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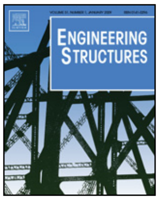

Simplified nonlinear response simulation of composite steel–concrete beams and CFST columns

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ABSTRACT

A computationally efficient macromodeling scheme to simulate the nonlinear behavior of composite structural connections consisting of steel–concrete composite beams and concrete-filled steel tubular (CFST) columns is investigated. The model proposed for composite beams, validated using four full scale composite beam tests, incorporates partial interaction between the concrete slab and the steel beam. The model proposed for CFST columns adopts fiber-based stress–strain relations that enable the consideration of strength and ductility for confined concrete and local buckling of the steel tube. The flexibility of the composite-beam-to-CFST-column connection is modeled as a panel zone. The validity of the simplified approach is evaluated by comparison of both overall response and local actions with those obtained from test results. The proposed methodology is shown to be viable for nonlinear analysis of composite structures wherein the modeling strategies are amenable to available features in modern nonlinear structural analysis software.

1. Introduction

Composite steel–concrete construction is gaining widespread use since the engineers can take advantage of the properties of both structural materials. For building systems, composite frames offer an economical solution to achieve the required stiffness and strength. In composite beams, significant composite action can be mobilized between steel beams and reinforced concrete slabs through shear studs that enable force transfer. In composite columns, concrete-filled steel tubes (CFST) may provide columns with higher bearing capacity and improved ductility since the concrete prevents local buckling of the steel tube and the steel tube provides confinement to the concrete and prohibits concrete spalling.

As suggested in the well-summarized review paper by Spacone and El-Tawil [1], current approaches to studying the nonlinear behavior of composite structural systems can be grouped into two categories: (1) micromodels, using 3D continuum finite element models by means of solid, shell, beam and truss elements to represent the constituents of the composite structural members in great detail, and (2) macromodels, based on 1D beam–column elements whereby the elements are derived by distributed or concentrated plasticity approaches. Hajjar et al. [2] modeled the composite frame connections using 3D finite elements to investigate the response of composite concrete floor slabs in moment frames. The details of the steel connections such as welds were modeled by highly discretized eight-node solid elements. Kim and Lu [3] analyzed 2D composite frames consisting of composite beams and encased composite columns by means of concentrated plasticity beam–column elements. Inelastic behavior was limited to each end of the beam–column element while the middle portion was assumed to remain elastic and the composite connections were modeled by inelastic springs. Bursi et al. [4] investigated the seismic performance of moment-resisting frames consisting of steel–concrete composite beams with full and partial shear connections. The layered distributed plasticity beam–column elements were used for the composite beams and the beam-to-column connections were assumed to be rigid. Bugeja et al. [5] used an enhanced version of the computer program IDARC [6] to perform inelastic dynamic analyses of composite frame systems consisting of steel-embedded reinforced concrete columns and composite beams. Tort and Hajjar [7] proposed analysis tools for composite frames composed of rectangular concrete-filled steel tube columns and steel girders. Column elements were formulated using 18-degree-of-freedom (DOF) distributed plasticity beam finite elements, in which translational DOFs of the steel tube and concrete core were defined independently to simulate slip behavior.

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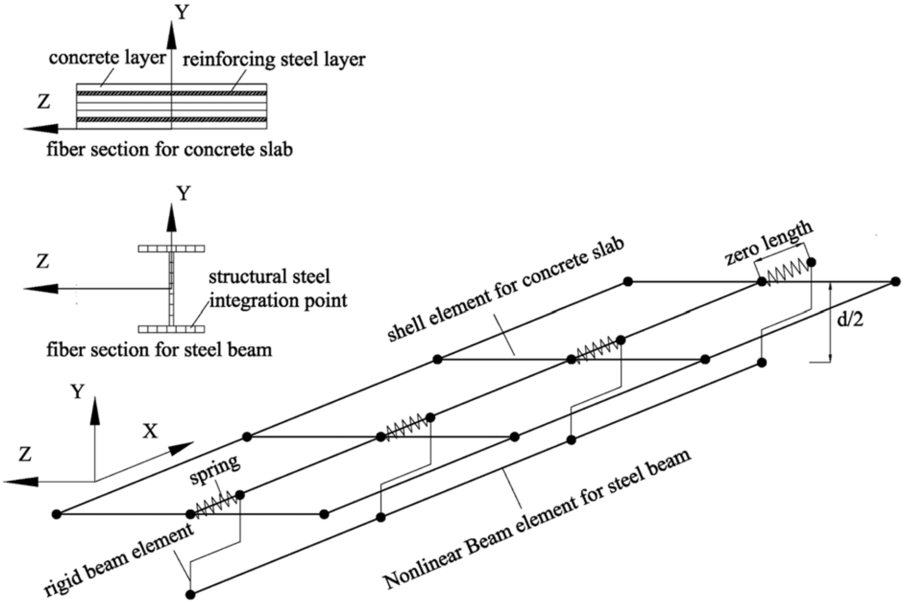

Fig. 1. Assembled macromodel representing a typical steel–concrete composite beam.

It is evident that most of the past research has focused on composite frames consisting of either steel–concrete composite beams and steel columns, or CFST columns and steel beams without considering the effects of concrete slab. Also, most of these models are typically based on the simplifying assumption that the beam-to-column joints are infinitely rigid and that the deformation of panel zone is insignificant. Future applications of composite systems to structures with larger spans and increased story heights necessitate the use of CFST columns and deeper composite beams. Very limited studies have been conducted to investigate the nonlinear response of composite frames consisting of steel–concrete composite beams and CFST columns.

While individual contributions in the past have considered composite elements in isolation, the analysis of complete structural systems calls for an investigation of critical load transfer mechanisms and important aspects of composite behavior that are essential to represent overall connection response. This study is therefore concerned with the development and validation of a simple macromodeling approach for the nonlinear analysis of composite frames comprised of steel–concrete composite beams and CFST columns. The contribution of this work lies in the examination of essential characteristics that need to be incorporated in a macromodel development of composite subassemblies and to develop modeling strategies that can be used with modern nonlinear finite element software.

The proposed approach considers partial interaction between the concrete slab and steel beam in composite beams. It also accounts for the strength and ductility of confined concrete and local buckling of the steel tube in CFST columns, and the flexibility of panel zones. A framework incorporating MDOF (multiple degrees of freedom) nonlinear discrete springs and rigid body constraints enables an assembly of beam–column and spring elements to represent essential actions in the response of composite structures. Inelastic effects can also be incorporated in the development of spring properties. The reliability of the present model is validated by comparisons with results from an experiment on a composite-beam-to-CFST-column subassembly conducted by Nie et al. [8].

2. Composite beam modeling

Nonlinear analysis models for composite structures that have appeared in the literature are either based on continuum finite elements [8,9] or macromodels based on line (frame) elements and spring connections [10,11]. Several researchers have also developed discrete line elements for composite members, incorporating both concentrated and distributed plasticity beam–column elements. Beam-with-hinges elements are a typical application of concentrated plasticity and have been formulated by Hajjar and Gourley [12], and Kim and Engelhardt [13]. Distributed plasticity models are usually based on discrete fibers of the cross section and can be found in work of Hajjar et al. [14], El-Tawil and Deierlein [15] and Lee and Pan [16]. However, most of these formulations are not amenable to generic and routine application in engineering analysis and design using currently available nonlinear software. Continuum-based micromodels predict the behavior of composite members accurately, but such models are computationally inefficient for nonlinear analysis of complete structural systems. Simple yet reliable macromodels therefore provide an alternative approach for evaluating nonlinear frame response.

The composite beam model proposed in this work is composed of layered 2D shell elements for the concrete slab and fiber-discretized 1D beam–column elements for the steel beam. The particular feature of this model is its ability to incorporate an interface shear connection deforming along the beam length, which is modeled by means of a series of nonlinear springs and suitable constraints. Vertical and lateral interaction between the slab and steel beam are not expected to be significant. Fig. 1 shows the assembled macromodel, the details of which are outlined below.

1. A set of four-node layered shell elements for the concrete slab, shown in Fig. 1, with reference surface located at the base of the slab to enable connection to the steel beam below. Reinforcement layers with the steel material properties are used to simulate the reinforcing steel located at the top and bottom layers;
2. A set of two-node fiber beam–column elements for the steel beam, with reference surface located at the centroid of the steel beam cross section;
3. A set of dummy nodes (“Set 1” nodes), at the same locations as beam–column element nodes, used for the connection between nodes of the steel beam and shell elements later;
4. A set of rigid beam elements, which connect “Set 1” nodes and the corresponding nodes of the shell elements occupying the same x- and z-coordinate as “Set 1” nodes; and