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Online Publication Date: 26 Oct 2015

URL: <http://www.jresm.org/archive/resm2015.13st0816.html>

DOI: <http://dx.doi.org/10.17515/resm2015.13st0816>

Journal Abbreviation: *Res. Eng. Struct. Mat.*

To cite this article

Carbas S, Saka MP. Optimum design of cold-formed thin-walled sections subjected to axial and bi-axial bending using artificial bee colony algorithm. *Res. Eng. Struct. Mat.*, 2016; 2: 29-37

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Research Article

Optimum design of cold-formed thin-walled sections subjected to axial and bi-axial bending using artificial bee colony algorithm

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Article Info

Article history:

Received 16 Aug 2015

Revised 18 Oct 2015

Accepted 19 Oct 2015

Keywords:

Structural optimization,
Discrete optimization,
Artificial bee colony
algorithm,
Metaheuristic
techniques,
Cold-formed thin-
walled open sections

Abstract

Sustainable development in construction industry is emerging as a major issue among cities and communities in the current century. As global climate change becomes an increasingly serious concern for the future and construction industry dependence on fossil fuels for energy creates greater adverse influence on human health and natural environment, an interest in high-efficient, low environmental impact buildings has begun to transform the notion of building design, construction, and operation. As it stands, the most of the standard buildings in the world consume an extraordinary amount of resources while taking an enormous toll on the environment. The utilization of cold-formed thin-walled open steel sections in structural sites supplies green structural opportunities demanding less material and cost while providing high strength. The developed algorithm for this study obtains the optimum geometric dimensions of cold-formed thin-walled open steel sections under various external loading. Moreover, this design algorithm takes into account of the effect of geometric nonlinearity as well as effect of warping. Also the displacement and stress constraints are included in the formulation of the design problem. The optimum design problem obtained turn out to be mixed integer and discrete programming problem. Artificial Bee Colony (ABC) algorithm is used to obtain its solution. This technique is a recent numerical optimization technique which mimics the intelligent behavior of honey bee swarm. The recent studies with the ABC method have shown its effectiveness and robustness in finding the optimum solution of combinatorial optimization problems. A design example is included to demonstrate the efficiency of the optimum design algorithm developed.

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1. Introduction

The buildings in which we live and work protect us from nature's extremes, yet they also affect our health and environment in countless ways. As the environmental impact of buildings during construction period becomes more apparent, a new field called "green and/or sustainable building" is gaining momentum [1]. Green or sustainable building is the practice of creating and using healthier and more resource-efficient models of construction. The overall objective of the sustainable construction is to develop an innovative high performance buildings that would provide a unique combination of ductility, strength, durability, and aesthetic flexibility at a competitive low cost in order to leave a lighter footprint on the environment through conservation of resources, while at the same time balancing energy-efficient, cost-effective, low-maintenance products for construction needs. The sustainable buildings made of cold-formed thin-walled open

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DOI: <http://dx.doi.org/10.17515/resm2015.13st0816>

Res. Eng. Struct. Mat. Vol. 2 Iss. 1 (2016) 29-37

sections are known to be safe, comfortable, durable, affordable, and energy efficient, thereby resulting in reduced environmental impact and reduced maintenance, often leading to the complete elimination of other environmental pollution reasons such as production and transportation. Potential benefits of the utilization of cold-formed thin-walled open sections in construction can include:

- Environmental benefits; enhance and protect biodiversity and ecosystems, improve air and water quality, reduce waste streams, conserve and restore natural resources,
- Economic benefits; reduce operating costs, create, expand, and shape markets for green product and services, improve occupant productivity, optimize life-cycle economic performance,
- Social benefits; enhance occupant comfort and health, heighten aesthetic qualities, minimize strain on local infrastructure, improve overall quality of life [1].

Cold-formed thin-walled members are used in building industry in many fields. The probably largest area of use is in conventional, mainly industrial, steel structures as secondary and tertiary load-bearing elements such as purlins or sheeting on a steel or reinforced concrete primary structure. Cold-formed members are extensively used in North America and Australia/New Zealand in residential housing as primary load-bearing structures; light-gauge building systems are gaining on popularity and compete with the traditional building material, wood. There are several examples of multi-storey office buildings with a primary load-bearing system consisting entirely of cold-formed thin-walled steel sections as well. Another large area of use is composite slabs, where trapezoidal sheeting and cold-formed sections are used as tension and a thin concrete slab as compression parts resulting in light floor systems applicable in buildings made of cold-formed members or in refurbishment. Cold-formed thin-walled open members are also extensively used in warehouse racks [2].

Cold-formed thin-walled open sections are defined as those where the wall thickness is assumed to be much smaller than a representative dimension of the cross section. This thickness is very small compare to the widths of walls of member that they buckle before the stresses reach to yield stress when they are subjected to axial load, shear, bending or bearing. Therefore one of their major design criteria is based on the local buckling of walls of these sections [3-4]. Furthermore open sections whether hot-rolled or cold-formed in general has relatively small torsional rigidity compare to closed sections. Plane sections do not remain plane and warping distortion takes place when subjected to torsional moments. Large warping deformations cause normal stresses in the cross section in addition to shear stresses. *Vlasov's* theory provides simple way of calculating these stresses [5-6]. This theory extends the simple bending stress formula to cover the normal stresses that come out due to warping by just adding a similar term to the same formula. This additional term necessitates computation of two new cross sectional properties that are called the sectorial coordinate and warping moment of inertia of the cross-section. Normal stresses develop in thin-walled open section due to warping can be larger than the bending stress depending on the magnitude of the torsional moment section subjected to [7-8]. It is shown in the literature that warping has substantial effect in the optimum design of steel frames made of thin-walled open sections [9].

2. Optimum Designs of the Cold-Formed Thin-Walled Open Steel Sections

The calculations of geometrical properties of a cold-formed thin-walled open section with a complex cross-section are tiresome and tough as comprehensively explained in [10]. The proposed algorithm in this study provides a facility for an automatic evaluation of open cross-sectional properties of thin-walled members. The geometrical data which needs to

be entered to perform the analysis have been brought to the minimum; i.e. the coordinates of joints, the elements connecting them and their thickness [4]. So, the determination of the torsional and flexural properties of thin-walled members with arbitrary open cross-sections is easily reified.

The optimum design problem of laterally supported cold-formed thin-walled open cross-section shown in Fig. 1 is formulated in the following. Consider that this section is used as a simply supported beam which is laterally supported and is subjected to various external loading. In the case where the design variables are selected as the cross-sectional dimensions of the section as shown in the same figure, the objective function becomes

$$\text{Minimize } W = l * \rho [x_1(x_2 + x_3 + x_4)] \tag{1}$$

where, W is the weight of the beam, l is the span of the beam and ρ is the density of steel. Consider the simply supported beam shown in Fig. 1 (a) subjected to various external loading. Assume that the beam is made of cold-formed thin-walled open section shown in Fig. 1 (b). The optimum design problem of the simply supported beam considered necessitates selection of the dimensions of thin plates used in the upper and lower flanges as well as web of the thin-walled section shown in Fig. 1 (b) such that the maximum displacement and stress occur in the beam under the external loading are less than their upper bounds and the weight of the beam is minimum.

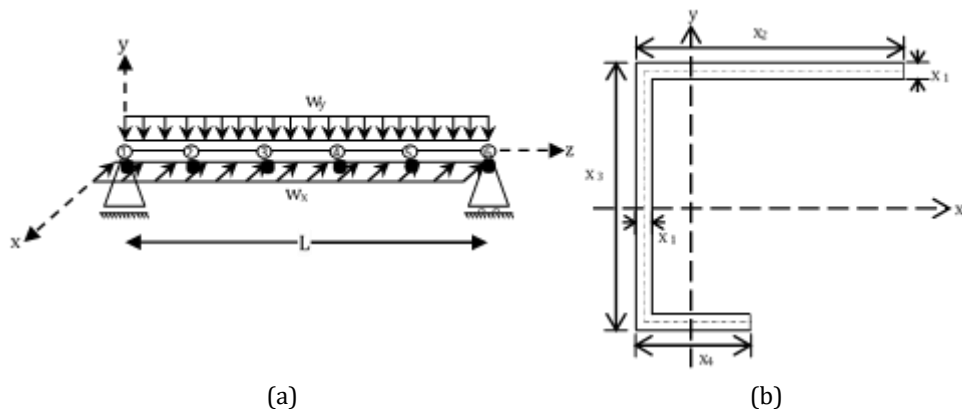


Fig. 1 Thin-walled steel beam with unsymmetrical channel (a) Simply supported thin-walled steel beam, (b) Thin-walled cross-section

The mathematical model of above mentioned problem can be expressed as;

$$\text{Min } W = f(x_i), \quad i = 1, \dots, n \tag{2}$$

Subjected to;

$$g_j(x_i) = \frac{\delta_j}{\delta_{ju}} - 1 \leq 0, \quad j = 1, \dots, p \tag{3}$$

$$g_s(x_i) = \frac{\sigma_s^{\max}}{\sigma_y} - 1 \leq 0, \quad s = 1, \dots, r \tag{4}$$

$$g_k(x_i) = \frac{x_k}{x_1} - u_k \leq 0, \quad k = 1, \dots, m \quad (5)$$

$$x_{li} \leq x_i \leq x_{ui} \quad (6)$$

Stress equations for a thin-walled beam are given as:

$$\sigma(s) = \frac{P}{A} + M_{xx} \frac{y(s)}{I_{xx}} + M_{yy} \frac{x(s)}{I_{yy}} + M_{\omega} \frac{\omega(s)}{I_{\omega}} \quad (7)$$

$$\tau(s) = Q_y \frac{S_x(s)}{t_s I_{xx}} + Q_x \frac{S_y(s)}{t_s I_{yy}} \pm T_v \frac{t(s)}{I_s} + T_{\omega} \frac{S_{\omega}(s)}{t_s I_{\omega}} \quad (8)$$

where $f(x_i)$ represents the weight of the beam given in Eq. (1) which is taken as objective function. X_i is the i^{th} design variable. X_{li} and X_{ui} are the lower and upper bound imposed on the design variable i . n is the total number of variables. $g_j(x_i)$ is the displacement constraint. The simply supported beam modeled as three dimensional structure as shown in Fig. 1 (a) in order to be able to consider general loading conditions that may act along any axis. Beam is subdivided into number of elements and joint displacements are computed using matrix displacement analysis which takes into account the effect of warping. δ_j is the displacement of joint j which is required to be restricted and δ_{ju} is its upper bound. p is the total number of restricted displacements in the design problem. $g_s(x_i)$ represents normal stress constraints. σ_y is the yield stress of the steel. r is the total number of elements considered along the beam. $g_k(x_i)$ is the local buckling constraints that is to be imposed on the web of the thin-walled section to prevent web buckling. σ_s^{max} is the maximum normal stress occurs in the beam. This stress is obtained by calculating the normal stresses for each element using Eqs. (7) and (8) and selecting the largest one. Where the last terms of the stress equations are the longitudinal stress of fiber caused by bi-moment M_{ω} and the shear stress in a fiber of a thin-walled beam caused by a flexural twist T_{ω} , respectively. Among the design variables X_1 represents the thickness of the steel plate out of which cold-formed thin-walled open section is formed. Steel plates are produced within a certain thickness in practice. Hence in the optimum design, the algorithm should select appropriate values from a discrete set. Similar tables can be presented for the flange, width and web depths which consist of list of practically preferable values. Therefore the optimum design problem turns out to be a discrete programming problem. The design algorithm is expected to select appropriate values for the design variables such that the design constraints are satisfied and the weight of the beam is the minimum. This is a combinatorial optimum design problem and recent meta-heuristic techniques are shown to be quite effective in finding the solution of such problems [11].

3. Artificial Bee Colony Algorithm

Artificial Bee Colony (ABC) algorithm mimics the intelligent foraging behavior of a honey bee colony [12]. In the artificial bee colony algorithm, there are three types of bees which carry out different tasks. The first group of bees are the *employed bees* that locate food source, evaluate its amount of nectar and keep the location of better sources in their memory. These bees when fly back to hive they share this information to other bees in the dancing area by dancing. The dancing time represents the amount of nectar in the food source. The second group are the *onlooker bees* who observe the dance and may decide to fly to the food source if they find it is worthwhile to visit the food source. Therefore food

sources reach in the amount of nectar attract more onlooker bees. The third group are *scout bees* that explore new food sources in the vicinity of the hive randomly. The employed bee whose food source has been abandoned by the bees becomes a scout bee. Overall, scout bees carry out the exploration, employed and onlooker bees perform the task of exploitation. Each food source is considered as a possible solution for the optimization problem and the nectar amount of a food source represents the quality of the solution which is identified by its fitness value. The artificial bee colony algorithm consists of four stages. These stages are initialization phase, employed bees phase, onlooker bees' phase and scout bees phase.

(1) Initialization phase: Initialize all the vectors of the population of food sources, X_p , $p=1, \dots, np$, by using Eq. (9) where np is the population size (total number of artificial bees). Each food source is a solution vector consisting of n variables (X_{pi} , $i=1, \dots, n$) and it is a potential solution to the optimization problem under consideration.

$$x_{pi} = x_{li} + \text{rand}(0, 1)(x_{ui} - x_{li}) \quad (9)$$

where X_{li} and X_{ui} are upper and lower bound on x_i .

(2) Employed bees phase: Employed bees search new food sources. Each employed bee x_p generates a new candidate solution v_p in the neighborhood of its present position by using Eq. (10).

$$v_{pi} = x_{pi} + \varphi_{pi}(x_{pi} - x_{ki}) \quad (10)$$

where $k \neq i$ is a randomly selected food source, φ_{pi} is a random number in range $[-1, 1]$. After producing the new food source its fitness is calculated. If its fitness is better than X_{pi} the new food source replaces the previous one. The fitness value of the food sources is calculated according to Eq. (11).

$$\text{fitness}(x_p) = \begin{cases} \frac{1}{1 + f(x_p)} & \text{if } f(x_p) \geq 0 \\ 1 + \text{abs}(f(x_p)) & \text{if } f(x_p) < 0 \end{cases} \quad (11)$$

(3) Onlooker bees phase: Unemployed bees consist of two groups. These are onlooker bees and scouts. Employed bees share their food source information with onlooker bees. Onlooker bees choose their food source depending on the probability value P_p which is calculated using the fitness values of each food source in the population as shown in Eq. (12).

$$P_p = \frac{\text{fitness}(x_p)}{\sum_{p=1}^{np} \text{fitness}(x_p)} \quad (12)$$

After a food source X_{pi} for an onlooker bee is probabilistically chosen, a neighborhood source is determined by using Eq. (11) and its fitness value is computed using Eq. (12).

(4) Scout bees phase: The unemployed bees who choose their food sources randomly called scouts. Employed bees whose solutions cannot be improved after predetermined number of trials become scouts and their solutions are abandoned. These scouts start to search for new solutions.

Phases (2)-(4) are repeated until a termination criterion is satisfied.

4. Optimum Design Algorithm with Discrete Variables

The solution of the discrete optimum design problem given in Eqs. (2) to (8) is obtained using the ABC algorithm. In the optimum design algorithm based on ABC the sequence number of the geometric dimensions of thin plates are treated as design variable. For this purpose a design pool is prepared that contains separate values for each design variable is considered from which the optimum design algorithms select the cross sectional dimensions. Once a sequence number is selected, then the sectional dimension of a cold-formed thin-walled open section becomes available for the algorithm. The ABC algorithm assumes continuous design variables. However the design problem considered requires discrete design variables. This necessity is resolved by rounding the numbers obtained through each algorithm. For example Eq. (9) of ABC algorithm is written as

$$I_{pi} = I_{min} + \text{INT}[\text{rand}(0,1)(I_{max} - I_{min})] \quad , \quad i = 1, \dots, ng \quad , \quad p = 1, \dots, np \quad (13)$$

where I_{pi} is the integer value for x_{pi} , the term $\text{rand}(0,1)$ represents a random number between 0 and 1, I_{min} is equal to 1 and I_{max} is the total number of values in the discrete set. ng is the total number of design variables and np is the number of bees in the colony which is equal to $(neb+nob)$ where (neb) is the number of employed bees and (nob) is the number of onlooker bees.

The analysis of cold-formed thin-walled open steel sections is achieved by using matrix displacement method. Noticing the fact that steel members made of cold-formed thin-walled sections are quite slender members, large deformations compare to their initial dimensions may take place under external loads. In structural members with large displacements, although the material behaves linear elastic, the response of the structure becomes nonlinear [13]. Under certain types of loading, namely, even when small deformations are presumed, nonlinear behavior can be predicted. Changes in stiffness and loads occur as the structure deforms. In such members, it is necessary to take into account the effect of axial forces to member stiffness. This is achieved by carrying out $P-\delta$ analysis in the application of the stiffness method. In each design cycle when the cross sectional properties of members is changed, steel member is analyzed by constructing the nonlinear stiffness matrix where the interaction between bending moments and axial forces is considered through the use of stability functions. The details of the derivation of the nonlinear stiffness matrix and consideration of geometric nonlinearity in the analysis of steel members made of cold-formed thin-walled sections are given in [10].

5. Design Example

The design algorithm developed is used to determine the optimum design of a cold-formed thin-walled column with L-lip open cross-section as shown in Fig. 2. The length (L) of the column is assigned as 1.5m. The design variables are assigned as geometric dimensions of thin plates (Fig. 2a) and the prepared design pool that contains separate values for each design variable. Namely, first column of the pool contains values from 1mm to 3mm with the increment of 0.25mm for x_1 which represents the thickness (t) of the section. The second column of the pool has values starting from 15mm to 30mm with the increment of 0.25mm for x_2 which represents the depth (d) of the section. The third column of the pool contains values from 30mm to 90mm with the increment of 0.25mm for x_3 which represents flange width (b) of the section, and finally the last column has values from 85mm to 305mm with the increment of 0.25mm for x_4 which represents the depth (h) of the section. Moreover, the following geometric limits are applied as size constraints [4] in order to control local buckling of thin walls; $50 < h/t < 200$, $25 < b/t < 100$, $6.25 < d/t < 50$,

$2 < h/b < 8$. That is to say, the design constraints are the stress, displacement and local buckling constraints. The column is subjected to 25N equipment load through its x-axis and 250N equipment load through its y-axis as well as a 10Nm moment through its x-axis at its free end. Besides, a 200N concentrated load is applied with 0.05m eccentricity through y-axis at free end of the column and 250N/m distributed load is applied all over the column. The loading of the column is represented in Fig. 2 (b). The deflection is limited to $length/360$ which is 4.167mm as recommended in the ASCE Ad Hoc Committee report [14]. The modulus of elasticity and shear modulus of steel are taken as $E=203\text{GPa}$ and $G=78\text{GPa}$ respectively.

The bee colony size is taken as 30 and the maximum cycle number (MCN) is chosen as 1000 for ABC algorithm. With these selections the total objective function evaluations become 30000. The value of the limit which is used to abandon the food source is selected as 30. The design example has been re-designed 5 times; each run starting from a random population with different seed values in order to investigate the variance of optimum results. Among these, the best optimum design is presented here.

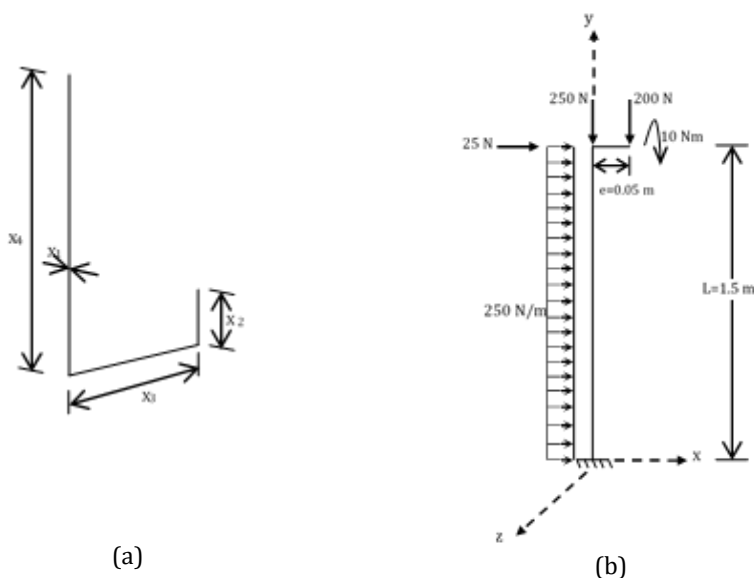


Fig. 2 A thin-walled L-lip column; (a) design variables, (b) loading of the column

The least weight produced by the ABC algorithm for cold-formed thin-walled column with L-lip open cross-section is 26.57N when warping is not taken into account. The minimum weight of the column is obtained as 45.92N when the effect of warping is taken into account in the design process. It is clear that consideration of the warping effect increases the minimum weight 72.87%. The total normal stress reaches to 344.5MPa for the case where warping is considered which is almost at its upper bound. This stress value includes both warping and bending stresses which are 329.3MPa and 15.2MPa, respectively. The normal stress due to warping constitutes 95.45% of the total stress. It is obvious that including warping produces very higher normal stress along the column. Exclusion of warping effects in this design example certainly yields to unsafe designs. It is obvious from Table 1 that while stress constraint is dominant in the case warping is considered, the displacement constraint is dominant in the case warping is not considered. Design histories of the optimum solutions accordance with warping are shown in Fig. 3.

Table 1. Optimum design results of thin-walled column with L-lip cross-section.

Design Variables	ABC algorithm without warping (mm)	ABC algorithm with warping (mm)
$x_1 (t)$	1.0	1.0
$x_2 (d)$	15.0	30.0
$x_3 (b)$	350.0	82.5
$x_4 (h)$	130.0	172.5
Min. weight (N)	26.57	45.92
Max. displacement (mm)	4.16	1.38
Max. stress (MPa)	91.00	344.50
Max. number of iterations	5000	5000

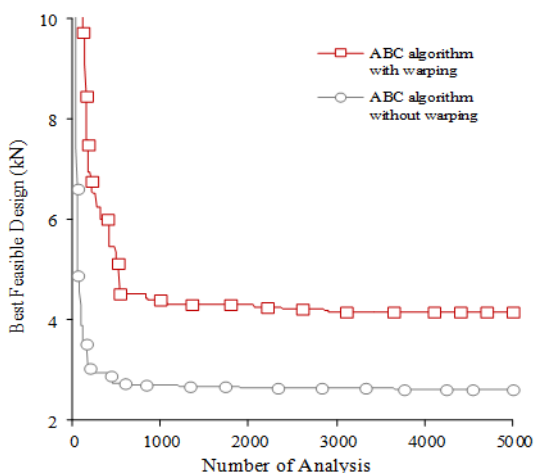


Fig. 3 Design history graph of cold-formed thin-walled column with L-lip open cross-section

6. Conclusions

Sustainable design and construction provide an opportunity to use resources more efficiently, while creating healthier and more energy-efficient homes and commercial buildings. The sustainable construction built up with cold-formed thin-walled open sections involves in finding the delicate balance between homebuilding and a sustainable environment. An artificial bee colony algorithm (ABC) is used to develop an optimum design algorithm for cold-formed thin-walled open sections subjected to various external loading. The optimum design algorithm presented determines the optimum geometric dimensions of a thin-walled section under external loading and it considers the effect of geometric nonlinearity as well as the effect of warping in the computation of stresses. Inclusion of the warping effect in the computation of stresses yields realistic behavior of thin-walled sections in the design process. It is shown that consideration of warping effect in results in significant change in the optimum designs. The minimum weights obtained in the design example with and without considering effect of warping has resulted around 72.87% increase in the optimum design. Therefore it is apparent that in the optimum

design of cold-formed thin-walled open steel sections the effect of warping should be considered in the design formulation.

The results obtained showed that the artificial bee colony method is an efficient and robust technique that can successfully be used in optimum shape design of cold-formed thin-walled open steel sections under various external loading, where the geometric nonlinearity and effect of warping is taken under consideration. The ABC algorithm does not require initial selection of too many parameters. It basically requires assigning initial values to bee colony size and the limit which is little compare to some other metaheuristic algorithms. The maximum number of iterations is also pre-selected parameter. However selection of this parameter is a necessity in each metaheuristic technique.

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