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Inelastic second order analysis of steel frame elements flexed about minor axis

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ABSTRACT

Frame elements may be subjected to significant bending moments about cross-sectional minor axis such as space frame elements and struts that buckle about minor axes. In some cases such as columns with compound cross-sections, the major bending moment acts about minor axes of cross-sectional components. The present paper proposes a simplified model for predicting the second order inelastic behavior of steel frame elements under axial compression force and bending moment about minor axis. New formulae are proposed to describe the plastic strength surface for steel I- and H-shaped cross-sections under axial force and bending moment about minor axis. Moreover, empirical formulae are developed to predict the tangent modulus for those cross-sections. The tangent modulus formulae are extended to evaluate the secant stiffness that is used for internal force recovery. The formulae are derived for steel sections considering the residual stresses as recommended by the European Convention for Construction Steelwork (ECCS). A finite element program is prepared to predict the inelastic second order behavior of plane frames using the derived formulae. The derived model exhibits good correlations when compared with the fiber model results. The analysis results indicate that the new model is accurate, furthermore it saves a lot of calculation time that may be consumed by iterations on the cross-sectional level.

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1. Introduction

Nowadays, considerable research is devoted to problems of steel frames considering geometric and material nonlinearities. In general, these studies may be categorized into two main types: plastic hinge analysis and plastic zone analysis. The plastic hinge formulation is the most direct approach for representing inelasticity in a beam–column element [1–3]. Numerous studies have shown that the elastic–plastic hinge approach is limited by its ability to provide the correct strength assessment of beam–columns that fail by inelastic buckling. This is because the elastic–plastic hinge analysis assumes that the cross-section behaves as either elastic or fully plastic, and the element is fully elastic between the member ends [4–6]. In this model, the effect of residual stresses between hinges is not accounted for either. The stability functions are introduced to consider geometric nonlinearities using only one beam–column element to define the second order effect of an individual member so that they are an economical method in frame analysis [7,8]. This method accounts for inelasticity but not the spread of yielding through the section or between the hinges. For slender members in which failure mode is dominated by elastic instability, the plastic hinge method compares well with plastic zone solutions. However, for stocky members that suffer significant yielding, it overestimates the capacity of members due to neglect of gradual reduction of stiffness as yielding progresses through and along the member. Research was directed in order to modify the plastic hinge method. The so-called refined plastic hinge analysis, based on simple refinements of the elastic–plastic hinge model, was proposed for frame analysis in recent works in order to overcome the disadvantages of the elastic–plastic hinge method [9–13].

On the other hand, the plastic zone method uses the highest refinement for predicting the inelastic behavior of framed structures. In the plastic zone method, a frame member is discretized into finite elements, and the cross-section of each finite element is subdivided into many fibers [14–17]. The internal forces are calculated by integrating the cross-sectional subelement forces. The residual stress in each fiber may be explicitly determined and can be easily considered, so, the gradual spread of yielding can be traced [18,19]. Because the spread of plasticity and residual stresses are accounted for directly, a plastic zone solution is considered an exact method. Although the plastic zone solution may be considered 'exact,' it is not conducive to daily use in engineering design, because it is too computationally intensive and too costly.

Recently, a new simplified model was proposed by the author based on the plastic zone method [20]. In this model, closed formulae were derived to predict the tangent modulus of steel I- and H-shaped cross-sections subjected to combined axial force and uniaxial bending moment about cross-sectional strong axis considering the residual stresses. The model eliminates

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