Steel and Composite Structures, *Vol. 26, No. 2 (2018) 163-170*
DOI: https://doi.org/10.12989/scs.2018.26.2.163

Jaya algorithm to solve single objective size optimization problem for steel grillage structures

Tayfun Dede *

Department of Civil Engineering, Faculty of Engineering, Karadeniz Technical University, Trabzon, Turkey

(*Received August 11, 2017, Revised October 21, 2017, Accepted November 16, 2017*)

Abstract. The purpose of this paper is to present a new and efficient optimization algorithm called Jaya for optimum design of steel grillage structure. Constrained size optimization of this type of structure based on the LRFD-AISC is carried out with integer design variables by using cross-sectional area of W-shapes. The objective function of the problem is to find minimum weight of the grillage structure. The maximum stress ratio and the maximum displacement in the inner point of steel grillage structure are taken as the constraint for this optimization problem. To calculate the moment and shear force of the each member and calculate the joint displacement, the finite elements analysis is used. The developed computer program for the analysis and design of grillage structure and the optimization algorithm for Jaya are coded in MATLAB. The results obtained from this study are compared with the previous works for grillage structure. The results show that the Jaya algorithm presented in this study can be effectively used in the optimal design of grillage structures.

Keywords: grillage structures; jaya optimization; LRFD-AISC; W-shapes

1. Introduction

Structural optimization problem has been investigated in many studies. The main purpose of this problem is to obtain minimum or maximum values of objective function such as minimum weight of total structure, maximum buckling load, maximum frequency or minimum cost of the structures. As a structure member, grillage systems are widely used in structures to cover large areas. These structures are generally optimized for the minimum weight of the total structures by selecting a discrete set of the available steel profiles. Displacement of the middle point and the stress ratio of the all grillage member are taken as constraint of the optimization problem. Until now, some researchers deal with the optimization of these structures. Kaveh and Talatahari (2010a) presented a study by using a meta-heuristic optimization technique named as charged system search (CSS). This algorithm inspired by the governing laws of electrostatics in physics and the governing laws of motion from the Newtonian mechanics (Kaveh and Talatahari 2010b). A study was conducted by Saka *et al*. (2000) to find optimum spacing of grillage structure by using genetic algorithm (GA). Application of GRID computing for optimization of grillages was presented by Šešok *et al*. (2010a). Using simulated annealing and high performance computing, global optimization of grillage structures was given by Šešok *et al.* (2010b). Ramanauskas *et al*. (2017) proposed a new genetic algorithm with modified crossover operator for the optimization of grillage structures. Saka and Erdal (2009), and Erdal and Saka (2008) used the harmony search (HS) to design the grillage structure.

The aim of the optimization algorithms is to find global optimal results with certain design variables. Also, the number of function evaluation and the CPU time used by the optimization algorithms are the most important parameters when comparing the performance of the selected algorithm. Among these optimization algorithms genetic algorithm (GA), ant colony optimization (ACO), particle swarm optimization (PSO), harmony search (HS) and simulated annealing (SA) are the most popular optimization algorithms. GA, which is a search strategy that models mechanism of genetic evolution, was first described by John Holland in the 1960s, and further developed by Holland and his students (Holland 1975, Goldberg 1989).

Artificial Bee Colony Algorithm (ABCA) is used to optimize the stacking sequences of simply supported antisymmetric laminated composite plates with critical buckling load as the objective functions by Topal and Öztürk (2014). Ant colony optimization inspired by the foraging behavior exhibited by real ant colonies was proposed by Dorigo (1991) for the solution of hard combinatorial optimization problems. Kaveh and Mahdavi (2015) developed meta-heuristic algorithm, called Colliding Bodies Optimization (CBO), for size and topology optimization of steel trusses. Social spider optimization algorithm with spider jump technique is used for the Optimum design of steel space structures by Aydogdu *et al.* (2017). The particle swarm optimization which is based on the behavior of animals was first developed by Kennedy and Eberhart (1995). This algorithm simulates a simplified social model. Fish schooling, physical movement of birds to avoid predators, and seeking food of insect are example of

*Corresponding author, Ph.D., Associate Professor,
E-mail: tayfundede@gmail.com

http://www.techno-press.org/?journal=scs&subpage=6
ISSN: 1229-9367 (Print), 1598-6233 (Online)

social sharing of information of animals. Harmony search developed by Geem *et al.* (2001) as an optimization algorithm is based on natural musical performance processes that take place when a musician searches for a better state of harmony (Kaveh and Abadi 2011). Simulated annealing was produced independently by Kirkpatrick *et al.* (1983) and Černý (1985). This algorithm simulates the annealing process of metals to solve optimization problems. A comparative study on optimum design of multi-element truss structures using Harmony Search (HS) and Genetic Algorithms (GA) is presented by Artar (2016a). Zula *et al.* (2016) studied on the MINLP optimization of a composite I beam floor system. Design of steel frames by an enhanced moth-flame optimization algorithm is made by Gholizadeh *et al.* (2017). Optimum design of braced steel frames via teaching learning based optimization and optimization of long span portal frames using spatially distributed surrogates have been presented by Artar (2016b) and Zhang *et al.* (2017), respectively.

In this study, a new optimization algorithm named as Jaya (a Sanskrit word meaning victory) is used to optimize the grillage structures. This new technique originally was developed by Rao (Rao *et al.* 2016). In the optimization process, displacements, moments and shear force constraints are taken into account as defined in the LRFD-AISC (Load and Resistance Factor Design-American Institute of Steel Construction) constraints.

2. Jaya algorithm

In the Jaya algorithm, based on the best and worst solutions in the current population, the new solutions are created for the new population by using the Eq. (1).

$$X'_{i,j,k} = X_{i,j,k} + r_{1,i,k}(X_{i,best,k} - |X_{i,j,k}|) - r_{2,i,k}(X_{i,worst,k} - |X_{j,j,k}|) \tag{1}$$

$X_{i,j,k}$ is the value of the i^{th} variable for the j^{th} candidate (solution) during the k^{th} iteration, $X_{i,best,k}$ and $X_{i,worst,k}$ are the values of the i^{th} variable for the best and worst candidate during the k^{th} iteration, respectively. $r_{1,i,k}$ and the $r_{2,i,k}$ are the random numbers in the range [0, 1]. The simple MATLAB code can be given by the following Equations.

$$\begin{aligned}
&for\ \ m = 1{:}P_n \\
&\quad pop_{new}(m,:) = pop(m,:) + \\
&\quad rand(1,D_n).*(pop_{best} - abs(pop(m,:))) - \\
&\quad rand(1,D_n).*(pop_{worst} - abs(pop(m,:))) \\
&end
\end{aligned} \tag{2}$$

$X_{i,j,k}$ is the value of the i^{th} variable for the j^{th} candidate (solution) during the k^{th} iteration, $X_{i,best,k}$ and $X_{i,worst,k}$ are the values of the i^{th} variable for the best and worst candidate during the k^{th} iteration, respectively. $r_{1,i,k}$ and the $r_{2,i,k}$ are the random numbers in the range [0, 1]. The simple MATLAB code can be given by the following Equations.

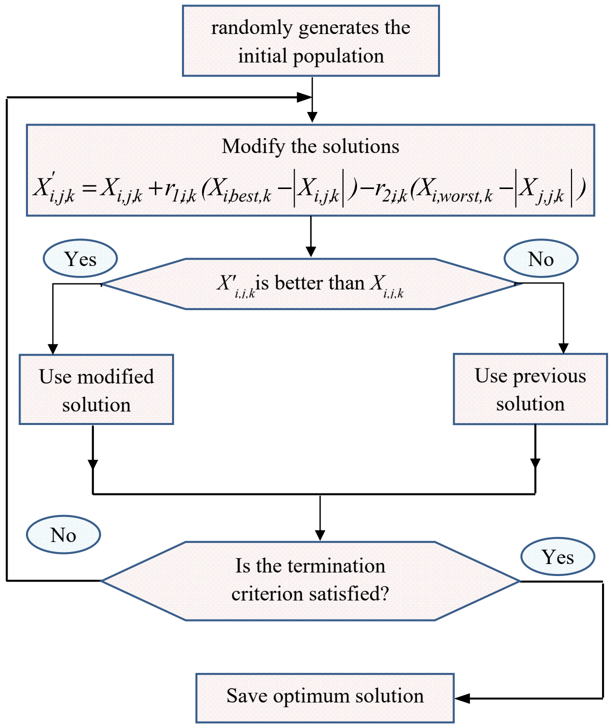

Fig. 1 Flow chart for Jaya algorithm

3. Objective function of the optimization problem

3.1 Finite element analysis of grillage structures

There are two rotational degrees and one translational degree of freedom in the node of the grillage member. These freedoms are shown in Fig. 2(a). For a grillage member, displacements vector "*D*" and joint forces vector "*F*" are given as

$$\begin{aligned}
\{D\} &= \{\theta_{xi}\ \ \theta_{yi}\ \ \delta_{zi}\ \ \theta_{xj}\ \ \theta_{yj}\ \ \delta_{zj}\} \\
\{F\} &= \{M_{xi}\ \ M_{yi}\ \ Q_{zi}\ \ M_{xj}\ \ M_{yj}\ \ Q_{zj}\}
\end{aligned} \tag{3}$$

Where M_{xi} and M_{yi} are the moments and the Q_{zi} is the shear force.

The element stiffness matrix k_e and transformation matrix T for a rigidly connected member shown in Fig. 2(b) are given in Eqs. (4) and (5), respectively.

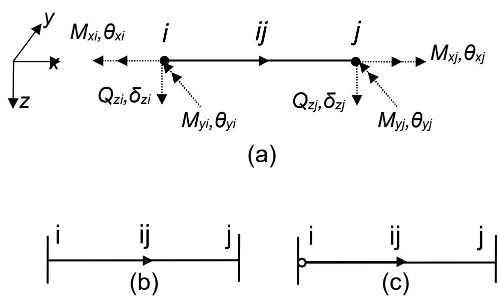

Fig. 2 A grillage member

$$[k]_e = \begin{bmatrix} \frac{GJ}{L} & 0 & 0 & -\frac{GJ}{L} & 0 & 0 \\ 0 & \frac{4EI}{L} & \frac{6EI}{L^2} & 0 & \frac{2EI}{L} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{12EI}{L^3} & 0 & \frac{6EI}{L^2} & -\frac{12EI}{L^3} \\ -\frac{GJ}{L} & 0 & 0 & \frac{GJ}{L} & 0 & 0 \\ 0 & \frac{2EI}{L} & \frac{6EI}{L^2} & 0 & \frac{4EI}{L} & -\frac{6EI}{L^2} \\ 0 & -\frac{6EI}{L^2} & -\frac{12EI}{L^3} & 0 & -\frac{6EI}{L^2} & \frac{12EI}{L^3} \end{bmatrix} \tag{4}$$

$$[T] = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 & 0 & 0 & 0 \\ -\sin\alpha & \cos\alpha & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -\frac{GJ}{L} & 0 & 0 & \cos\alpha & \sin\alpha & 0 \\ 0 & 0 & 0 & -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Where G is shear modulus, J is torsional constant, L is length of grillage member, E is modulus of elasticity, and I is moment of inertia. If there is a hinge in the grillage element (Fig. 2(c)), the stiffness matrix must be changed. For a grillage member with a hinge at the first end ($M_{yi} = 0$), the element stiffness matrix and the joint forces vector are given as

$$[k]_e = \begin{bmatrix} \frac{GJ}{L} & 0 & -\frac{GJ}{L} & 0 & 0 \\ 0 & \frac{3EI}{L^3} & 0 & \frac{3EI}{L^2} & -\frac{3EI}{L^3} \\ -\frac{GJ}{L} & 0 & \frac{GJ}{L} & 0 & 0 \\ 0 & \frac{3EI}{L^2} & 0 & \frac{3EI}{L} & -\frac{3EI}{L^2} \\ 0 & -\frac{3EI}{L^3} & 0 & -\frac{3EI}{L^2} & \frac{3EI}{L^3} \end{bmatrix} \tag{6}$$

$$\{F\} = \{M_{xi} \;\; Q_{zi} \;\; M_{xj} \;\; M_{yj} \;\; Q_{zj}\} \tag{7}$$

In this case, the second column and second raw of transformation matrix must the extracted from the transformation matrix.

3.2 Design of grillage structures to LRFD – AISC

A beam member as a structural element of grillage structures is designed for flexure and shear as defined in LRFD-AISC (1999). The design strength for flexural members is $\phi_b M_n$, where ϕ_b is the resistance factor for flexure which is given as 0.90, and M_n is the nominal flexural strength which is computed as

$$M_n = \begin{Bmatrix} M_p = F_y Z \le 1.5 F_y S & for \;\; \lambda \le \lambda_p \\ M_p - (M_p - M_r)(\frac{\lambda - \lambda_p}{\lambda_r - \lambda_p}) & for \;\; \lambda_p < \lambda \le \lambda_r \\ M_{cr} = F_{cr} S & for \;\; \lambda > \lambda_r \end{Bmatrix} \tag{8}$$

In this equation, M_p is plastic moment, F_y is specified minimum yield strength, Z is plastic section modulus, S is section modulus, M_{cr} is buckling moment, and M_r is limiting buckling moment which is given as

$$M_r = \begin{cases} F_L S_x & for \;\; FLB \\ R_e F_{yf} S_x & for \;\; WLB \end{cases} \tag{9}$$

where F_L is smaller of $[(F_{yf} - F_r)$ or $F_{yw}]$,*FLB*: flange local buckling, *WLB*: web local buckling, F_r is compressive residual stress in flange which is given as 10 ksi (69 N/mm^2) for rolled shapes, F_{yf} is yield strength of flange, F_{yw} is yield strength of web, and R_e is hybrid girder factor which is given as 1.0 for non-hybrid girders. F_{cr} is critical stress and it is given as for rolled shapes LRFD-AISC (1999).

$$F_{cr} = \frac{0.69E}{\lambda^2} \tag{10}$$

Where, λ is slenderness parameter, λ_p is the largest value of λ for which $M_n = M_p$, λ_r is the largest value of λ for which buckling is inelastic and they are given as,

$$\lambda = \begin{cases} b_f/(2t_f) & for \;\; flange \\ h/t_w & for \;\; web \end{cases} \tag{11}$$

Where b_f and t_f are the width and thickness of flange, respectively. h is clear distance between flanges less the fillet or corner radius, and t_w is thickness of web. The values of $b_f/(2t_f)$ and h/t_w can be taken from the tables of the properties of W-shapes.

$$\lambda_p = \begin{cases} 0.38\sqrt{\frac{E}{F_y}} & for \;\; compressive \;\; flange \\ 3.76\sqrt{\frac{E}{F_y}} & for \;\; web \end{cases} \tag{12}$$

$$\lambda_r = \begin{cases} 0.83\sqrt{\frac{E}{F_y}} & for \;\; compressive \;\; flange \\ 5.70\sqrt{\frac{E}{F_y}} & for \;\; web \end{cases} \tag{13}$$

Minimum value of M_n computed for flange or web according to the values of λ is taken as the nominal moment strength for the section under consideration. The design shear strength of web is $\phi_v V_n$, where ϕ_v is the resistance factor for shear which is given as 0.90, and V_n is the nominal shear strength which is computed as

$$V_n = \begin{cases} 0.6F_{yw}A_w \\ \quad\quad for \ \frac{h}{t_w} \le 2.45\sqrt{E/F_{yw}} \\ 0.6F_{yw}A_w(2.45\sqrt{E/F_{yw}})/\frac{h}{t_w} \\ \quad\quad for \ \ 2.45\sqrt{E/F_{yw}} < \frac{h}{t_w} \le 3.07\sqrt{E/F_{yw}} \\ A_w(4.52E)/(\frac{h}{t_w})^2 \\ \quad\quad for \ \ 3.07\sqrt{E/F_{yw}} \le \frac{h}{t_w} < 260 \end{cases} \tag{14}$$

where A_w is cross sectional area of web.

3.3 Optimization process of grillage structures

The objective function for the grillage structure can be formulated as

$$\min W = \sum_{k=1}^{ng} Ak \sum_{z=1}^{nk} \rho_z L_z \tag{15}$$

Where, W is the objective function which is also the minimum weight of the structure, ρ is the density of materials, A is the cross-section area of the each member, nk is the number of member belonging to the group k in grillage structures, and ng is the number of group. When the grillage system is optimized, the displacement and strength constraints are taken into account.

$$\delta_i \le \delta_u, \quad c_{\delta,i} = \frac{\delta_i}{\delta_u} \rightarrow \quad i = 1,2,\ldots,p \tag{16}$$

$$M_{u,j} \le (\phi_b M_{n,u}), \quad c_{m,j} = \frac{M_{u,j}}{\phi_b M_{n,u}} \rightarrow \quad j = 1,2,\ldots,nm \tag{17}$$

$$V_{u,j} \le (\phi_v V_{n,u}), \quad c_{m,j} = \frac{V_{u,j}}{\phi_v V_{n,u}} \rightarrow \quad j = 1,2,\ldots,nm \tag{18}$$

Where δ_i and δ_u are the calculated and allowable displacement for point "*i*", respectively. p is the number of points with restricted displacements. $M_{u,i}$ and $V_{u,i}$ are the factored service load moment and the factored service load shear for member "*j*", respectively. nm is the total number of member of the structure.

To obtain an unconstraint objective function a penalty function calculating value of violation of constraints is determined. By means of this function, the objective function is changed to a function including constraints. Penalty function is calculated as the summation of the violation of displacement, moment and shear constraints.

$$C = \sum_{i=1}^{p} c_{\delta,i} + \sum_{j=1}^{n} (c_{m,j} + c_{v,j}) \tag{19}$$

Where, m is the number of the constraints. Objective function is changed to penalized objective function by adding penalty function to it. The penalized objective function, Φ, can be formulated as

$$\Phi = W[1+C] \tag{20}$$

At the end of the optimization process, penalized objective function must be equal to the objective function W.

4. Numerical examples

To show the efficiency of the Jaya algorithm, grillage systems from literature are considered. The material properties of all grillage structures are A 36 mild steel. The other material properties; yield stress is 250 Mpa, modulus of elasticity is 205 kN/mm^2, and shear modulus is 81 kN/mm^2. W-sections are used to optimize this example as a discrete set of the available steel profiles. Allowable displacement is 25 mm for all examples.

As a first example, 23 member grillage, whose members are collected in three groups, is given in Fig. 3. The outer and inner longitudinal beams are considered to be group 2 and group 3, respectively, and the all transverse beams are considered to be group 1. The external loading for F_1, F_2 and F_3 are 50 kN, 100 kN and 200 kN, respectively. The length of transverse beams is 4 m (Ly = 2×2 m), and the length of longitudinal beams is 10 m (Lx = 5×2 m).

Weight of this structure is obtained as 4,644kg with Jaya while it is 4,718.40 kg, 4,488 kg, and 4,688 kg for the HS (Erdal 2007), Saka and Erdal (2009), and for the TLBO (Dede 2013), respectively. The maximum strength ratio is 0.69 (Rmax) and displacement is 24.83 mm. Comparison of the results with those of HS (Erdal 2007), Saka and Erdal (2009), and Dede (2013) is given in Table 1.

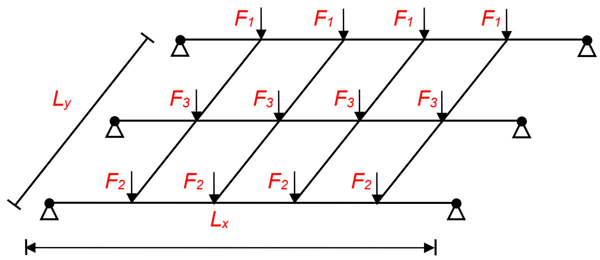

Fig. 3 23-member grillage structure

Table 1 Comparison for the 23-member grillage structure

Element group	Erdal (2007)	Saka and Erdal (2009)	Dede (2013)	This study
	(HS)	(HS)	(TLBO)	(Jaya)
1	W150×13.5	W150×13.5	W150×13.5	W150×13.5
2	W840×176	W690×125	W690×125	W760×134
3	W530×66	W846×176	W840×193	W840×176
δ_{max}(mm)	24.5	25.0	24.83	22.97
R_{max}	0.79	0.77	0.69	0.75
W (kg)	4,718	4,488	4,668	4,644

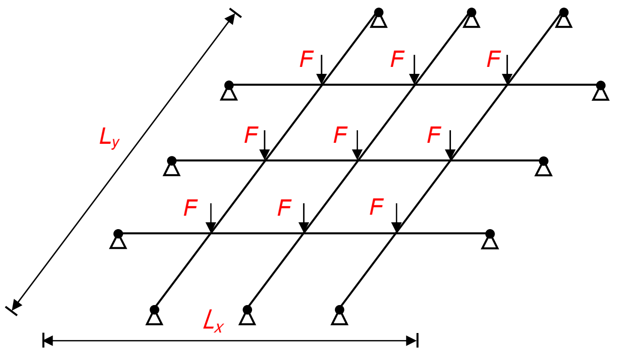

Fig. 4 24-member grillage structure

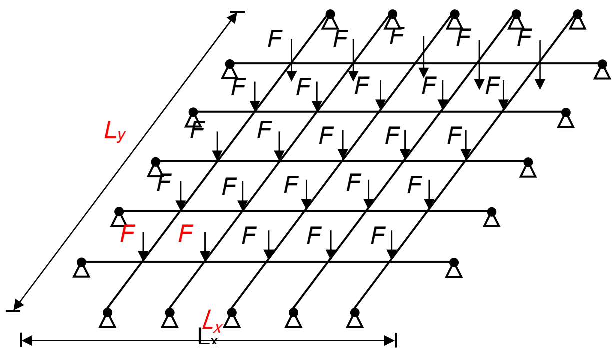

Fig. 5 60-member grillage structure

Table 2 Comparison for the 24-member grillage structure

Element group	Erdal and Saka (2008) (HS)	Dede (2013) (TLBO)	This study (Jaya)
1	W610×174	W150×13.5	W150×13.5
2	W610×262	W920×253	W1000×249
δ_{max} (mm)	15.6	23.33	21.16
R_{max}	0.99	0.59	0.58
W (kg)	15,712	9,616	9,447

As seen from this table, the minimum weight is obtained by Saka and Erdal (2009) with the algorithm HS, but the maximum vertical displacement obtained from this solution is so close to its bound. The weight of structure obtained by using Jaya is lighter than the design by the HS (Erdal 2007), TLBO (Dede 2013) and is heavier than that of the Saka and Erdal (2009).

The second example is the 24-member grillage structure is shown in Fig. 4. The transverse beams are considered to be group 2 and the longitudinal beams are considered to be group 1. The loading for all inner joints is 240 kN. The length of all beams is 12 m (Lx = Ly = 4×3 m).Weight of this structure is obtained as 9,447 kg by using Jaya in this study while it is 15,712 kg for the HS (Erdal and Saka 2008) and 9,616 kg for TLBO (Dede 2013). The maximum strength ratio is 0.59 and maximum displacement is 23.33 mm. Comparison of the results with those of HS (Erdal and Saka; 2008) and TLBO (Dede 2013) is given in Table 2. As seen from this table, the minimum weight of structure obtained by using Jaya algorithm.

Another example is 60-member grillage structure shown in Fig. 5. This example is optimized for two different cases. Member of structure are collected in two groups and four groups for case I and case II, respectively. Definitions of the groups can be found the study Dede (2013).

The external loading for all inner joints is 86.4 kN. The length of each beam is 12 m (Lx = Ly = 6×2 m), beam spacing is 2 m in all directions, and this grillage structure covers a square area of 12 m by 12 m for each case.

For case I, weight of this structure is obtained as 11,358.00 kg with Jaya, while it is 14,384.00 kg for the HS (Erdal and Saka 2008). The results are the same as TLBO (Dede 2013). For case II, the minimum weight of this structure is obtained as 9,153 kg with Jaya, while it is 9,251.00 kg for CSS (Kaveh and Talahatari 2010a). The maximum strength ratio is 0.97 and maximum displacement is 24.19 mm. The results are given in Tables 3 and 4 for each case. As seen from these tables, the results obtained from this study (Jaya) are lighter than the results obtained harmony (HS) search, Charged System Search (CSS) and equal to the TLBO (Dede 2013).

Table 3 Comparison for the 60-member grillage structure (two groups)

Element group	Erdal and Saka (2008) (HS)	Dede (2013) (TLBO)	This study (Jaya)
1	W200×22.5	W150×13.5	W150×13.5
2	W690×217	W840×176	W840×176
δ_{max} (mm)	25.0	24.2	24.2
R_{max}	0.48	0.54	0.54
W (kg)	14,384	11,358	11,358

Table 4 Comparison for the 60-member grillage structure (four groups)

Element group	Kaveh and Talahatari (2010) (CSS)	Dede (2013) (TLBO)	This study (Jaya)
1	W150×13.5	W150×13.5	W150×13.5
2	W910×201	W920×201	W920×201
3	W300×21	W310×23.8	W310×23.8
4	W300×32.5	W310×28.3	W310×28.3
δ_{max} (mm)	24.3	24.19	24.19
R_{max}	0.99	0.97	0.97
W (kg)	9,251	9,153	9,153

The last example is the 112-member grillage structure shown in Fig. 6. Member of this structure is collected in two cases as defined by Dede (2013). The external loading for all inner joints is 44.1 kN, the length of each beam is 12 m (Lx = Ly = 8×1.5 m), beam spacing is 1.5 m in all directions.

For case I, minimum weight of this structure is obtained as 13,471 kg with Jaya, while it is 16,198 kg and 13,519 kg

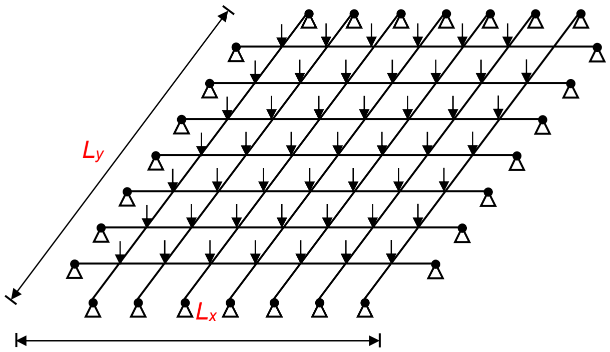

Fig. 6 112-member grillage structure

Table 5 Comparison for the 112-member grillage structure (two groups)

Element group	Erdal and Saka (2008) (HS)	Kaveh and Talahatari (2010) (CSS)	Dede (2013) (TLBO)	This study (Jaya)
1	W690×170	W150×13.5	W150×13.5	W150×13.5
2	W200×22.5	W770×147	W760×147	W760×147
δ_{max} (mm)	24.1	24.3	24.07	24.07
R_{max}	0.45	0.45	0.48	0.48
W (kg)	16,198	13,519	13,471	13,471

Table 6 Comparison for the 112-member grillage structure (four groups)

Element group	Erdal and Saka (2008) (CSS)	Dede (2013) (TLBO)	This study (Jaya)
1	W150×13.5	W150×13.5	W150×13.5
2	W840×176	W760×161	W310×21
3	W150×13.5	W150×13.5	W150×13.5
4	W300×21	W250×17.9	W760×161
δ_{max} (mm)	24.4	23.45	23.92
R_{max}	0.75	0.92	0.74
W (kg)	11,548	11,329	11,527

for the HS (Erdal and Saka 2008) and CSS (Kaveh and Talahatari 2010a), respectively. The maximum strength ratio is 0.48 and maximum displacement is 24.07 mm. For case II, minimum weight of this structure is obtained as 11,329 kg with Jaya, while it is 11,548 kg for the CSS (Kaveh and Talahatari 2010a). The maximum strength ratio is 0.92 and maximum displacement is 23.45 mm. The results are given in Tables 5 and 6 for each case. As seen from these tables, the results obtained from this study (Jaya) are lighter than the results obtained harmony (HS) search, Charged System Search (CSS) and heavier than the TLBO (Dede 2013).

In this study, the proposed algorithm was run in a personal computer havingIntel(R) Core(TM) i5-3470 CPU @3.20 GHz 8,00 GB RAM. To show the performance of

Table 7 Optimization parameters

Example	Size of population	Design variables: Type	Design variables: Size	Constraints: Displacement	CPU time
23 member	30	discrete	3	≤ 25 mm	111.34s
24 member	30	discrete	2	≤ 25 mm	99.56s
60 member (2 group)	30	discrete	2	≤ 25 mm	219.64s
60 member (4 group)	40	discrete	4	≤ 25 mm	815.53s
112 member (2 group)	30	discrete	2	≤ 25 mm	111.34s
112 member (4 group)	30	discrete	4	≤ 25 mm	385.34s

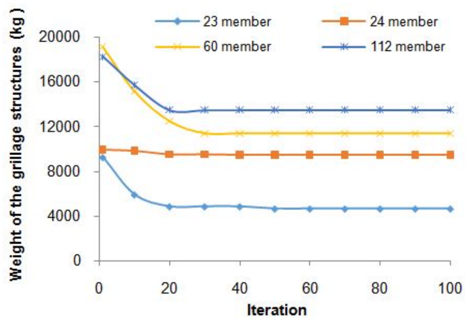

Fig. 7 History of the best solutions of all grillage structures

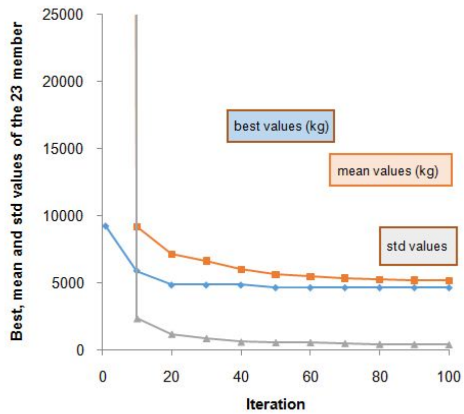

Fig. 8 Best, mean and *std* solutions of 23 member grillage

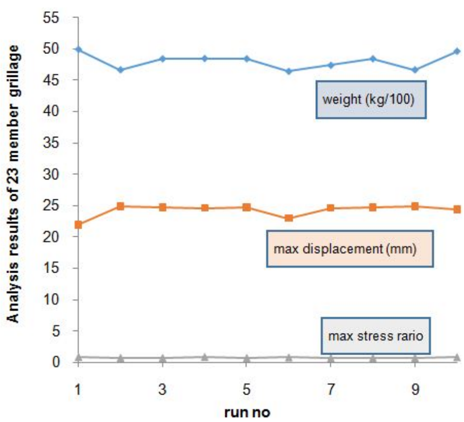

Fig. 9 Analysis results of 23 member grillage structures

the developed algorithm the constraints, number of design variables, the CPU times and the size of optimization model are given in Table 7.

As seen from the Tables 1-6, the jaya algorithm generally found a good result when it compared with the other optimization technique. This case shows the efficiency of this algorithm. In the last example, the results obtained by jaya are not the best, but it is so close to the optimum results.

It will not always be possible to say that an algorithm will yield the best results compared to other algorithms. But performance measures such as CPU time and population size are taken into account for preferring the algorithm. In the view of this point, applying the Jaya algorithm on the optimization of structural optimization problem is simple. It does not require much computation time and effort.

The convergence history for all grillage structures are given in Fig. 7. As seen from this figure, the convergence is achieved after about 30 generations.

To demonstrate the robustness and efficiency the Jaya algorithm, the best and the mean values of objective function for 23 member grillage structures are given in the Fig. 8. As seen from this figure, the best and the mean solutions have a convergence and the standard derivation of solutions becomes a small value when the best solution getting close to the global optimum.

For different 10 run, in the design process, the maximum displacement, maximum stress ratio and the total weight of the 23 member grillage structures are given in the Fig. 8. As seen from this figure, the constraint of the optimization problem is not violated for al run cases. Also, the weights of the structure obtained from 10 run are close to each other.

5. Conclusions

In this study, a recently proposed new optimization technique called Jaya algorithm is implemented for the optimization of steel grillage structures. By taking into account two different structural constraints which are the joint displacement and stress ratio, the original jaya algorithm is tested for the constrained single objective problem. The steel grillage structures are optimized by taking into account the LRFD-AISC. In the design, W-shapes are considered as design variables.

The jaya algorithm showed a good performance when searching minimum weight of the grillage system. It does not require control parameters as in other optimization technique. The design results are compared with the results given in literature. Comparison between the results clearly shows that the proposed algorithm named Jaya can be effectively used in the design of grillage structures.

References

Artar, M. (2016a), "Optimum design of braced steel frames via teaching learning based optimization", *Steel Compos. Struct., Int. J.*, **22**(4), 733-744.

Artar, M. (2016b), "A comparative study on optimum design of multi-element truss structures", *Steel Compos. Struct., Int. J.*, **22**(3), 521-535.

Aydogdu, I., Efe, P., Yetkin, M. and Akin, A. (2017), "Optimum design of steel space structures using social spider optimization algorithm with spider jump technique", *Struct. Eng. Mech., Int. J.*, **62**(3), 259-272.

Černý, V. (1985), "Thermodynamical approach to the travelling salesman problem: An efficient simulation algorithm", *J. Optim. Theory Appl.*, **45**(1), 41-51.

Das, M., Rudrapati, R., Ghosh, N. and Rathod, L. (2016), "Input Parameters optimization in EDM Process using RSM and Jaya Algorithm", *Int. J. Current Eng. Technol.*, **6**, 109-112.

Dede, T. (2013), "Optimum design of grillage structures to LRFD-AISC with teaching-learning based optimization", *Struct. Multidisc. Optim.*, **48**(5), 955-964.

Dorigo, M. (1991), "Ant Colony Optimization, New Optimization Techniques in Engineering", by Onwubolu, G.C. and Babu, B.V., Springer-Verlag Berlin Heidelberg, pp. 101-117.

Erdal, F. (2007), "Optimum design of grillage system using harmony search algorithm", M.S. Thesis; Middle East Technical University, Ankara, Turkey.

Erdal, F. and Saka, M.P. (2008), "Effect of beam spacing in the harmony search based optimum design of grillages", *Asian J. Civil Eng.*, **9**(3), 215-228.

Geem, Z.W., Kim, J.H. and Loganathan, G.V. (2001), "A new heuristic optimization algorithm: harmony search", *Simulation*, **76**(2), 60-68.

Gholizadeh, S., Davoudi, H. and Fattahi, F. (2017), "Design of steel frames by an enhanced moth-flame optimization algorithm", *Steel Compos. Struct., Int. J.*, **24**(1), 129-140.

Goldberg, D.E. (1989), *Genetic Algorithms in Search, Optimization and Machine Learning*, New York, USA.

Holland, J.H. (1975), *Adaptation in Natural and Artificial Systems*, The University of Michigan Press, Ann Arbor, MI, USA.

Kaveh, A. and Abadi, A.S.M. (2011), "Harmony search based algorithms for the optimum cost design of reinforced concrete cantilever retaining walls", *Int. J. Civil Eng.*, **9**(1), 1-8.

Kaveh, A. and Mahdavi, V.R. (2015), "Colliding bodies optimization for size and topology optimization of truss structures", *Struct. Eng. Mech., Int. J.*, **53**(5), 847-865.

Kaveh, A. and Talatahari, S. (2010b), "A novel heuristic optimization method: Charged system search", *ActaMechanica*, **213**(3), 267-289.

Kaveh, A. and Talatahari, S. (2010a), "Charged system search for optimum grillage design using the LRFD-AISC code", *J. Construct. Steel Res.*, **66**(6), 767-771.

Kennedy, J. and Eberhart, R. (1995), "Particle swarm optimization", *Proceedings of IEEE International Conference on Neural Networks*, Vol. 4 (held in Perth), pp. 1942-1948. Piscataway: IEEE Service Center.

Kirkpatrick, S., Gelatt, C.D. and Vecchi, M.P. (1983), "Optimization by simulated annealing", *Science*, **220**(4598), 671-680.

Kurada, R.R. and Kanadam, K.P. (2016), "Automatic Unsupervised Data Classification Using Jaya Evolutionary Algorithm", *Adv. Computat. Intel.: Int. J.* (*ACII*), **3**(2), 35-42.

LRFD-AISC, Manual of Steel Construction (1999), "Load and resistance factor design. Metric conversion of the second edition", Volume 1-2, AISC, Chicago, IL, USA.

Phulambrikar, S. (2016), "Solving combined economic emission dispatch solution using jaya optimization algorithm approach", *Int. Res. J. Eng. Technol. (IRJET)*, **3**(11), 501-512.

Ramanauskas, M., Sesok, D., Belevicius, R., Kurilovas, E. and Valentinavicius, S. (2017), "Genetic algorithm with modified crossover for grillage optimization", *Int. J. Comput. Commun. Control*, **12**(3), 393-401.

Rao, R.V. and Rai, D.P. (2017a), "Optimisation of welding processes using quasi-oppositional-based Jaya algorithm", *J. Experim. Theor. Artif. Intel.*, **29**, 1099-1117.

Rao, R.V. and Rai, D.P. (2017b), "Optimization of submerged arc welding process parameters using quasi-oppositional based Jaya algorithm", *J. Mech. Sci. Technol.*, **31**(5), 2513-2522.

Rao, R.V., Rai, D.P., Ramkumar, J. and Balic, J. (2016), "A new multi-objective Jaya algorithm for optimization of modern machining processes", *Adv. Production Eng. Manage.*, **11**(4), 271-286.

Rao, R.V., Rai, D.P. and Balic, J. (2017), "A multi-objective algorithm for optimization of modern machining processes", *Eng. Appl. Artif. Intel.*, **61**, 103-125.

Saka, M.P. and Erdal, F. (2009), "Harmony search based algorithm for the optimum design of grillage systems to LRFD-AISC", *Struct. Multidiscipl. Optimiz.*, **38**(1), 25-41.

Saka, M.P., Daloglu, A. and Malhasc, F. (2000), "Optimum spacing design of grillage systems using a genetic algorithm", *Adv. Eng. Software*, **31**(11), 863-873.

Šešok, D., Belevičius, R. Kačeniauskas, A. and Mockus, J. (2010a), "Application of GRID computing for optimization of grillages", *Mechanika*, **2**(82), 63-69.

Šešok, D., Mockus, J., Belevicius, R. and Kaceniauskas, A. (2010b), "Global optimization of grillages using simulated annealing and high performance computing", *J. Civil Eng. Manage.*, **16**(1), 95-101.

Topal, U. and Öztürk, H.T. (2014),"Buckling load optimization of laminated plates via artificial bee colony algorithm", *Struct. Eng. Mech., Int. J.*, **52**(4), 755-765.

Warid, W., Hizam, H., Mariun, N. and Abdul-Wahab, N.I. (2016), "Optimal power flow using the jaya algorithm", *Energies*, **9**(678), 1-18.

Zhang, Y., Yang, X., Cattani, C., Rao, R.V., Wang, S. and Phillips, P. (2016), "Tea category identification using a novel fractional fourier entropy and jaya algorithm", *Entropy*, **18**(77), 1-17.

Zhang, Z., Pan, J., Fu, J., Singh, H.K., Pi, Y.L., Wu, J. and Ra, R. (2017), "Optimization of long span portal frames using spatially distributed surrogates", *Steel Compos. Struct.*, *Int. J.*, **24**(2), 227-237.

Žula, T., Kravanja, S. and Klanšek, U. (2016), "MINLP optimization of a composite I beam floor system", *Steel Compos. Struct.*, *Int. J.*, **22**(5), 1163-1192.

CC

Nomenclature

A	:	cross-section area
b_f	:	width of flange
C	:	penalty function
D	:	vector of joint displacements
D_n	:	number of design variables
E	:	modulus of elasticity
F	:	joint forces
F_{cr}	:	critical stress
FLB	:	flange local buckling
F_y	:	yield strength
G	:	shear modulus
J	:	torsional constant
k	:	element stiffness matrix
M	:	moment
M_{cr}	:	buckling moment
M_n	:	nominal flexural strength
M_p	:	plastic moment
M_r	:	limiting buckling moment
pop	:	population
r	:	random vector
T	:	transformation matrix
t_f	:	thickness of flange
t_w	:	thickness of web
V	:	Shear force
V_n	:	nominal shear strength
W	:	objective function
WLB	:	web local buckling
X	:	a set of design variable
Z	:	plastic section modulus
ϕ_b	:	resistance factor
λ	:	slenderness parameter
ρ	:	density of materials
δ_u	:	allowable displacement
Φ	:	ffapenalized objective function