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A computer method for nonlinear inelastic analysis of 3D semi-rigid steel frameworks

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ABSTRACT

This paper presents an efficient computer method for inelastic and large deflection analysis of steel space frames with non-linear flexible joint connections, based on the most refined type of second order inelastic analysis, the plastic zone analysis. The method employs modeling of structures with only one element per member, which reduces the number of degree of freedom involved and the computational time. Gradual yielding of cross-sections is modeled using the nonlinear inelastic force strain relationships, and then using the flexibility approach the elasto-plastic tangent stiffness matrix and equivalent nodal loads vector of 3-D beam-column element is developed. The method ensures also that the plastic bending moment is nowhere exceeded once a full plastified section develops. A zero-length rotational spring element is used for incorporating the connection flexibility into the element tangent stiffness matrix and equivalent nodal forces. The combined effects of material, geometric and connection behaviour nonlinearity sources are simulated into an object oriented computer program automatically. This program was used to study the ultimate response of several steel frames, which have been studied previously by other researchers. The example of computations and the comparisons made have proved the robustness, accuracy and time saving of the proposed analysis method.

1. Introduction

With the rapid advancement of computer technology, research works are currently in full swing to develop advanced nonlinear inelastic analysis methods and integrate them into the new and more rational advanced analysis and design procedures. There currently exist several methods of large deflection elasto-plastic analysis that calculate strength limit states of 3-D steel frames with rigid and semi-rigid connections [1–8]. These methods, that use ‘‘line elements’’ approach, are based on the degree of refinement in representing the plastic yielding effects and can be categorized in two main types, plastic hinge versus spread of plasticity approaches. In the plastic hinge approach, the effect of material yielding is ‘‘lumped’’ into a dimensionless plastic hinge. Regions in the frame elements other than at the plastic hinges are assumed to behave elastically, and if the cross-section forces are less than cross-section plastic capacity, elastic behaviour is assumed. The plastic hinge approach eliminates the integration process on the cross section and permits the use of fewer elements for each member, and hence greatly reduces the computing effort. Unfortunately, as plastification in the member is assumed to be concentrated at the member end, the plastic hinge model is usually less accurate in formulating the member stiffness.

In the spread of plasticity approach, the gradual spread of yielding is allowed throughout the volume of the members. There are two main approaches that have been used to model the gradual plastification of members in a second-order inelastic analysis. In both cases the member needs to be subdivided into several elements along its length to model the behaviour accurately [9,6]. Cross sectional behaviour may be described by moment-curvature-truss (M–Φ–P) relations derived for each cross-section in the analysis. Alternatively, the cross-section can be subdivided into elemental areas and the states of strain, stress and yield stress are monitored explicitly for each of the elemental areas during the analysis. In this case, the effects of residual stresses, geometric imperfections and material strain hardening can be accurately included in the plastic-zone analysis. Hence, the plastic-zone approach is considered to closely simulate the actual behaviour of a member, but the computational effort is greatly enhanced and the method becomes prohibited computational in the case of large scale frame structures.

However, the rapid development of computer technology in recent years has enabled the plastic zone theory in which the spreading of plastic zones in members is taken into account to be developed. A number of computer programs have been developed on this theory in recent years by researchers. Unfortunately, the currently available methods for second-order spread of plasticity analysis and advanced analysis are not user friendly for practical applications. These methods ignore many important characteristics and requirements for practical design, consistency between

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the linear and nonlinear models due to the need to use several elements per member to model the distributed loads and spread of plasticity along the member length and the computational effort.

The approach presented in this paper is intended to overcome these inconveniences and represents an efficient computer method for large displacement distributed plasticity analysis of 3D semi-rigid steel frames fulfilling the practical and advanced analysis requirements. The non-linear inelastic static analysis employed herein uses the accuracy of the most refined type of second order inelastic analysis, the spread-of-plasticity analysis and addresses its efficiency and modeling shortcomings through the use of only one element to model each physical member of the frame. Gradual plastification through the cross-section is handled by fitting nonlinear equation to data for the force–strain behaviour of a unit-length segment of the element. Because these relations depend on the characteristics of each cross-section in the analysis, the gradual plastification of the cross-section of each member is accounted for by smooth force–strain curves that are experimentally calibrated. This way, inelastic behaviour in the member is modeled in terms of member forces instead of the detailed level of stresses and strains, with favourable effects on the computational effort. The inelastic cross-section model is then used to obtain flexibility coefficient for the full member by numerical integrations along its length. The effects of material yielding along the member, on the element stiffness degradation, are considered by axial and flexural rigidity, of the element, depending on the sectional efforts, at each load increment. The development of the element stiffness matrix is carried out through the flexibility matrix of the element. The geometrical nonlinear local effects are taken into account in analysis, for each element, by the use of stability stiffness functions in a beam-column approach, and updating at each load increment the length, flexural rigidity, and axial force of the element, following an approach outlined in the next section. A procedure is presented to enforce the force-point movement to remain on the plastic strength surface of a member, once a full plastified section develops. In this way, since the force-point movement remains on the plastic strength surface of a member, the yield criterion is always satisfied after the full plastic strength of cross-section is reached. To perform the nonlinear analysis of frame structures, in the majority of previous publications, the loads are assumed to apply only at the nodes. In the present investigation, the loading due to the member lateral loads is transferred to the nodes and included automatically in the analysis. This leads to a significant saving in imputing the member loads, without the need to divide a member into several elements for simulation of these loads. The effect of semi-rigid connections is included in the second-order elasto-plastic analysis using the zero-length rotational spring element approach. A procedure is presented to asses this effect on element stiffness matrix and equivalent nodal forces. The analytical model proposed in [10,11] is used to describe the non-linear behaviour of semi-rigid connections.

Using an updated Lagrangian formulation, the global geometrical effects are considered updating the geometry of the structure at each load increment. In the present spread-of-plasticity analysis the web plane vector approach proposed in [12] is effectively used to update the frames element coordinate.

For normal building frameworks, the lateral response of the floor slab may be characterized by two translational and one rotational degrees of freedom located at the floor master node. In the present approach, the multi-freedom constraints, required by the rigid body floor model, are imposed by augmenting the beam-column element model, with the penalty elements.

The combined effects of these three nonlinearity sources are simulated into an object-oriented computer program automatically. This program was used to study the ultimate response of several rigid and semi-rigid steel frames that has been studied previously by other researchers [11,13,5,6]. The example computations and the comparisons made have proved the effectiveness and time saving of the proposed method. The proposed software is presented as an efficient, reliable tool ready to be implemented into design practice for advanced analysis and pushover analysis of spatial frame structures.

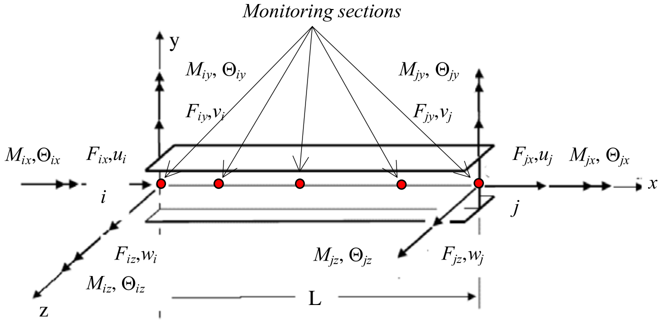

Fig. 1. Positive convention for force and displacement components of a beam column element.

2. Mathematical formulation

In this paper, the following assumptions are adopted in the formulation of analytical model: (1) Plane section remain plane after flexural deformation; warping and cross-section distortion are not considered; (2) flexural-torsional buckling do not occur; (3) small strain but arbitrarily large displacements and rotations are considered; (4) nonlinearity is due to flexural joint flexibility, material inelasticity, local and global geometrical change; (5) the connection element is of zero length. A frame member (Fig. 1) is idealized as 2-noded 3D beam-column element with 12 degrees of freedom. Each of the element nodes has 6 DOF (3 displacements and 3 rotations). The elastic unloading effect is included in analysis, but hysteretic and softening effects associated with damage in building frames under severe loadings are not taken into account. The proposed approach is based on the most refined type of second order inelastic analysis, the plastic zone analysis, and employs modeling of structures with only one element per member, which reduces the number of degree of freedom involved and the computational time.

2.1. Elasto-plastic tangent stiffness matrix and equivalent nodal loads

2.1.1. Elasto-plastic cross section analysis

The cross-section stiffness may be modeled by explicit integration of stresses and strains over the cross-section area (e.g., as micro model formulation) or through calibrated parametric equations that represent force-generalized strain curvature response (e.g. macro model formulation). In the micro model formulation, the cross-sections are subdivided into elemental areas and the states of strain and stress monitored explicitly for each elemental area during the analysis, but the computational efforts are greatly enhanced [1,14]. As it was stated previously, in the present elasto-plastic frame analysis approach, gradual plastification through the cross-section subjected to combined action of axial force and biaxial bending moments may be described by moment-curvature-thrust (M–Φ–N), and moment-axial deformation-thrust (M–ε–N) analytical type curves that are calibrated by numerical tests. The effect of axial forces on the plastic moments capacity of sections is considered by standard strength interaction curves [5,15]. Two force-deformations type curves are taken into account in the present investigation, Ramberg–Osgood and modified Albermani force–strain curves, respectively.

2.1.1.1. Ramberg–Osgood force–strain relationship. Gradual plastification through the cross-section subjected to combined action of