Engineering Structures 57 (2013) 125–152

Contents lists available at ScienceDirect

Engineering Structures

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

A computer method for nonlinear inelastic analysis of 3D composite steel–concrete frame structures

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ARTICLE INFO

Article history:
Received 21 March 2013
Revised 12 September 2013
Accepted 16 September 2013
Available online 18 October 2013

Keywords:
Distributed plasticity
Large deflection
Tangent flexural rigidity
Residual stresses
3D frameworks
Advanced inelastic analysis

ABSTRACT

This paper presents an efficient computer method for nonlinear inelastic analysis of three-dimensional composite steel–concrete frameworks. The proposed formulation is intended to model the geometrically nonlinear inelastic behaviour of composite frame elements using only one element per physical member. The behaviour model accounts for material inelasticity due to combined bi-axial bending and axial force, gradual yielding is described through basic equilibrium, compatibility and material nonlinear constitutive equations. In this way, the states of strain, stress and yield stress are monitored explicitly during each step of the analysis, the arbitrary cross-sectional shape, various stress–strain relationships for concrete and steel and the effect of material imperfections such as residual stresses are accurately included in the analysis. Tangent flexural rigidity of cross-section is derived 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 ultimate strength capacity of the cross-section is nowhere exceeded once a full plastified section develops. The proposed nonlinear analysis formulation has been implemented in a general nonlinear static purpose computer program. Several computational examples are given to validate the effectiveness of the proposed method and the reliability of the code to approach large-scale spatial frame structures.

1. Introduction

In recent years, have witnessed significant advances in nonlinear inelastic analysis methods for steel and composite steel–concrete framed structures and integrate them into the new and more rational advanced analysis and design procedures [1,2]. Reliable nonlinear analysis tools are, for instance, essential in performance-based earthquake engineering, and advanced analysis methodologies, that involves accurate predictions of inelastic limit states up or beyond to structural collapse. A number of approaches have been proposed in the last years to model the nonlinear response of composite steel–concrete elements [3–24]. A detailed discussion about this issue can be found in [3,4].

There currently exist several methods and computer programs concerning the nonlinear inelastic analysis that calculate strength limit states of steel and composite steel–concrete frame structures. At one extreme, two-and three dimensional finite elements enhanced with advanced material constitutive laws [14,15,17] were used to investigate the nonlinear response of steel and composite steel–concrete frame members. Currently the available tools for such analysis are general purpose FE programs that require very fine-grained modelling that is often impractical to the structural engineer. At the other extreme, the line elements approach in conjunction with either *distributed* or *concentrated* plasticity models, have been devoted to the development of nonlinear analysis tools for frames that provide a desirable balance between accuracy and computational efficiency [5–13,16–31].

In the concentrated plasticity approach [16,18–20] which is usually based on the plastic hinge concept, the effect of material yielding is "lumped" into a dimensionless plastic hinge. Regions in the beam-column elements other than at the plastic hinges are assumed to behave elastically. In the plastic hinge locations if the cross-section forces are less than cross-section plastic capacity, either elastic behaviour or gradual transition (*refined plastic hinge*) from elastic to plastic behaviour is assumed. The plastic hinge approach could eliminate 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 ends, the plastic hinge model is usually less accurate in formulating the member stiffness, requires calibration procedures, but make possible to use only one element per physical member to simulate geometric and material nonlinearities in composite building frameworks [16,20]. In the distributed plasticity models gradual yielding and spread of plasticity is allowed throughout

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0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.09.025

cross-section and along the member length [5–14,17,22–32]. There are two main approaches that have been used to model the gradual plastification of members in a second-order inelastic analysis, one based on the *displacement method* or finite element approach [17,25] and the other based on the *force or flexibility method* [5–14,22–24,26–32]. Because displacement based elements implicitly assumed linear curvatures along the element length, accuracy in this approach when material nonlinearity is taken into account can be obtained only using several elements in a single structural member, thus the computational effort is greatly enhanced and the method becomes prohibited computational in the case of large scale frame structures. On the other hand in the flexibility based approach *only one element* per physical member can be used to simulate the gradual spread of yielding throughout the volume of the members but the complexity of these methods derives from their implementation in a finite element analysis program and the inclusion of the element geometrical effects [26]. Mixed finite element approaches have been developed also to model composite beams with bond slip [3,5,6,8,22]. However in order to allow the concrete and steel to have independent displacements all these methods include additional degrees of freedom at the element ends. When modelling the semi-rigid composite frameworks some difficulties may arise enforcing the compatibility conditions at the semi-rigid composite connections [23].

In the efforts to develop an intermediate solution that has the computational efficiency of plastic hinge methods and the accuracy of distributed plasticity methods several researchers developed *quasi-plastic hinge* [23,30–32] or *stress-resultant constitutive* models [21]. Although subject to some limitations of required calibration these methods have been shown to make distributed plasticity analyses practical for large scale 3D steel [30,31] and composite steel–concrete frameworks [21,23], usually only one element per member is necessary to analyze.

In spite of the availability of such nonlinear inelastic algorithms and powerful computer programs, the advanced nonlinear inelastic analysis of real large-scale composite steel–concrete frame structures still posses huge demands on the most powerful of available computers and still represents unpractical tasks to most designers.

The present work attempts to develop accurate yet computational efficient tools for the nonlinear inelastic analysis of real large-scale 3D composite steel–concrete frameworks fulfilling the practical and advanced analysis requirements. Essentially, nonlinear inelastic analysis employed herein uses the accuracy of the fibre elements approach for inelastic frame analysis and address its efficiency and modelling shortcomings both to element level, through the use of only one element to model each physical member of the frame, and to cross-sectional level through the use of path integral approach to numerical integration of the cross-sectional nonlinear characteristics. This is an essential requirement to approach real large spatial frame structures, combining modelling benefits, computational efficiency and reasonable accuracy.

Recent studies show that the slip effect between the steel and concrete interface has negligible influence on the global behaviour of multi-storey and high-rise fully connected steel–concrete composite frames [14]. In the proposed approach perfect bond between steel beam and concrete slab is assumed.

Within the framework of flexibility based formulation a 3D frame element with 12 DOF able to take into account the distributed plasticity and element second order effects is developed. Comparing the proposed method with the related methods developed in [26–29] the present approach has several features that make the proposed element more practical in the context of implementation in finite element analysis program and posses accuracy comparable to that of fibre-flexibility or fibre-displacement finite elements.

As will be briefly described in the following sections, the element incremental stiffness matrix and the equivalent nodal loads are derived directly from energetic principles. In this way the elements of the stiffness matrix and equivalent nodal loads can be obtained analytically and readily evaluated by computing the *correction coefficients* that affect the elastic flexibility coefficients and equivalent loads. In this way numerical integrations are required only to evaluate these correction coefficients and not the entirely flexibility or stiffness matrix elements as in [26–29]. Besides, the effect of the transverse shear deformation can be readily included in the element formulation, both in stiffness matrix and equivalent nodal loads. The resulting flexibility matrix of the element may have both elastic and plastic contributions. During the loading process unsymmetrical distribution of plastic zone throughout the cross-section may occur and consequently there are coupling between axial force and bending moments in elasto-plastic domain. The present formulation does not consider the plastic interaction terms relating the axial and bending terms in the flexibility/stiffness matrix of the element. However the neglected terms in flexibility matrix have only plastic contributions and may be ignored. This is obviously a simplification of the proposed approach whose acceptance must be justified by verification studies, but the resulting stiffness matrix does not incurring the expense of a detailed flexibility based methods [26–29]. In its final computerized implementation the proposed method is very similar to *quasi-plastic hinge* approaches [32]. Moreover, in the proposed approach, the effects of the discontinuity and/or discrete loading along element can be efficiently taken into account by writing a single moment equation in such a way that it becomes continuous for entire length of the element in spite of the discontinuity of loading. Thus the separate moment equation for each change of loading point is not required.

The element stiffness matrix are evaluated in [26–29] by an iterative procedure carried out at the element level, nested in the iterative procedure adopted to solve the nonlinear global structural response [33]. Thus approximations in the strain distribution along the element length, in the control sections, are required in the force-based frame elements. This fact makes these methods to be more complicated in implementation in finite element analysis framework. On the other hand, in the proposed approach the element force fields are described by the second order transfer matrix as function of the nodal and applied element forces and the inelastic response of the cross-sections (control points) is rigorously evaluated by enforcing the equilibrium between external and internal forces for each cross-section by a global convergence iterative procedure. In this way gradual yielding throughout the cross-section subjected to combined action of axial force and bi-axial bending moments is described through basic equilibrium, compatibility and material nonlinear constitutive equations, the states of strain, stress and yield stress are monitored explicitly during each step of the analysis, the arbitrary cross-sectional shape and the effect of material imperfections such as residual stresses are accurately included in the analysis. Tangent flexural and axial rigidity of the cross-sections are explicitly derived and the inelastic response at the element level is determined by integrating the variable section flexural EI_y and EI_z and axial EA rigidity along the member length, depending on the bending moments and axial force level, cross-sectional shape and nonlinear constitutive relationships.

Comparing the proposed formulation with those described in [23,25–29] another difference of the proposed approach refers to how the element geometrical effects are taken into account. In displacement-based formulations [23,25], the deformed shape of the element is obtained directly based on the nodal displacement values and the adopted shape functions. Thus the implementation of the element second-order effects are straightforward, but the accu-