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Inelastic large deflection analysis of space steel frames using an equivalent accumulated element

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ABSTRACT

This paper presents a new model to perform inelastic large deflection analysis of space steel frames depending on the spread of plasticity method. A stiffness matrix of a beam-column element with only two nodes and six degrees of freedom for each node is derived to represent the space frame member. The proposed matrix includes the effect of section yielding along the member as well as the effect of large deflection. Stiffness degradation at the cross-section due to yielded parts is calculated using a formula for the tangent modulus which is affected by the sectional internal forces. The proposed technique of accumulation of rigidity factors is submitted as a first step to get exact first order stiffness factors for a member with variable cross sections. The effect of large deflection is included by considering the axial force while deriving the stiffness factors. Both cubic and higher order shape functions are tried to produce an element that can represent the member without discretization. A finite element program based on stiffness matrix method is developed to predict the inelastic large deflection behavior of steel space frames using the derived stiffness matrix. The proposed finite element technique exhibits good correlation when compared with the conventional spread of plasticity model results. Verification by solving benchmarked steel structures is carried out. The analysis results indicate that the new model is accurate with simple equations and it achieves a significant improvement to the run time.

1. Introduction

The use of computers in structural analysis helped carrying out a huge amount of computations to explore more realistic response of structures by including effects that were ignored before. Nowadays, advanced analysis including effects of geometric and material nonlinearity is allowed in some specifications [1,2]. Geometric nonlinearity was studied by many researchers through the last five decades. Instead of using k factors to check member stability, many beam-column elements were submitted to merge the second order effect in element stiffness matrix. Large deflection analysis of frames using a beam-column element can find the structure manner with little amount of computations comparing to other finite element nonlinear analyses. The stiffness coefficients derived by Oran [3,4] formed a beam-column tangent matrix of stiffness containing large deflection effect by adding stability functions. Despite of the accuracy of Oran's stability functions, problems may occur because of the different equations used according to the case of normal force. To improve Oran's matrix, Kassimaly and Oran [5] added coupling terms and studied the response under dynamic loads considering large deformation. Many researchers used the stability functions for large deflection frame analysis [6–8]. Member initial out-of-straightness was represented by an exact function developed by Chan and Gu [9]. In addition to the well-known stability functions, equations for the lateral torsion buckling effect were included by Kim et al. [10]. Cubic shape function was used by many researchers developing cubic Hermite element [11–14]. For asymmetric thin walled sections, Chan and Kitipornchai [14], employed the cubic element for non-linear analysis. Meek and Tan [11], derived the cubic element using the principle of minimum potential energy using arc-length method for non-linear solving. Unlike the expressions of stability functions, the expressions of cubic-Hermite element are simple and similar in both tension and compression. The disadvantage of the cubic-Hermite element is its low accuracy when using one element for the member. Chan and Zhou [15] derived a new element based on a fifth order shape function. As an initial imperfection, the member out-of-straightness was included by Chan and Zhou [16] during the formulation of a fifth order element. The previous shape function was modified by Zhou and Chan [17] to include member lateral loads. Seismic response of imperfect member was studied by Liu and Chan [18] using an element based on the same higher order function. Using one element per member, acceptable accuracy was achieved employing a fourth order element by So and Chan [19]. Elastic and inelastic buckling analysis were studied by Iu and Bradford [20–22] producing a new higher order element. Third additional

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node was added by Chen and Chan [23] to generate a beam-column element with springs at the ends and mid-span. Liu [24] included the span loads and arbitrary location for the span point with rotational spring to model the yield along the member span.

Ordinary finite element can represent the inelasticity at any location of the member with the help of member dividing to shell or solid element. To avoid huge amount of calculation, techniques based on beam-column element were proposed by many researchers [25–27]. For the plastic hinge and plastic zone approaches, concentrated plasticity is considered during plastic hinge analysis. Abbasina and Kassimaly [28], used plastic hinges for studying space frames with large deformations. Chandra et al. [29], employed plastic hinges to model inelasticity while developing a technique for non-linear solving. Liew et al. [30], calculated forces at five points along the member and permitted plastic hinge to form at member span. While Shungyo [31], used plastic hinge to model semi-rigid connections of space frames. For seismic analysis, plastic hinges achieved good results by Liu et al. [18]. Because of the saved analysis time by plastic hinges, it was developed to give more accurate results by considering gradual yielding [32,33]. Chen and Chan [23], used refined plastic hinge (RPH) to model plasticity. Zhou and Chan [34], modified fifth order shape function to include one RPH with arbitrary position along the member. The work in [34] was extended by Zhou and Chan [35], to find the displacement function of a member with three hinges. Movable RPH for member with span loads was studied by Kim and Choi [36]. Using flexibility-based inelastic analysis, Chiorean and Marchis [37], used plastic hinges for tapered elements without dividing the member. Fiber hinge assumes the member to consist of one elastic part between two inelastic parts. At the mid length of assumed inelastic part, dividing section to many fibers helps to model inelasticity [38]. Accuracy of fiber hinge and its effective factors were investigated to get more realistic modeling [39,40]. The main disadvantage of plastic hinge approach, assumed concentrated plasticity, can be avoided by plastic zone analysis. By discretizing the member, inelasticity at any location along the span can be captured to get reference solutions [41,42]. More calculations are required for plastic zone than plastic hinge but more accuracy is gained [43]. Jiang et al. [43], submitted a mixed element to obtain advantages of two approaches. Zubydan [44–46], suggested formulae to evaluate tangent modulus instead of section discretizing to save analysis time. Initial imperfections were included by Du et al. [47], using flexibility based analysis. Using one element per member, the distributed plasticity can be captured in the flexibility based analysis but it costs much computations for the required integrations [47,50]. Residual stresses were documented by specifications like ECCE [48]. To get more realistic modeling, the residual stresses should be included in the analysis because the plasticity spread along the member span increases in the presence of residual stresses [52]. Because of the advantages of representing the frame member with one element, it has been examined for steel-concrete composite frames by Faella et al. [53].

This paper suggests a new element intended to capture effects of distributed plasticity along member with large deflections using only one proposed element per member. A higher order displacement function is employed to represent the large deflections of the proposed element. Accumulation technique is suggested to form stiffness coefficients for inelastic member. The proposed stiffness coefficients are calculated using closed form expressions without numerical integrations. The proposed two-nodes element aims to represent a space frame member with distributed plasticity during an accurate analysis with less computational costs.

2. Numerical models

2.1. The equivalent element

For a loaded frame member, the spread of plasticity is assumed to be distributed along the volume of the member. Rigidity degradation at span cross-sections reduces the stiffness of the overall member. Using only one proposed element, the frame member will be represented including plasticity spread along the span. Fig. 1 shows the proposed equivalent element which will be used to model space frame member with yielded parts. The proposed element assumes the member consists of n number of internal segments. Every internal segment starts with a monitored section and ends with another one. During analysis steps, the internal forces at any cross-section along the member can be obtained from nodal forces and displacement function. At any span section, the calculated internal forces provide accurate indication of section modulus (EI) which degrades due to the plasticity spread. The value of EI_k for every internal segment can be found using the average value of section modulus at start and end monitored sections.

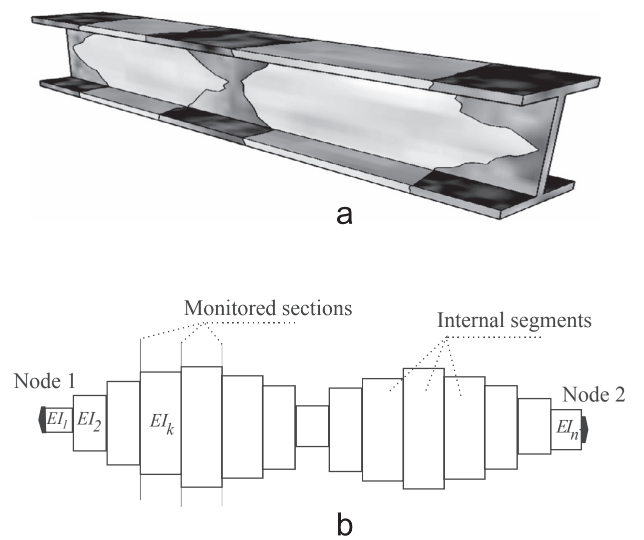

Fig. 1. Proposed equivalent element. a. Member with yielded parts. b. Two nodes equivalent element with (n) number of internal segments.

Section 2.3 is concerning about deriving stiffness coefficients of first order moments neglecting axial force effects. Material nonlinearity is included with first order stiffness coefficients by updating the degraded values of (EI) for the monitored sections according to the plasticity spread. The stiffness coefficients derived in Section 2.3 can be used for inelastic frame analysis neglecting effects of second order due to axial force. As the proposed element has varying values of EI for its internal segments, the displacement functions cannot exactly approach the actual behavior of the element. So, the stiffness coefficients would not be accurate if they have been derived using the displacement functions. The nodal moments can overcome this problem and provide accurate relations between the displacements and the corresponding forces. Therefore, the nodal moments are used to derive the first order stiffness coefficients as shown in Section 2.3.

To include second order effects due to axial force, displacement functions are used to find only the second order terms in the stiffness coefficients (Sections 2.4 and 2.5). Because the first order terms in the stiffness coefficients are based on the nodal moments, the effects of the approximations due to using the displacement function are trapped in the second order terms only. Second order effect is included in the derivation of stiffness coefficients by using Cubic displacement function (Section 2.4) and, alternatively, fourth order displacement function (Section 2.5).

2.2. Basic assumptions

1. Plane sections remain plane after deformation.
2. All members are assumed to be restrained against lateral torsional buckling.
3. All cross-sections are bi-symmetric and have no local buckling.
4. Only nodal loads are permitted.