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A new improved fiber plastic hinge method accounting for lateral-torsional buckling of 3D steel frames

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ABSTRACT

This paper presents a new advanced analysis method, specifically a new improved fiber plastic hinge method, for analyzing the nonlinear inelastic behavior of 3D steel frames accounting for lateral-torsional buckling. The second-order effects are considered by the use of the geometric stiffness matrix and stability functions obtained from the exact solution of beam-columns under axial force and bending moments at two ends. The spread of plasticity along the member length due to both residual stresses and the impact of axial force is considered by utilizing the Column Research Council (CRC) tangent modulus concept, while the gradual yielding due to flexure is represented by two fiber plastic hinges at the ends of the element. The lateral-torsional buckling stiffness matrix is established by the virtual work principle using the updated Lagrangian formulation. The generalized displacement control method is applied to solve the nonlinear equilibrium equations in an incremental-iterative scheme. The nonlinear load-displacement behavior and ultimate load results compare well with those of previous studies. It is concluded that accurately using only one element per member likely predicts the second-order inelastic behavior of 3D steel frames including the effect of lateral-torsional buckling.

1. Introduction

There are two common approaches for advanced analysis of three-dimensional (3D) steel frameworks: the plastic hinge approach (concentrated plasticity) [1–16] and the distributed plasticity approach [17–27]. In the distributed plasticity approach, elements of the structure must be discretized into several sub-elements to accurately predict the second-order effects and inelastic behavior of the structure. This method is generally evaluated to be too computationally expensive since it consumes a lot of computer resources and computational time due to the numerous discretizations of elements that are used in the analysis modeling. Vogel [17] presented some calibrating frames for verifying the accuracy in the second-order inelastic analysis of proposed methods. Clarke [28] and Teh and Clarke [21] proposed finite element formulations using cubic interpolation functions for plastic-zone analysis of 3D framed structures. Foley and Vinnakota [29,30] developed a nonlinear finite element program for second-order spread-of-plasticity analysis of 2D multi-storey semi-rigid steel frames. In order to save computer resources and computational time, Foley [31] proposed parallel processing and vectorization for advanced analysis of multi-storey steel frames on a multi-core computer. The structure is divided into a few sub-structures to reduce the unknown of nonlinear equilibrium equations. Chiorean [25] proposed a beam-column method for the nonlinear inelastic analysis of 3D semi-rigid steel frames. The nonlinear inelastic force-strain relationship and stability functions are used in representing the inelastic behavior and second-order effects, respectively. The advantage of this study is that it is able to trace the spread of plasticity along the member length by using only one element per member in the analysis modeling. However, it seems that the shape parameters a and n of the Ramberg-Osgood model and α and p of the proposed modified Albermani model for the force-strain relationship of the cross-section, which considerably affect the inelastic behavior of the steel frames, are not adequately investigated. Recently, Nguyen and Kim [27] proposed an advanced analysis method using stability functions for considering the second-order effects and monitoring fibers at other sections for considering the spread-of-plasticity. However, up to now the distributed plasticity approach has still not been applied for daily engineering design yet because of its complexity and computational expensiveness.

The plastic hinge approach [5,7–10,14–16] based on stability functions obtained from the closed-form solution of the beam-column under end forces can capture the second-order effects using only one element per member. The inelastic behavior of element is considered through two plastic hinges lumping at the two ends of the members. In

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order to consider the effect of residual stresses distributed along the member length, the tangent modulus concept [11,12,16] is employed. Ziemian and McGuire [12] proposed a modified tangent modulus approach for the second-order plastic hinge method that can produce the accuracy of more sophisticated plastic zone methods in analyzing the in-plane behavior of compact doubly symmetric sections. Researchers have recommended that further systematic research be undertaken for the purpose of establishing the terms, constants, and limits of applicability for additional groupings of sections, imperfections, and residual stresses. This method is called the "practical advanced analysis method" [11,12,16] because it can consider all key factors, influencing the ultimate strength of the steel frameworks efficiently. Recently, Ngo-Huu and Kim [15] presented a fiber-hinge method based on source code of the DRAIN-3DX program [6] for considering the initial residual stress directly. The analysis result depends on the length of fiber hinges, and it also cannot predict the effects of spread-of-plasticity along the member length. As a result, the above studies are limited due to their inability to capture the more complex behaviors that involve lateral-torsional buckling, local buckling, and severe yielding under the combined action of axial force and bi-axial bending moments, which significantly reduce the load-carrying capacity of the structure.

In 1970, Barsoum and Gallagher [32] studied the instability problems of thin-walled structures but this study focused on the numerical methods that permitted to treat only linear elastic lateral-torsional buckling. After that, geometric nonlinear elastic studies on thin-walled structures considering lateral-torsional buckling were carried out by Bazant and Nimeiri [33], Argyris et al. [34], Yang and McGuire [35], Chan and Kitipornchai [36], Teh and Clarke [37], and so on. Nonlinear inelastic analysis of lateral-torsional buckling were presented by Pi and Trahair [38,39], Gruttmann et al. [40], and Battini and Pacoste [41]. However, these methods need to be used several elements for accurately capturing the behavior of the structure, so it is not practical for daily engineering design. Kim et al. [42] developed a second-order inelastic method considering lateral-torsional buckling by using AISC-LRFD equations, but this method cannot predict the real behavior of an entire structural system.

The purpose of this paper is to present an advanced analysis method that can predict second-order inelastic response including the effects of lateral-torsional buckling of the overall structure. This method is efficient and accurate because it uses only one element per member by using stability functions for considering the second-order effects. Residual stresses in fiber plastic hinges and along the member length are taken into account. The spread-of-plasticity is predicted by gradually reducing elastic stiffness and Young's modulus. Local buckling and warping are ignored. The generalized displacement control method proposed by Yang and Shieh [43] is employed for solving nonlinear equilibrium equations. Several numerical examples are presented to verify the accuracy, efficiency, and applicability of the proposed method.

2. Nonlinear inelastic beam-column element

In the development of the nonlinear inelastic beam-column beam-column element, the following main assumptions are made: (1) the element is initially straight and prismatic; (2) plane cross-sections remain plane after deformation and normal to the deformed axis of the element; (3) the effect of Poisson are neglected; (4) yielding of the cross-section is governed by normal stress alone; (5) the material model is elastic-perfectly plastic; and, (6) Local buckling and warping are ignored.

2.1. Stability functions accounting for second-order effects

To capture the effects of the interaction between axial force and bending moments, the stability functions reported by Chen and Lui [44] are used to minimize modeling and solution time. Generally, only one element per member is needed to capture the $P-\delta$ effect accurately. From Kim et al. [11], the incremental form of member basic force and deformation relationship of 3D beam-column element can be expressed as

$$\begin{Bmatrix} \Delta P \\ \Delta M_{yA} \\ \Delta M_{yB} \\ \Delta M_{zA} \\ \Delta M_{zB} \\ \Delta T \end{Bmatrix} = \frac{1}{L}\begin{bmatrix} EA & 0 & 0 & 0 & 0 & 0 \\ 0 & S_{1y}EI_y & S_{2y}EI_y & 0 & 0 & 0 \\ 0 & S_{2y}EI_y & S_{1y}EI_y & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{1z}EI_z & S_{2z}EI_z & 0 \\ 0 & 0 & 0 & S_{2z}EI_z & S_{1z}EI_z & 0 \\ 0 & 0 & 0 & 0 & 0 & GJ \end{bmatrix}\begin{Bmatrix} \Delta\delta \\ \Delta\theta_{yA} \\ \Delta\theta_{yB} \\ \Delta\theta_{zA} \\ \Delta\theta_{zB} \\ \Delta\phi \end{Bmatrix} \tag{1}$$

where ΔP, ΔM_{yA}, ΔM_{yB}, ΔM_{zA}, ΔM_{zB}, and ΔT are incremental axial force, end moments with respect to y and z axes, and torsion, respectively; $\Delta\delta$, $\Delta\theta_{yA}$, $\Delta\theta_{yB}$, $\Delta\theta_{zA}$, $\Delta\theta_{zB}$, and $\Delta\phi$ are the incremental axial displacement, the joint rotations, and the angle of twist, respectively; A, I_y, I_z, J and L are area, moments of inertia with respect to y and z axes, torsional constant, and length of beam-column element; E and G are elastic and shear modulus of material; S_{1n} and S_{2n} are the stability functions with respect to the n axis ($n = y, z$) given by Chen and Lui [44] as

$$S_{1n} = \begin{cases} \dfrac{k_nL\sin(k_nL) - (k_nL)^2\cos(k_nL)}{2-2\cos(k_nL) - k_nL\sin(k_nL)} & \text{if } P < 0 \\[2ex] \dfrac{(k_nL)^2\cosh(k_nL) - k_nL\sinh(k_nL)}{2-2\cosh(k_nL) + k_nL\sinh(k_nL)} & \text{if } P > 0 \end{cases} \tag{2}$$

$$S_{2n} = \begin{cases} \dfrac{(k_nL)^2 - k_nL\sin(k_nL)}{2-2\cos(k_nL) - k_nL\sin(k_nL)} & \text{if } P < 0 \\[2ex] \dfrac{k_nL\sin(k_nL) - (k_nL)^2}{2-2\cosh(k_nL) + k_nL\sinh(k_nL)} & \text{if } P > 0 \end{cases} \tag{3}$$

where $k_n^2 = |P|/EI_n$.

2.2. Improved fiber plastic hinge model accounting for inelastic effects

In this study, a new improved fiber plastic hinge model as illustrated in Fig. 1 is presented. The material nonlinearity includes gradual yielding of steel associated with residual stresses, axial force and bending moments. The spread of plasticity along the member length due to residual stresses and the impact of axial force is considered by utilizing the Column Research Council (CRC) tangent modulus concept E_t, while the gradual yielding due to flexure is represented by two fiber plastic hinges at the ends of the element. Since inelastic behavior in beam-column elements often concentrates at the ends of the member, the monitoring of the end sections of the element is advantageous from

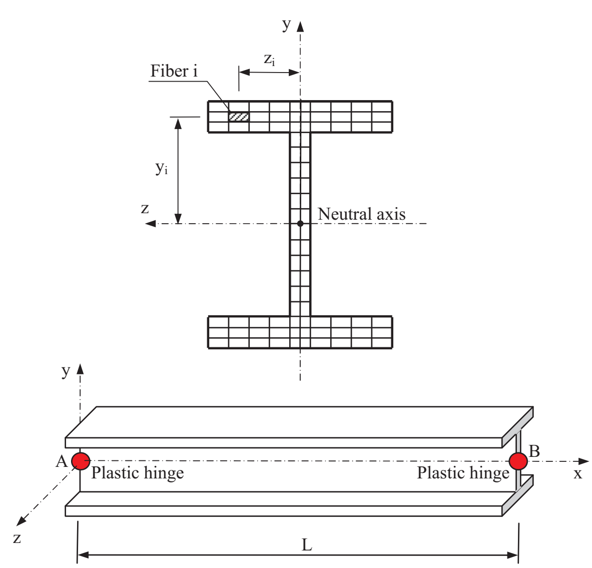

Fig. 1. New improved fiber plastic hinge method.