A FIREFLY ALGORITHM FOR OPTIMUM DESIGN OF CORRUGATED STEEL WEB BEAMS

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Abstract - In this study, the designation of corrugated steel web beams is formulated as optimum design problem. The minimum weights of these new generation steel beams are taken as the objective functions while the design constraints are respectively implemented from BS EN1993-1:2005 (Annex-D, Eurocode 3) ve DIN 18-800 Teil-1. Firefly stochastic optimization technique is used for obtaining the solution of the design problem. The thickness and height of web, distance between the peaks of the following two web curves, the width and thickness of flange will be considered as the problem design variables. The formulation of the design problem considering the limitations of the above mentioned turns out to be a discrete programming problem. Number of design examples considered to demonstrate the efficiency of the proposed algorithm.

Keywords - Structural optimization, corrugated web beams, stochastic searh methods, firefly algorithm.

I. INTRODUCTION

The use of long span steel beams results in a range of benefits, including flexible, free internal spaces and reduced foundation costs. Many large clear-span design solutions are also well adapted to simplify the integration of mechanical or utility services. Corrugated steel web beams provide economical solution and pleasing appearance for space structures. In steel construction applications, the web part of beam usually carries the compressive stress and transmits shear in the beam while the flanges support the applied external loads. By using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the load-carrying capability of the beam. In this case, the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability and deforms transversely. Corrugated structure of the web cross-section not only increases the resistance of the beam against to shear force and other possible local effects, but also prevents the buckling due to loss of moment of inertia before the plastic limit. This specific structure of the web leads to a decrease in the beam unit weight and increase in the load carrying capacity. These efficient construction materials, commonly used in developed countries over years, can be utilized at the roofs as an alternative to space truss and roof truss, at the slabs as floor beams or columns under axial force.

Although the designers are aware of the advantages of the composite systems to be produced with that beams, there is still not a detailed technical specification about their design and behavior. The first studies on the corrugated web beams were focused on the vertically trapezoidal corrugation. Elgaaly investigated the failure mechanisms of trapezoidal corrugation beams under different loading conditions, namely shear mode [1], bending mode [2]. They found that the web could be neglected in the beam bending design calculation due to its insignificant contribution to the beam's load-carrying capability. Besides that, the two distinct modes of failure under the effect of patch loading were dependent on the loading position and the corrugation parameters. These are found agreeable to the investigation by Johnson and Cafolla and were further discussed in their writings [3]. In addition, the experimental tests conducted by Li et al. [4] demonstrated that the corrugated web beam has 2 times higher buckling resistance than the plane web type. According to Pasternak et al., [5], the buckling resistance of presently used sinusoidal corrugated webs is comparable with plane webs.

II. DESIGN OF CORRUGATED STEEL WEB BEAMS

Corrugated web beams shown in Fig. 1 are built-up girders with a thin-walled, corrugated web and plate flanges.

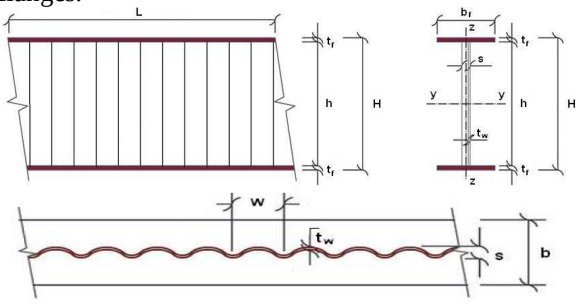


Figure 1. Geometric properties of Corrugated Web Beam

Design constraints include the displacement limitations, buckling capacities of web and flanges, bearing and torsional-flexural buckling capacities of flanges.

A. Transverse load carrying capacity of corrugated webs

Based upon the experimental tests and finite element analysis results, the following design procedure has been suggested: The corrugated web is regarded as an orthotropic plate with rigidities Dx and Dy. According to [5], the following formula therefore applies to the corrugated web:

$$D_x = \frac{E \times w \times t^3}{12 \times s},\ D_y = \frac{E \times I_y}{w} \text{ for } D_x \le D_y \quad (1)$$

For transverse buckling stress of corrugated web;

$$\tau_{EG} = \frac{162}{5 \times t_w \times h^2} \sqrt{(D_x \times D_y^3)} \quad (2)$$

For slenderness parameter of corrugated web;

$$\lambda_{GN} = \sqrt{\frac{f_y}{\sqrt{3} \times \tau_{EG}}} \quad (3)$$

With the buckling coefficient of corrugated web;

$$K_B = \frac{1}{(\lambda_{GN})^{3/2}} \quad (4)$$

the transverse force load carrying capacity for the corrugated web finally results in:

$$V_{TK-MAX} = \frac{K_B \times f_y \times h \times t_w}{\sqrt{3}} \quad (5)$$

A. Normal load carrying capacity of flanges

In determining the normal bearing force of the flanges, a distinction must be made between tensile and compressive stresses. In the case of tensile stress, the load carrying capacity of the flange is derived as follows:

$$\sigma_{ALLOW} = \frac{N_{T-MAX}}{b_f \times t_f} \quad (6)$$

Reformulation of the expression for ψ = 1 leads to the following elastic limit stress:

$$\sigma_{EL} = \frac{4000}{\left(b_f \times t_f\right)^2} \quad (7)$$

Therefore the reduced normal force on the flange:

$$N_{NORMAL} = \sigma_{EL} \times b_f \times t_f \quad (8)$$

Global failure of stability - lateral buckling of the flange - is equivalent to the verification against torsional-flexural buckling. If the restraining effect of the web is ignored, the torsional-flexural verification is carried out as the buckling verification for the "isolated" flange in accordance with [5]. The following condition for the distance between lateral supports is obtained:

$$\tau_{EG} = \frac{\pi}{4\sqrt{3}} \sqrt{E \times f_y} \times \frac{b_f^2 \times t_f}{k_c \times c} \quad (9)$$

III. METAHEURISTIC SEARCH TECHNIQUES IN OPTIMIZATION

The solution methods available among the mathematical programming techniques to obtain the optimum results for discrete programming problems are not very efficient for practical use. Fortunately, the emergence of innovative stochastic search techniques that are based upon the mimicking of paradigms found in nature has changed this situation altogether. The basic idea behind search techniques is to simulate natural phenomena, such as the survival of the fittest in genetic algorithms [6], flock migration in swarm intelligence [7], the shortest path to a food source in ant colony optimization [8], the cooling process of molten metals through annealing into a numerical algorithm [9], looking for prey in the hunting search algorithm [10], accelerations of charge particles in charged system search [11], the and the best harmony of instruments in the harmony search technique [12]. All of them are automated by nature to achieve their own task of optimization. The design algorithms developed using these techniques are very effective for global search owing to their ability to find the optimum solutions in the search space in an affordable time. A firefly algorithm (FFA) is proposed in this paper as an efficient algorithm for solving new generation beam optimization problems. The robustness of the algorithm lies in its ability to implement the aforementioned parameters during the search for the most efficient optimization process.

3.1. Firefly Algorithm

FFA is one of the recent additions to such stochastic search techniques and is founded on simulating the idealized behaviour of the flashing characteristics of fireflies to solve combinatorial optimization problems [13-16]. This approach utilizes the communication of insects to search for prey and find mates using bioluminescence with varying flashing patterns to find the optimum design process that seeks to find the optimum solution. The movement of a firefly is determined by a brighter firefly to which it is attracted; in just the same way as the objective function value is determined by the set of values assigned to each decision variable. Although FFA has been successfully applied to different practical optimization problems since its origination, the applications of the method in structural optimization are still immature and require a substantial amount of further research. So far, there are only a limited number of publications in the literature describing the application of the technique in different problem areas encountered in the field. Amongst these restricted studies that look at the effectiveness of the

FFA, The technique was used by Gandomi et al. [17] for solving mixed continuous structural optimization problems. The optimum design of tower-shaped structures using an adaptive version of the FFA method was done by Talatahari et al. [18]. Later, the success of an enhanced FFA method in mixed variable structural optimization problems was investigated by Brajevic and Ignjatovic [19]. Mainly small-scale applications that consist of a small number of design variables were used in these aforementioned studies and all of them concluded that the FFA algorithm was a very rapid and effective method for the optimum design of such systems. In comparison to those of other metaheuristic techniques, the performance of the FFA algorithm was qualified as above standard with its fast convergence rate and reliable search efficiency. The FFA technique was recommended for its application to the optimization of new generation beam problems, which in fact led to the motivation of the present study. Before initiating the design process, a set of steel beam sections selected from an available UB profile list are collected in a design pool. Each steel section is assigned a sequence number that ranges from 1 to the total number of sections (N_{sec}) in the list. During the optimization process, the selection of sections for design variables is carried out using these numbers. The basic components of the firefly algorithm can now be outlined as follows.

Attractiveness

In the firefly algorithm, the attractiveness of a firefly is assumed to be determined by its brightness which is related with the objective function. The brightness i of a firefly at a particular location x can be chosen as $I_{(x)} \propto f_{(x)}$, where $f_{(x)}$ is the objective function. However, the attractiveness β is relative, and it should therefore be judged by the other fireflies. Thus, it will vary with the distance r_{ij} between firefly i and firefly j. In the firefly algorithm, the attractiveness function is taken to be proportional to the light intensity of adjacent fireflies and it is defined as

$$\beta(r) = \beta_0 e^{-\gamma r^m}, \quad (m \geq 1) \qquad (25)$$

Distance

The distance between any two fireflies i and j at x_i and x_j is calculated as

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} \left(x_{i,k} - x_{j,k} \right)^2} \qquad (26)$$

where $x_{i,k}$ is the k^{th} component of the spatial coordinate x_i of the i^{th} firefly.

Movement

The movement of a firefly i which is attracted to another brighter firefly j is determined by

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} (x_j - x_i) + \alpha \left(rand - \frac{1}{2} \right) \qquad (27)$$

where the second term is due to the attraction, while the third term is the randomization, with α being the randomization parameter. "rand" is a random number generator uniformly distributed in [0,1]. The values of parameters in the above equations are generally taken as $\beta_0 = 1$ and $\alpha \in 1$ [0,1]. The randomization term can be extended to a normal distribution N(0,1) or other distributions. γ characterizes the variation of the attractiveness, and its value determines the speed of convergence and performance of the firefly algorithm. In most applications its value is taken between 0 and 100.

```
begin;
  Objective function f(x), (x) = (x1, … , xd )
  Generate initial population of fireflies xi , (i =1, … , n)
  Light intensity Ii at xi is determined by f(xi)
  Define light absorption coefficient γ
while (until the termination criteria is satisfied)
        for i = 1 : n all n fireflies
        for j = 1 : i all n fireflies
 if (Ij > Ii)
   Move firefly i towards j in d-dimension
end if
  Attractiveness varies with distance r via exp[−γr2]
Evaluate new solutions and update light intensity
end for j
end for i
   Rank the fireflies and find the current best
end while
   Post-process results and visualization
end procedure;
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Figure 2. Pseudo code of firefly algorithm

DESIGN EXAMPLES

The firefly algorithm explained in the previous section is used to determine the optimum solutions of new generation steel beams. In the first part of the numerical examples, a simple benchmark problem chosen from the literature is studied to verify the effectiveness of the proposed solution algorithms employed for the FFA technique. The result of the sensitivity analysis carried out to determine the appropriate value ranges of the FFA parameters is given in Table 1.

Table 1 Parameters of FFA optimization technique

Technique	Values of parameter
FFA	$\mu = 10$, $\beta_0 = 0.25$, $\beta = 1$, $\alpha = 0.01$, $\gamma = 1$, $N_{ite} = 100000$

The optimum solution located by the algorithm and the number of structural analyses required to obtain this solution is reported in Table 2. In the second part, two structural design examples are selected to minimize and compare the weights of optimally designed sinusoidal, castellated and cellular steel beams. The solution algorithm of the FFA algorithm for new generation steel beams is computerized in the optimization software, which is compiled in FORTRAN source code. It is common practice to use universal beam (UB) sections. Among the steel section list of these UBs, sections ranging from 254×102×28 to 914×419×388 are chosen to constitute the discrete set, consisting of 64 steel sections from which the design algorithm selects the sectional designations for the beam members. Both design examples use the following material properties of the steel: modulus of elasticity (E) = 205 kN/mm^2 and Grade 37 steel is adopted for the steel, with the design strength (P_y) = 235 MPa.

Kuhn–Tucker Condition Example

In this example, we refer to the following optimization problem. The values of x_1 and x_2 are restricted to the set $\{0.5, 1.0, 1.5, 2.0, 2.5, 3.0, \ldots, 10.0\}$. It minimizes $f(x) = 5x_1^2 - 9x_1x_2 + 5x_2^2$ which is subject to $g(x) = 25 - 16x_1x_2 \le 0$.

The objective function is $f_{(x)}$, which is one of the standard test functions in optimization problems. The discrete optimum for the example problem is {1.5, 1.5}^{T}, which was verified from the Kuhn–Tucker conditions. When applying the and HS algorithm to the function, possible value bounds between 0.5 and 10.0 were used for the design variables, x_1 and x_2 shown in the objective function. The parameterization of the technique is conducted in line with its recommended settings in preceding studies, as well as extensive numerical experimentations conducted in the present study. The following parameter value set is used in solving the problem: a population size of fireflies μ=10, and a maximum search number of N_s = 1000. The attractiveness variants β_0 and β are selected as 0.25 and 1, while the random step size (α) and absorption coefficient (γ) are considered as 0.01 and 1, respectively.

Table 2 Population size matrix after 50 searches

Firefly Algorithm (FFA)			
Row Number	x_1	x_2	$f(x)$
1	1.5	1.5	2.25
2	2.0	1.5	4.25
3	2.5	2.5	6.25
4	2.5	3.0	8.75
5	3.0	3.0	9.00
6	3.0	3.5	11.75
7	3.5	3.5	13.75
8	3.0	1.5	15.75
9	4.0	3.0	17.00
10	4.5	4.0	19.25

The optimum result presented in Table 2 is obtained after 80 iterations. Finally, the combinations given in the first row of the population size which is improvised give the optimal solution, $x^* = (1.5, 1.5)$, which has a minimum function value. It is noticed that these design vectors remained the same even though the design cycles were continued, reaching 1000, which was the pre-selected maximum number of iterations. Consequently, the technique is recommended for its application to optimize the new generation beam problems. It is interesting to see the function $f(x) = 5x_1^2 - 9x_1x_2 + 5x_2^2$ that we have optimized and we give both a contour plot and a three-dimensional plot in Figure 6.

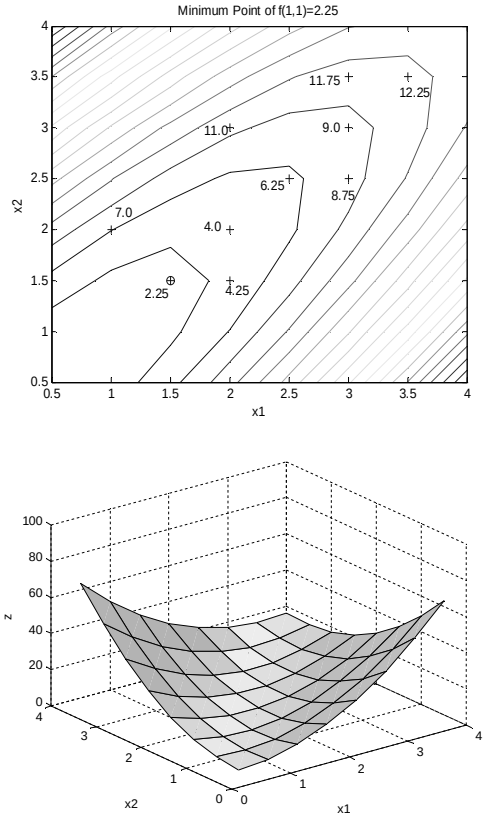


Figure 6 The contour and three dimenional plot of the objective function

OPTIMUM DESIGN PROBLEM

The design of a corrugated web beam requires the selection of width and thickness of a plate from which the corrugated web is to be produced, distance between the peak points of each corrugate, the length of corrugate web, the selection of width and thickness of a plate for upper and lower flanges in the beam. For this purpose a design pool is prepared. The optimum design problem formulated considering the design constraints explained in the previous sections yields the following mathematical model. Find a integer design vector $\{I\} = \{I_1, I_2, I_3, I_4, I_5\}^T$ where I_1 is the sequence number of for the width of upper and lower flanges, I_2 is the sequence number for the thickness values of upper and lower flanges, I_3 is the thickness of corrugated web, I_4 is distance between the peak points of each corrugate web and I_5 the height of corrugate,. Hence the design problem turns out to be minimize the weight of the corrugated web beam.

$$W_{SOB} = \rho_s \left(\left(2 \times b_f \times t_f \times L\right) + \left(h \times t_w \times L_{düz}\right) \right) \quad (13)$$

where, ρ_s density of steel, b_f the width of flange, t_f thickness of flange, L span of beam, h height of corrugated web, t_w thickness of corrugated web ve $L_{düz}$ span of beam before corrugation process. Design of a corrugated beam requires the satisfaction of some geometrical restrictions that are formulated through Eqns. (14-17).
Web dimensions:

$$333\ mm \le h \le 1500\ mm \quad (14)$$

$$1.5\ mm \le t_w \le 5.0\ mm \quad (15)$$

Flange dimensions:

$$120\ mm \le b_f \le 450\ mm \quad (16)$$

$$6.0\ mm \le t_f \le 30.0\ mm \quad (17)$$

DESIGN EXAMPLE

Optimum design algorithms presented are used to design a corrugated steel web beam with 5-m span shown in Fig. 3. The beam is subjected to point loading. The upper flange of the beam is laterally supported by the floor system that it supports. The maximum displacement is limited to 17 mm. The modulus of elasticity is 205 kN/mm^2.

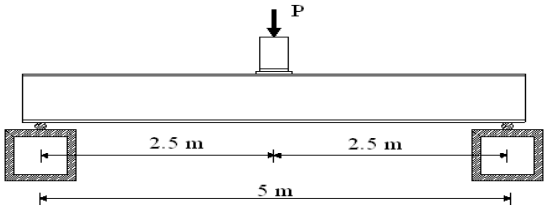


Figure 3. Loading of 5-m span Corrugated Web beam

The design example is separately solved by hunting search (HSM) and firefly algorithm (FFO). The size of the initial population and the maximum number of generations are kept the same in HSM and FFA (Table I).

TABLE I. PARAMETERS OF HSA AND FFO TECHNIQUES

Technique	The values of parameters
HSA	$HGS = 90$ $MML = 0.002$ $HGCR = 0.90$ $Ra_{max} = 0.01$, $Ra_{min} = 0$ $par = 0.45$ $\alpha = 0.9, \beta = 0.02, IE = 25$, $N_{cyc} = 50000$
FFO	$\mu = 40$ $\beta_0 = 0.25$ $\beta = 1$ $\alpha = 0.01$ $\gamma = 1$ $N_{ite} = 50000$

The result of the sensitivity analysis carried out for the FFO parameters is given in Table II.
In steel construction applications, the web part of beam usually carries the compressive stress and transmits shear in the beam while the flanges support the applied external loads. By using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the load-carrying capability of the beam. In this case, the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability and deforms transversely.

TABLE II. OPTIMUM DESIGN OF CORRUGATED BEAM WITH 5-M SPAN

Optimum Section	t_w (mm)	h(mm)	t_f (mm)	H_c (mm)	L_c (mm)	Minimum Weight(kg)
OGK_330	5	330	8	43	155	176.33

It is apparent from the table that FFO produces the least weight for corrugated web beam which is equal to 176.33 kg. The maximum value of the strength ratio is 0.98 which is almost upper bound. This reveals the fact that the strength constraints are dominant in the problem. FFO algorithm presented selects OGK_330 for the root beam. The optimum corrugated web beam should be produced such that it should have 5 mm web thickness 330 mm web height, 8 mm flange thickness and 160 mm flange width. HSA produces 185.76 kg weight for this design example. The design history curve for FFO and HSA techniques is shown in Fig. 4. It is apparent from the figure that FFO method performs better convergence rate and better solution than HSA technique in this design problem.

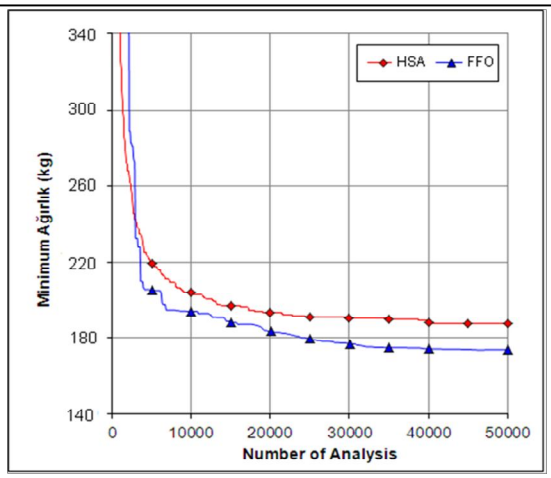


Figure 4. Design History Graphic of 5-m Corrugated Web Beam

The optimum shape of the corrugated steel web beam for the loading considered is shown in Fig. 5.

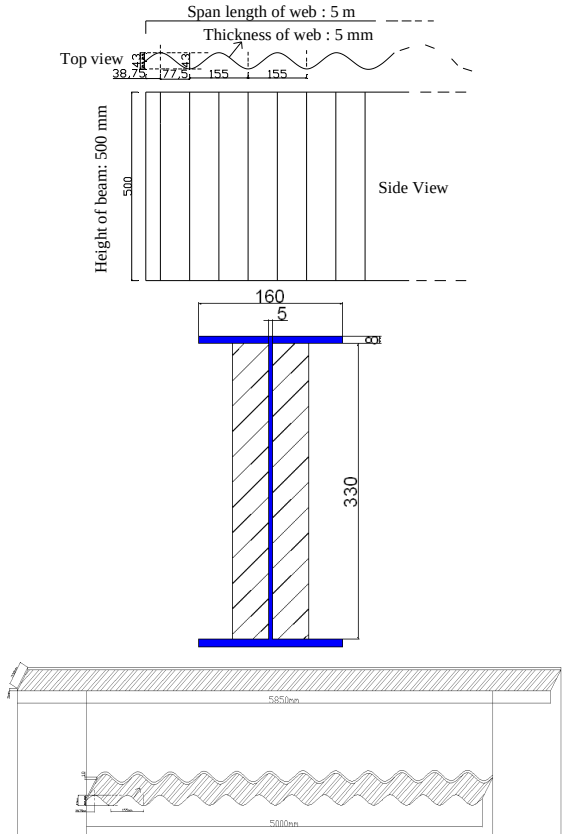


Figure 5. The optimum shape of the corrugated web beam with different views

CONCLUSIONS

This study concerns with the application of a firefly algorithm to demonstrate the robustness of the proposed algorithm and to find the optimum design of corrugated web beams. The design algorithm is mathematically simple but effective in finding the solutions of optimization problems. Fly-back mechanism is employed for handling the problem constraints and feasible ones being candidate solutions to give the minimum weight are determined. A corrugated web beam example is designed to illustrate the efficiency of the algorithm. Comparison of the optimum designs attained by HSA and FFO clearly shows that the FFO outperforms the latter in the particular design problem. In view of the results obtained, it can be concluded that the FFO is an efficient and robust technique that can successfully be used in optimum design of corrugated web beams.

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REFERENCES

[1] Elgaaly M, Hamilton RW ve Seshadri A, Shear Strength of Beams with Corrugated Webs, Journal of Structural Engineering (ASCE), 122, 4, 390-398, 1996.

[2] Elgaaly M, Hamilton RW and Seshadri A, Bending Strength of Steel Beams with Corrugated Webs, Journal of Structural Engineering (ASCE), 123, 6, 772-782, 1997.

[3] Johnson RP ve Cafolla J, Local Flange Buckling in Plate Girders with Corrugated Webs, Structures and Buildings (ICE), 123, 148-156, 1998.

[4] Li Y, Zhang W, Zhou Q, Qi X ve Widera GEO, Development and Research on H-beams with Wholly Corrugated Webs, Journal of Materials Processing Technology, 101, 1-3, 115-118, 2000.

[5] Pasternak H ve Kubieniec G, Plate Girders with Corrugated Webs, Journal of Civil Engineering and Management, 16, 2, 166-171, 2010.

[6] Goldberg D.E., Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley Publishing, 1989.

[7] Kennedy, J, Eberhart R, Shi, Y. Swarm Intelligence. Morgan Kaufmann Publishers, 2001.

[8] Dorigo M, Stutzle T. Ant colony optimization a Bradford book. USA: Massachusetts Institute of Technology; 2004.

[9] Kirkpatrick, S., Gerlatt, C. D., Vecchi, M. P., Optimization by Simulated Annealing, Science, 220, 671-680, (1983).

[10] Oftadeh ., Mahjoob MJ, Shariatpanahi M, A novel meta-heuristic optimization algorithm inspired by group hunting of animals: Hunting search, Computers and Mathematics with Applications, 60, 2087-2098, 2010.

[11] Kaveh A, Talatahari S. Charged system search for optimum grillage system design using the LRFD-AISC code. Journal of Constructional Steel Research, 66, 767-771, 2010.

[12] Geem ZW, Kim JH. A new heuristic optimization algorithm: harmony search. Simulation, 76, 60-68, 2001.

[13] X. S. Yang, (2008) Nature-Inspired Metaheuristic Algorithms, Luniver Press, UK.

[14] X. S. Yang, (2009) 'Firefly algorithms for multimodal optimization', in: Stochastic Algorithms:Foundations and Appplications (Eds O. Watanabe and T. Zeugmann), SAGA 2009, Lecture Notes in Computer Science, 5792, Springer-Verlag, Berlin, pp. 169-178.

[15] X. S. Yang,, Firefly algorithm, stochastic test functions and design Optimisation, Int. J. Bio-Inspired Computation, Vol. 2, No: 2, 78–84, 2010.

[16] X. S. Yang,, and X. He,Firefly algorithm: Recent advances and applications, International Journal of Swarm Intelligence, Inderscience Publishers, Artificial Intelligence and Intelligent Systems, Vol. 1, 36-50, Science, Engineering and Technology, 2013.

[17] Gandomi AH, Yang XS, Alavi AH. Mixed variable structural optimization using firefly algorithm. Computers and Structures, 89(23–24), 2325–36, 2011.

[18] Talatahari S., Gandomi AH and Yun GJ Optimum Design of Tower Structures using Firefly Algorithm. The Structural Design of Tall and Special Bıildings, 23-5, 350-361, 2014.
[19] Brajevic I, Ignjatovic J, An enhanced firefly algorithm in mixed variable structural optimization problems, International Journal of Modelling, Identification and Control, 18(2), DOI: 10.1504/IJMIC.2013.052298, 2013.
[20] British Standards, BS 5950, Structural Use of Steelworks in Building, Part 1. Code of Practice for Design in Simple and Continuous construction, hot rolled sections, British Standard Institution, London, U.K., 2000.
[21] DIN V ENV 1993-1-1, EUROCODE 3: Design of Steel Structures; Part 1- General Rules and rules for buildings.
[22] DIN 18 800 Teil1-3, Stahbauten; Bemessung und Konstruktion.
[23] British Standards, BS 8110, Structural Use of Concrete, Part 1. Code of Practice for Design and Construction, British Standard Institution, London, U.K.
[24] Steelwork design Guide to BS 5950: Part 1, Section Properties, Member Capacities, Vol.1, 4th edition, The Steel Construction Institute, U.K., 1990.

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