0.015	0.9	0.01	0.01	312.97

Table 5 Comparison of LPOA results with hand design and optimum designs obtained by PSO, CS and HS

Segment	solution (ton)	Average (ton)	Standard deviation (ton)	Functional evaluation
LPOA	29.40	32.61	2.68	6000
GWO	35.11	36.94	2.30	6000
ALO	37.53	40.28	3.71	6000
CS	32.77	N.A.	N.A.	7000
PSO	33.34	N.A.	N.A.	7000
HS	38.36	N.A.	N.A.	7000
Hand design	37.69	-	-	-

Finally, parameter values of the LPOA in the evaluation of the bridge design problem are depicted in Table 3. The numbers of pride members selected randomly from 4 to 8 and each pride has one or two male members. Also, the diversification factor decreases to 10^{-4} in the end. In addition, twenty lions are used for finding the optimum solutions and five individual optimization runs have been carried out for the design example.

5. Optimum design solution

The convergence curves of the goal function versus iteration number for the best try of LPOA, GWO, and ALO are shown in Fig. 5. Notably, 10 independent runs performed to solve the design problem. This figure shows that the LPOA has better performance as the speed of convergence and shows the fastest convergence rate compared to other algorithms studied for this problem.

The best optimal design solution of the discussed practical problem, obtained by LPOA, is tabulated in Table 4 and the comparison of the results of the mentioned algorithms are shown in Table 5. This table shows that the LPOA algorithm outperforms other metaheuristics (best in minimum, average, and standard deviation). In addition, the LPOA obtained the optimum design with less number of analyses (function evaluation) in compare to CS, PSO, and HS. The best optimal weight of the girder obtained by LPOA is 29.4 which is better than the conventional design and the results of other considered algorithms.

The dominance of the design constraints in controlling the final optimized results of LPOA is also investigated as the following. Furthermore, trapezoidal steel boxes' geometric requirements which were mentioned in subsection 3.5.1, are depicted in Fig. 7 and Table 6. The figure shows that g_4 is ineffective to control the optimization method. In contrast, other geometric constraints have an impact in the design solution.

Table 6 Geometry constraints of each section for optimal design obtained by LPOA

Segment	Section	g_1	g_2	g_3	g_4
S1	A1	1.00	0.60	0.87	0.37
	A2	1.00	0.60	0.87	0.37
S2	A3	1.00	0.95	0.87	0.58
	A4	1.00	0.80	0.87	0.49
S3	A5	1.00	0.80	0.87	0.49
S4	A6	1.00	0.80	0.87	0.49
S5	A7	0.75	0.80	0.65	0.49
	A8	0.60	0.80	0.52	0.49
S6	A9	0.60	0.95	0.52	0.58
	A10	0.60	0.45	0.52	0.28
S7	A11	1.00	0.45	0.87	0.28
S8	A12	1.00	0.45	0.87	0.28
Min		0.60	0.45	0.52	0.28
Max		1.00	0.95	0.87	0.58
Average		0.88	0.70	0.76	0.43
Standard deviation		0.17	0.18	0.15	0.11

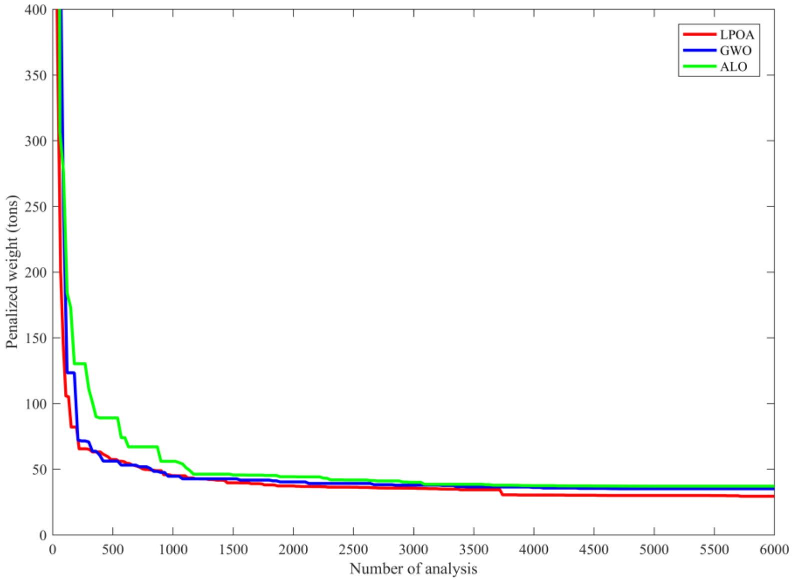


Fig. 5 Comparative of the convergence curves of LPOA, GWO, and ALO for the design of the multi-span composite box girder bridge

The flexural stress limitations of steel box flanges, described in 3.5.2, and shear stress limitation of steel box girders, detailed in 3.5.4, is depicted in Figs. 7 and 8 respectively. According to these figures, two constraints of shear stress of webs and flexural stress of flanges are effective to the optimal weight of a girder. The compressive stress limitation of concrete slab deck, described in 3.5.3, and the serviceability constraint described in 3.5.5. are depicted in Figs. 9 and 10. These figures show that the two mentioned constraints are not effective on optimization procedure.

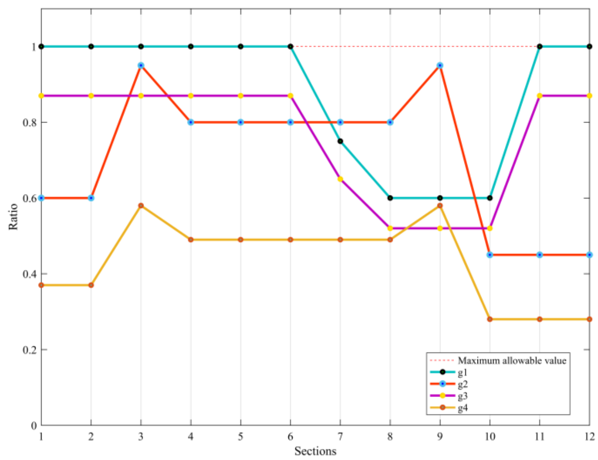
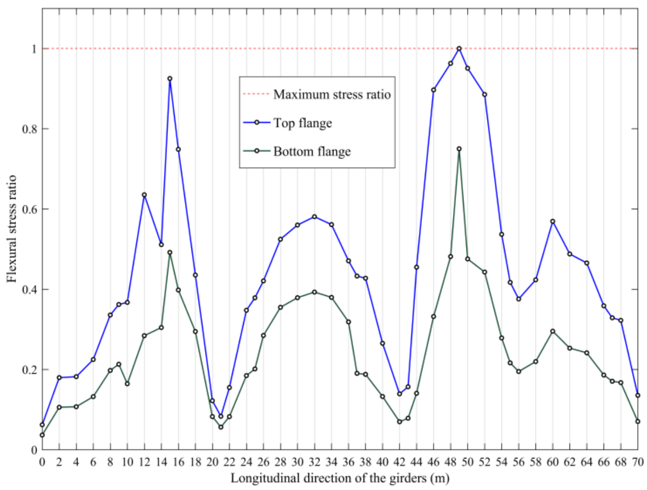


Fig. 6 Geometry constraints of each section for optimal design obtained by LPOA



Fig, 7 Flexural stress constraints of the top and bottom flanges of each section for optimal design obtained by LPOA

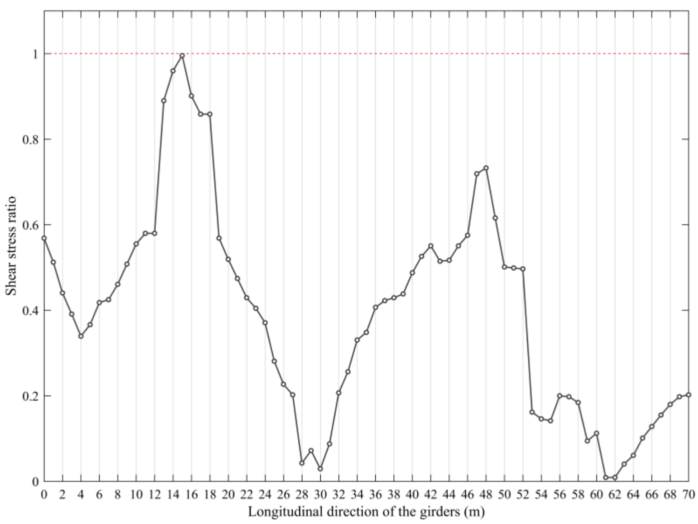


Fig. 8 Shear stress limitations of webs of each section for optimal design obtained by LPOA

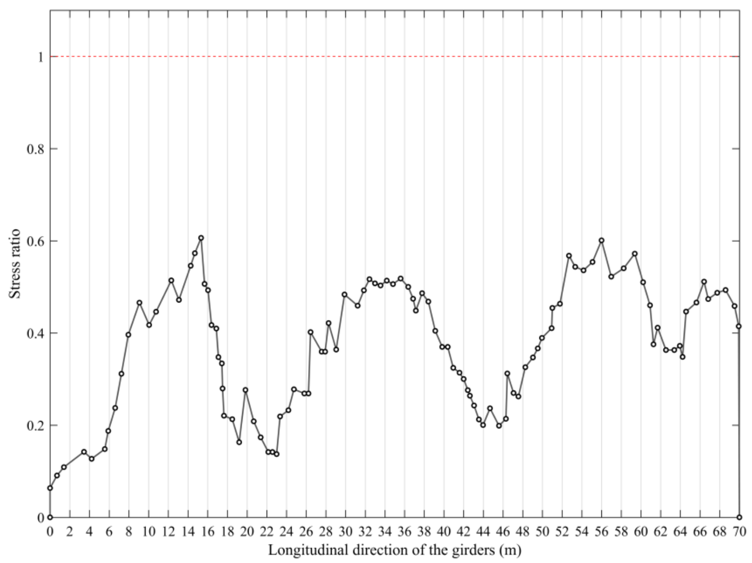


Fig. 9 Compressive stress limitations of the concrete slab for the optimal design by LPOA

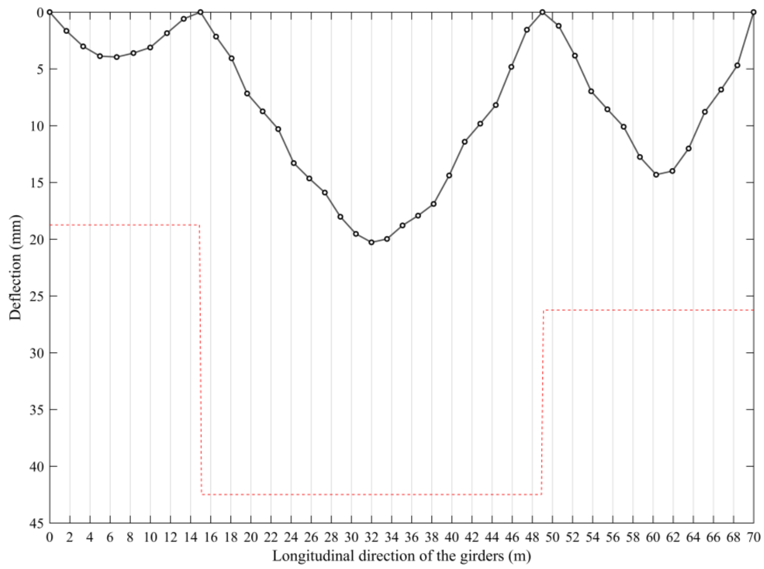


Fig. 10 Deflection limitations of the composite bridge for optimal design obtained by LPOA

6. Conclusions

In this study, the discrete optimization design of a composite multi-span steel box girder bridge is performed based on AASHTO code using a nature-based non-gradient optimization technique, the Lion Pride Optimization algorithm. The composite steel box girder bridge is a reinforced concrete slab, on top of a single or multiple steel box girders and all members act together compositely. The design example has a 30-dimensional design vector that contains the dimensions of girders.

The results show that the lion pride optimization algorithm has a high ability in finding the optimum solution of the considered design example. Additionally, the LPOA requires less number of function evaluations compared to the PSO, CS and HS optimization techniques. The best optimal weight of the girder obtained by LPOA is 29.4 ton which is better than the conventional design (37.69 ton), and the results of the other metaheuristic algorithms. Finally, the dominance of the design constraints in controlling the final optimized results of the LPOA are depicted in details.

It should be mentioned that, SAP2000 program is used to model and analyze the composite bridge and MATLAB program is utilized as the coding tool for developing the optimization technique. The Open Application Programming Interface (OAPI) is used as a third-party to integrate MATLAB, with SAP2000 to optimize the considered steel box girder bridge.

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