Advances in Engineering Software 44 (2012) 150–169

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Ant colony optimization of irregular steel frames including elemental warping effect

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ARTICLE INFO

Article history:
Available online 28 June 2011

Keywords:
Optimum structural design
Stochastic search techniques
Ant colony optimization
Minimum weight
Steel space frame
Warping effect

ABSTRACT

The effect of warping in the design of steel space frames having members of thin walled steel sections is significant. In this paper the optimum design problem of steel space frames is formulated according to the provisions of LRFD-AISC (Load and Resistance factor design of American Institute of Steel Construction) in which the effect of warping is also taken into account. Ant colony optimization technique is used to obtain the solution of the design problem. A number of space frame examples are designed by the algorithm developed in order to demonstrate the effect of warping in the optimum design.

1. Introduction

Steel structures are preferred in the construction of residential and commercial buildings due to their high strength and ductility particularly in regions that are prone to earthquakes. In some cases architects give form to these tall buildings in order to obtain a fascinating image such that structures have irregular shapes and unsymmetrical plans. These three dimensional frames when subjected to lateral loads caused by wind or earthquake loading undergo twisting as a result of their unsymmetrical topology. On the other hand, even in three dimensional steel frames with symmetrical topology, the bending of one member in one direction causes torsion of the other member in the orthogonal direction which is connected to this member. The members of steel frames are generally made out of W sections that are thin walled open sections with relatively small torsional rigidity. As a result, large warping deformations occur in the cross section of these members. Plane sections do not remain plane and normal stresses develop in addition to shear stresses. Computation of these stresses can be carried out using *Vlasov* theory [1,2] This theory is simple in the sense that it includes an additional term in simple bending expressions to accommodate the effect of warping resistance. However, this additional term requires the computation of the sectorial coordinate and warping moment of inertia of a thin walled open section. The effect of warping in the design of thin walled sections is studied by number of researchers [3–6]. It is shown in these studies that warping has significant effect in the computation of normal stresses in thin walled members subjected to torsional moments. Consequently it is worthwhile to investigate the effect of warping in the optimum design of steel frames of unsymmetrical plan.

Structural design optimization of steel frames generally requires selection of steel sections for its beams and columns from a discrete set of practically available steel section tables. This selection should be carried out in such a way that the steel frame has the minimum weight or cost while the behavior and performance of the structure is within the limitations described by the code of practice. Such problems fall into the subject of discrete optimization in which finding the optimum solution is a difficult task. The metaheuristic search techniques developed recently have provided an efficient tool for solving discrete programming problems. These stochastic search techniques make use of the ideas taken from nature, biology or music and do not need gradient computations of the objective function and constraints as is the case in mathematical programming based optimum design methods. The basic idea behind these techniques is to simulate the natural, biological, physical or musical phenomena such as survival of the fittest, immune system, swarm intelligence and the cooling process of molten metals, foraging of ant or bee colonies and improvising of a musical performance into a numerical algorithm. These methods are non-traditional search and optimization methods and they are very suitable and powerful obtaining the solution of combinatorial optimization problems. They use probabilistic transition rules not deterministic rules. Many optimization algorithms used in structural design problems developed in recent years which are based on these effective, powerful and novel techniques [7–15].

In this study, the optimum design problem of three-dimensional steel frames is formulated according to LRFD-AISC [16] including the effect of warping. The members of the frame are to be selected among the W-section list given in LRFD-AISC. The mathematical model obtained as a result of such formulation

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0965-9978/$ - see front matter
doi:10.1016/j.advengsoft.2011.05.029

yields a discrete programming problem. Ant colony optimization is employed to determine the optimum solution. Number of space steel frames is designed by the optimum design algorithm presented both with and without considering the effect of warping in order to demonstrate the consequences of warping on the optimum design.

2. Analysis of space frames including the effect of warping

In a thin walled member subjected to a torsional moment, the vertical fibers twist and their particles moves up or down from their initial position in space. The top and bottom surfaces of the beam do not remain plane and become warped. If far end of the beam is rigidly fixed, then warping of the top and bottom surfaces of beam will be restrained. This restraint causes longitudinal strains and stresses. The torsional moment that causes the warping is called flexural twist. Flexural twist causes bending of rectangular components of a beam around their respective minor axes of symmetry. As a result plane sections do not remain plane and the section warps as shown in Fig. 1 [17]. The total twisting moment acting on the section can be written as summation of the *St. Venant* twist and the flexural twist as described in following equation.

$$T = T_{SV} + T_w \tag{1}$$

where T_{SV} is the *St. Venant* torsional moment and T_w is the *flexural* twist. When these are expressed in terms of the twisting of the member then the following differential equation is obtained.

$$T = GJ\frac{d\theta}{dz} - EI_w\frac{d^3\theta}{dz^3} \tag{2}$$

where G is shear modulus, E is modulus of elasticity, J is torsional moment of inertia and I_w warping moment of inertia. In case of distributed torque along the beam Eq. (2) becomes;

$$t = \frac{dT}{dz} = GJ\frac{d^2\theta}{dz^2} - EI_w\frac{d^4\theta}{dz^4} \tag{3}$$

If both sides are divided by EI_w and a constant torque is considered along the beam, Eq. (3) becomes

$$\theta_x^{iv} - \alpha^2\theta_x^{II} = 0 \tag{4}$$

where $\alpha^2 = \frac{GJ}{EI_w}$. The general solution to this differential equation is given by

$$\theta_x = A\sinh(\alpha x) + B\cosh(\alpha x) + Cx + D \tag{5}$$

where A, B, C, D are constants determined according to the boundary conditions.

The warping of a thin walled section is caused by bi-moment M_w which results from the non-uniform torsion of the member. Due to its simplicity in the formulation, it is common practice to consider the twisting of unit length as $\theta_w = d\theta/dy$ a corresponding deformation for M_w in deriving the torsional stiffness matrix of a member where warping deformations are required to be considered. Hence the vector of member end displacement for the member connecting joint i to joint j has the form $\{\theta\} = \{\theta_{xi} \quad \theta_{wi} \quad \theta_{xj} \quad \theta_{wj}\}$ and the corresponding vector of member end forces becomes $\{M_{ij}\} = \{M_{xi} \quad M_{wi} \quad M_{xj} \quad M_{wj}\}$ as shown in Fig. 2. In order to obtain the torsional stiffness matrix of the beam the following boundary conditions are applied [18].

The terms in the first column of the torsional stiffness matrix are obtained by using the boundary conditions $\theta_{xi} = 1 \quad \theta_{xj} = 0$ $\theta_{wi} = 0\theta_{wj} = 0$. The end moments obtained after applying these conditions are given in following equations.

$$M_{xi} = -M_{xj} = -GJ\cdot\sqrt{\frac{GJ}{EI_w}}\frac{\sinh(\alpha\ell)}{2\ \cosh(\alpha\ell) - \alpha\ell\cosh(\alpha\ell) - 2} \tag{6}$$

and

$$M_{wi} = -M_{wj} = -GJ\cdot\frac{\cosh(\alpha\ell) - 1}{2\ \cosh(\alpha\ell) - \alpha\ell\cosh(\alpha\ell) - 2} \tag{7}$$

The terms in the second column of the torsional stiffness matrix are obtained by using the boundary conditions $\theta_{xi} = 0 \quad \theta_{xj} = 0$ $\theta_{wi} = 1\theta_{wj} = 0$. The end moments obtained after applying these conditions are given in following equations.

$$M_{xi} = -M_{xj} = -GJ\cdot\frac{\cosh(\alpha\ell) - 1}{2\cosh(\alpha\ell) - \alpha\ell\cosh(\alpha\ell) - 2} \tag{8}$$

$$M_{wi} = \frac{GJ}{\alpha}\cdot\frac{\sinh(\alpha\ell) - \alpha\ell\cosh(\alpha\ell)}{2\cosh(\alpha\ell) - \alpha\ell\cosh(\alpha\ell) - 2} \tag{9}$$

$$M_{wj} = \frac{GJ}{\alpha}\cdot\frac{\alpha\ell - \sinh(\alpha\ell)}{2\cosh(\alpha\ell) - \alpha\ell\cosh(\alpha\ell) - 2} \tag{10}$$

Collecting the above expressions in a matrix form, the torsional stiffness matrix of the member in local coordinates is attained.

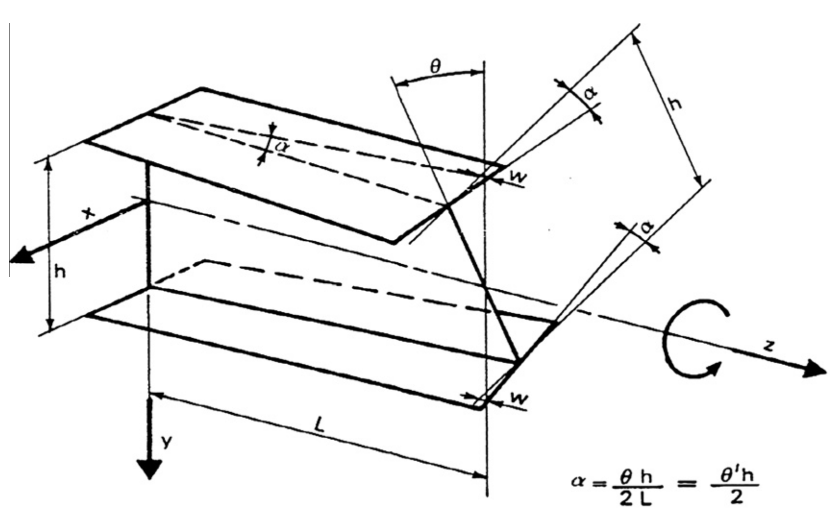

Fig. 1. Warping deformation of a thin walled beam.