Engineering Structures 48 (2013) 155–165

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Inelastic large deflection analysis of space steel frames including H-shaped cross sectional members

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ARTICLE INFO

Article history:
Received 11 April 2012
Revised 15 August 2012
Accepted 21 September 2012
Available online 24 November 2012

Keywords:
Inelastic
Large deflection
Space frame
Nonlinear analysis
Residual stresses
Beam–column

ABSTRACT

This paper presents an efficient inelastic and large deflection analysis of space frames using spread of plasticity method. New accurate formulae are proposed to describe the plastic strength surface for steel wide-flange cross sections under axial force and biaxial bending moments. Moreover, empirical formulae are developed to predict the tangent modulus for cross sections under the combined forces. The tangent modulus formulae are extended to evaluate the secant stiffness that is used for internal force recovering. The formulae are derived for steel sections considering the residual stresses as recommended by European Convention for Construction Steelwork (ECCS). A finite element program based on stiffness matrix method is prepared to predict the inelastic large deflection behavior of space frames using the derived formulae. The finite element model exhibits good correlations when compared with the fiber model results as well as previous accurate models. The analysis results indicate that the new model is accurate and computational efficient.

1. Introduction

In recent years, there were numerous researches on the simulation of the nonlinear behavior of beam–columns in space steel frames [1–6]. In general, the nonlinear behavior of steel frame can be predicted by using finite element method in which frame members are modeled by using solid, plate or shell elements [7,8]. This method could successfully capture the nonlinear behavior of the structure but it is too time-consuming because of the great number of elements required for this type of analysis. Moreover, the model processing of this analysis type is not easy at all. In the other direction of nonlinear analysis of steel frames, a "line elements" approach is widely used. These studies may be categorized into two main types: plastic hinge analysis and spread of plasticity analysis. The plastic hinge formulation is the most direct approach for representing inelasticity in a beam–column element [9–12]. In plastic hinge approach, the effect of material yielding is lumped into a dimensionless plastic hinge. Generally, this type of analysis is limited by its ability to provide the correct strength assessment of beam–columns that fail by inelastic buckling. This is because the 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 [13–15]. In this model, the effect of residual stresses between hinges is not accounted for either. The advantages of this method are its simplicity in formulation as well as implementation and the least elements needed for member modeling. The stability functions may be introduced to consider geometric nonlinearities using only one beam–column element to define the second-order effect of an individual member so it is an economical method for frame analysis [16,17]. This method accounts for inelasticity but not the spread of yielding through the section or between the plastic hinges. For slender members in which failure mode is dominated by elastic instability, the plastic hinge method compares well with spread of plasticity 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. The so-called refined plastic-hinge analysis, based on simple refinements of the plastic hinge model, was proposed for frames analysis in order to overcome disadvantages of the elastic–plastic hinge method [18–20].

On the other hand, the spread of plasticity method uses the highest refinement for predicting the inelastic behavior of framed structures. In the spread of plasticity method, the gradual spread of yielding is allowed through the volume of the members. In this method, a frame member is divided into subelements, and the cross-section of each element is subdivided into many fibers [21–25]. The internal forces are calculated by integrating the cross sectional subelement forces. In such case, residual stress in each fiber can be explicitly considered, so, the gradual spread of yielding can be traced [26–31]. Because of considering the spread of plasticity and residual stresses in a direct way, a spread of plasticity solution is considered an exact method. Although the spread of

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http://dx.doi.org/10.1016/j.engstruct.2012.09.024

plasticity solution may be considered ‘exact’, it is still too computationally intensive and too costly. Among these two types of analysis the co-called fiber hinge method was developed in an attempt to take the advantages of the two methods [32]. In which, the element is divided into three segments, two end-fiber hinge segments and an interior elastic segment, to simulate the inelastic behavior of the material according to the concentrated inelastic approximation. The mid-length of end hinge segment is divided into fibers so that the uniaxial stress–strain relationships of the fibers can be monitored during the analysis process.

Recently, a new simplified model was proposed by the Author based on the spread of plasticity method in an attempt to eliminate the need of cross section discretization [33,34]. In this model, closed form formulae were derived to predict the tangent modulus of steel cross sections subjected to combined axial force and uniaxial bending moment about major or minor axis considering the residual stresses. Due to eliminating the integration of internal forces on the cross section level, a lot of consumed computational time could be saved. In the present paper tangent modulus of wide-flange steel cross sections subjected to axial compression force and biaxial bending is derived. New formulae are derived by simulation of the results obtained from the fiber model. Prior to the derivation of tangent modulus, new plastic strength surfaces for H-shaped cross sections subjected to axial force and biaxial bending moment are proposed. The model achieves the accuracy of the spread of plasticity method but in an easy and a direct way. The research aims to eliminate complex calculations and so minimizing the consumed running time and the cost. The updated-Lagrangian method is applied in the formulation of the incremental matrix equilibrium equations of the proposed beam–element model [35,36]. The minimum residual displacement combined with Newton–Raphson method is used to satisfy the convergence when solving the nonlinear equilibrium equations.

2. Numerical model

2.1. Basic assumptions

The following assumptions are made in the formulation of the beam–column element:

(1) A plane cross section remains plane after deformation.
(2) Local buckling and lateral torsional buckling are not considered.
(3) Small strains but large displacements and rotations are considered.
(4) Only H-shaped sections are considered.
(5) Strain hardening is not considered.
(6) The effects of shear forces and torsional moment are not considered when deriving the cross sectional plastic surface as well as the tangent modulus.

2.2. Cross-section plastic strength

The determination of cross-section plastic strength surface is very essential in order to predict the nonlinear behavior of structural members. The most common formulae that describe the full plastification surface for cross sections are those proposed by AISC–LRFD and Orbison. Recently, analytical plastic interaction criteria for steel I-sections under biaxial moment and axial force were developed by Baptista [37]. Although the method requires many calculations, it is considered as an exact method.

For cross sections subjected to axial force and biaxial bending moments about both axes, Orbison’s formula is given as [38]

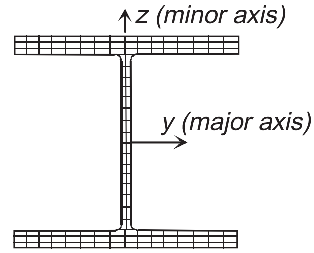

Fig. 1. Cross sectional fiber model.

$$1.15p_r^2 + m_{ry}^2 + m_{rz}^4 + 3.67p_r^2m_{ry}^2 + 3p_r^6m_{rz}^2 + 4.65m_{rz}^2m_{ry}^4 = \alpha \quad (1)$$

while the AISC–LRFD plastic surface formula is given as [39]

$$\frac{1}{2}p_r + m_{rz} + m_{ry} = \alpha \quad \text{for } p_r \leqslant \frac{2}{9}m_{rz} + \frac{2}{9}m_{ry} \quad (2.a)$$

$$p_r + \frac{8}{9}m_{rz} + \frac{8}{9}m_{ry} = \alpha \quad \text{for } p_r > \frac{2}{9}m_{rz} + \frac{2}{9}m_{ry} \quad (2.b)$$

where α is a factor that equal unity at full plastification surface, p_r is the ratio of the applied normal force P to the yield value P_y at the plastic strength envelope ($p_r = P/P_y$), and m_{rz} and m_{ry} are the ratios of the applied bending moments M_z (about minor axis) and M_y (about major axis) to the corresponding plastic moments M_{pz} and M_{py}, respectively, at the plastic strength envelope.

In the present paper, a new formula is derived to describe the wide flange cross section plastic strength surface based on the results obtained from the analysis of many cross sections. The cross sections are analyzed using the fiber model in which the cross section is discretized into small fibers as shown in Fig. 1. The analyzed cross sections are selected to cover all popular universal column cross sections. Twenty universal column sections (H-shaped section) are analyzed in which the ratios B/T = 5.5–22.4, D/t = 10–34.2 and D/B = 0.97–1.13, where D, B are the cross section depth and the flanges breadth, respectively, and t and T are the thicknesses of cross section web and flanges, respectively.

The cross sections are analyzed using linear strain distribution along their axes. For each cross section, curvatures with different ratios are gradually increased until reaching the maximum possible bending moments at a fixed value of axial force. The internal forces (P, M_y and M_z) are evaluated by accumulation of uniaxial stresses for all cross section discrete as follows:

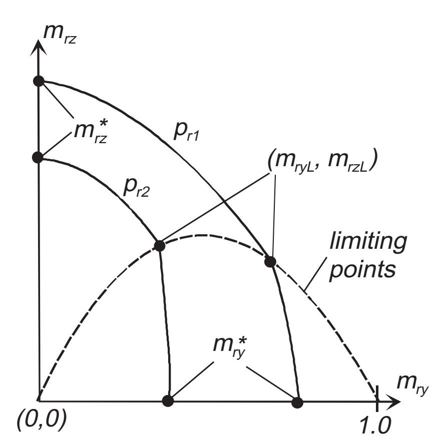

Fig. 2. Proposed cross sectional plastic strength.