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An efficient method for optimizing space steel frames with semi-rigid joints using practical advanced analysis and the micro-genetic algorithm

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ABSTRACT

In this paper, we propose an effective and accurate method for optimizing space steel frames with semi-rigid joints using practical advanced analysis (PAA) and micro-genetic algorithm (μGA). The PAA method using the beam-column approach is applied for capturing the second-order effects and the inelastic behavior of systems, while the zero-length element model is employed for estimating nonlinear behavior of semi-rigid joints. μGA is utilized for finding the global optimal solution, and OpenMP is employed to perform parallel computing in order to efficiently reduce computational time. In this study, unlike many previous researches, not only cross-sectional areas of beam and column members but also semi-rigid connection types are variables of the optimization. The results of some steel frame examples prove that the proposed method is computationally efficient and reliable.

1. Introduction

For simplicity, the beam-to-column joints of steel frames in classical analysis methods are considered as perfectly pinned or fully rigid joints. However, experimental results have shown that the behavior of real beam-to-column joints lie somewhere between these two idealized models, so they should be considered as semi-rigid joints [1–4]. Therefore, modern steel design codes, including American steel specification AISC LRFD [5] and Eurocode 3 [6], permit the evaluation of the connection flexibility in steel frame design. In structural analysis, semi-rigid joints do not only reduce the forces transferring from some elements to other ones, but they also increase the frame drift based on their real stiffness and moment-rotation relationship. From this point of view, it is necessary to model beam-column connections as semi-rigid joints in optimizing steel frames where the frame drift is a deterministic constraint.

In order to investigate the actual behavior of semi-rigid joints, considerable experiments have been conducted in last four decades. The experimental results of the works by Krishnamurthy [7], Chen et al. [8], Kishi et al. [9], Aggarwal [10], and Cruz et al. [11] showed that the rotational behavior of semi-rigid joints in the major axis of the column is nonlinear and can be described by the in-plane moment-rotation curve. The experiments of the nonlinear out-of-plane behavior of three-dimensional semi-rigid joints in both column axes were also conducted by Gibbons et al. [12], Janss et al. [13], Vertes and Ivanyi [14], Cabrero and Bayo [15], Loureiro et al. [16], and Gil et al. [17].

Numerous studies in optimization of semi-rigid steel frames have been conducted in both mathematical programming and heuristic optimization techniques. In the mathematical programming technique, Simoes [18] optimized planar semi-rigid steel frames considering both beam-column member and connection costs, and the optimum results indicated that the frames are lighter when using semi-rigid connections than fully rigid connections. However, this procedure is not efficient when dealing with the discrete character of the optimization problem of large-scale systems. In the heuristic optimization techniques, Xu and Grierson [19] optimized the semi-rigid steel frame considering the rotational stiffness of a semi-rigid connection as a design variable, and the cost of connections was represented by the equivalent weight of steel. However, the structural analysis in this study was limited to the linear elastic analysis model so applying practical design of steel frames was not guaranteed. Applying the method of Xu and Grierson [19] for estimating the cost of semi-rigid connections, the total cost of planar semi-rigid frames was minimized by Hayalioglu and Degerterkin [20] and Kameshki and Saka [21] using genetic algorithm (GA). In these models, all connections of a frame were the same and given in each optimization problem; namely, the type of connections was not considered as a design variable. To overcome this limitation, the optimal planar semi-rigid frame problems was formulated by Hagishita and Ohsaki [22] where semi-rigid joint types and the brace placement were design variables. Moreover, semi-rigid steel frames were also optimized by Ali et al. [23] who considered the manufacturing, erection, and material costs of the structure, and it was concluded that less

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expensive frame designs could be obtained using semi-rigid connections. Furthermore, the cost of the steel frames with perfectly pinned and fully rigid connections was minimized by Kripakaran et al. [24] and Alberdi et al. [25] assuming the cost of a connection to be independent on its size. Thus, a fixed value of connection cost was taken. It is important to note that all of the aforementioned researches are limited to plane frames. Furthermore, all of these studies, except [22], ignored gradual yielding, second-order effects, and geometric imperfections. Xu and Grierson [19] also neglected the nonlinear behavior of the frame, while Hagishita and Ohsaki [22] did not consider transverse shear deformation effects of the beams and columns. Since the exclusion of gradual yielding, second-order influence, geometric imperfection, transverse shear deformation influence, and nonlinear behavior of structure may lead to improper assessments of frame stability, and subsequently the results obtained in these studies may be unreliable.

In this paper, an effective method for micro-GA (μGA) based optimization of 3D steel frames with semi-rigid joints is presented. The total cost of beam-column members and semi-rigid connections is the objective function of optimization, while the constraints of optimization are stress and displacement limits of the structure. In this study, unlike many previous researches, not only cross-sectional areas of beam and column members but also semi-rigid connection types are variables of the optimization. To improve the computational efficiency of the proposed method, practical advanced analysis (PAA) is employed, in which the beam-column approach is applied for predicting all inelastic and nonlinear behaviors of a structure including the gradual yielding, second-order effects, geometric imperfections, and transverse shear deformation effects. The advantage of this method is that computational time is significantly reduced since only one or two elements per member are needed to predict accurately nonlinear inelastic responses of the structure. In addition, the zero-length element model is employed for performing the nonlinear behavior of semi-rigid joints. OpenMP is also employed to perform parallel computing in order to reduce computational time. To evaluate the proposed program, some numerical examples of space steel frame with different stories and bays are shown.

2. Practical advanced analysis

The benefit of a nonlinear analysis is that it considers the inelastic force redistribution, so design by using nonlinear analysis is more economical than by using linear analysis. Furthermore, a nonlinear analysis describes more realistically the behavior of structures, including the nonlinear behavior of semi-rigid connections. Therefore, using nonlinear analysis is preferable to the design of semi-rigid frames.

In order to perform nonlinear inelastic analysis of space steel semi-rigid frames, the PAA method, in which beam and column members are modeled as beam-column elements and beam-to-column joints are considered as zero-length elements, is presented in this section.

2.1. Nonlinear inelastic beam-column element

Nonlinear inelastic behavior of a 3D beam-column element in this study will consider many factors such that $P-\delta$ and $P-\Delta$ effects, the effects of initial geometric imperfection and residual stresses, and the gradual stiffness degradation. For capturing $P-\delta$ effect of beam-column elements, the stability functions given in [27] is applied herein. The incremental displacement vector of a 3D beam-column element is determined by using follow equation:

$$\{\Delta F\} = [K_e]\{\Delta d\}, \tag{1}$$

in which

$$\{\Delta F\} = \left[\Delta P \;\; \Delta M_{yI} \;\; \Delta M_{yJ} \;\; \Delta M_{zI} \;\; \Delta M_{zJ} \;\; \Delta T\right]^T, \tag{2}$$

$$\{\Delta d\} = \left[\Delta\delta \quad \Delta\theta_{yI} \quad \Delta\theta_{yJ} \quad \Delta\theta_{zI} \quad \Delta\theta_{zJ} \quad \Delta\phi\right]^T, \tag{3}$$

where ΔP and ΔT are the increments of axial force and torsional moment, respectively; ΔM_{yI}, ΔM_{zI},ΔM_{yJ}, and ΔM_{zJ} are the increments of moments at ends I and J of element corresponding to y and z axes. Similarly, $\Delta\delta$ and $\Delta\phi$ are the increments of axial displacement and twist angle, respectively; $\Delta\theta_{yI}$, $\Delta\theta_{zI}$,$\Delta\theta_{yJ}$, and $\Delta\theta_{zJ}$ are the increments of joint rotations at ends I and J corresponding to y and z axes. K_e is the stiffness matrix.

The influence of initial geometric imperfection and residual stresses of beam-column elements is captured by using the CRC tangent modulus concept of Chen and Lui [28]. In this concept, the reduced elastic modulus E_t is defined as follows:

$$E_t = E \;\; for\ {}^P/_{P_y} \le 0.5, \tag{4.a}$$

$$E_t = 4\frac{P}{P_y}E\left(1-\frac{P}{P_y}\right) \;\; for\ {}^P/_{P_y} > 0.5, \tag{4.b}$$

where P_y is the axial yield force. Eqs. (4.a) and (4.b) are not applicable in the case of small axial force and large bending moments, so the model of gradual stiffness degradation is employed for capturing the partial plastification effects of plastic hinges. Eq. (1) now can be expressed as

$$\{\Delta F\} = \left[K_{gd}\right]\{\Delta d\}, \tag{5}$$

where K_{gd} is the gradual stiffness degradation matrix, which can be determined based on the parabolic function η expressed as:

$$\eta = 1.0 \;\; \text{for} \;\; \alpha \le 0.5, \tag{6a}$$

$$\eta = 4\alpha(1-\alpha) \;\; \text{for} \;\; \alpha > 0.5, \tag{6b}$$

where α is a force-state parameter. In this study, the term α proposed by Orbison et al. [29] is used since the advantage of this method is that the least amount of elements is required in modeling as follows:

$$\alpha = 1.15p^2 + m^2 + 3.67p^2m^2, \quad p = P/P_y \quad \text{and} \quad m = M/M_p \tag{7}$$

The transverse shear deformation effects can also be considered by modifying the incremental force-displacement equation as follows [30]:

$$\{\Delta F\} = [K_{sd}]\{\Delta d\}, \tag{8}$$

where K_{sd} is the shear deformation stiffness matrix.

In order to capturing $P-\Delta$ effect, the geometric stiffness matrix $[K_g]$ is developed as follows:

$$\left[K_g\right]_{12\times12} = \begin{bmatrix} [K_s] & -[K_s] \\ -[K_s]^T & [K_s] \end{bmatrix}, \tag{9}$$

where $[K_S]$is a 6×6matrix which is dependent on the axial load, the length, and the moments at two end points of the element.

The element deformation increment $\{\Delta d\}$ in Eq. (1) can be determined by multiplying the element displacement increment $\{\Delta D\}$ with the transformation matrix $[T]$ as follows equation:

$$\{\Delta d\} = [T]_{6\times12}\{\Delta D\}. \tag{10}$$

The tangent stiffness matrix $[K]$ can be finally determined as

$$[K] = [T]^T[K_e][T] + \left[K_g\right]. \tag{11}$$

The detailed forms of $[K_e]$, $[K_{gd}]$, $[K_{sd}]$, $[K_S]$, and $[T]$ can be found in Ref. [26].

2.2. Zero-length element model for semi-rigid joints

The zero-length element model for semi-rigid joints proposed by Cuong et al. [31] is employed since the efficiency of this method is that the stiffness matrix of beam-column element in Section 2.1 is not