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Nonlinear Analysis of Composite Concrete-Filled Steel Tube Frames

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Summary

This paper outlines the formulation, calibration and verification of a three-dimensional, cyclic, distributed plasticity finite element model for composite frames composed of square or rectangular concrete-filled steel tube (CFT) beam-columns and steel wide-flange beams. The CFT model accounts for slip between the steel and concrete, and a brief study is presented which demonstrates that slip often has little effect on the global response of composite frames, although it may affect straining at beam-to-column connections.

1. Introduction

Research to date on CFTs has included tests on circular and rectangular columns, beams, beam-columns, and composite frames and trusses (Gourley et al. 1995), push-out tests to determine the bond strength at the steel-concrete interface, and connection studies to determine moment-rotation relationships and slip characteristics at connections (Hajjar et al. 1997a). However, relatively few computational models have been developed for analysis of composite frames composed of steel wide-flange girders framing into CFT beam-columns with fully-restrained or partially-restrained connections (termed "composite CFT frames"). This paper outlines the formulation of a finite element model for CFT beam-columns. This computational model is capable of accounting comprehensively for material nonlinear behavior at the stress-strain level, and for all significant geometrically nonlinear behavior. The resulting formulation is able to analyze complete three-dimensional composite CFT frames. This formulation has been verified against a large number of experimental results, and it may be used to assess the static and cyclic seismic behavior of individual CFT beam-columns, composite CFT subassemblages, or complete composite CFT frames. It is also suitable for conducting parametric studies to determine the significant factors which affect CFT behavior, including cross section geometry, constitutive behavior, slip characteristics, and end restraint, with the goal of developing improved design code recommendations.

2. Finite Element Model

The current research utilizes a three-dimensional 18 degree-of-freedom (DOF) beam finite element developed by Hajjar et al. (1997a, b) to model CFT members. The formulation consists of a stiffness-based fiber element approach, in which the end cross-sections of each element are discretized into a grid of fibers, with the stress-strain behavior at each grid point monitored during the analysis. Through application of the material constitutive relationships, the spread of plasticity through the member end cross sections can be tracked. Linear shape functions are used to describe the change in member rigidity between the ends of the element. Traditional cubic Hermitian shape functions are used to describe the transverse deformation of the element between the end cross sections, and a quadratic shape function is used to describe the axial deformation (White 1985).

The current formulation models slip between the steel tube and concrete core of the CFT element along the element centroidal axis. The finite element model for slip follows the work of Amadio and Fragiacomo (1993), who developed a two-dimensional composite beam finite element which accounted for slip between an elastic steel girder and the concrete slab for monotonic loading. For the current CFT finite element formulation, three extra translational DOFs are added at each element end to permit the steel tube and concrete core to translate separately for a CFT which is arbitrarily oriented in space during a geometrically nonlinear analysis. The transverse displacements of the steel and concrete are constrained to be identical using penalty functions, thus allowing slip only along the longitudinal axis of the CFT, due either to flexural or axial loading. The separate axial DOFs are coupled through a layer of nonlinear slip springs along the material interface. Slip resistance is provided by friction and adhesion at this interface. The resulting computational model uses a bilinear load-slip relationship, with an initial stiffness (k_{slip}) up to the bond strength of the interface (f_{bond}), followed by a zero stiffness. This relation is representative of load-slip data seen in experimental studies of CFTs subjected to slip.

The current CFT finite element formulation extends the work of Amadio and Fragiacomo (1993) by including the significant geometrically and materially nonlinear effects which may be expected in CFT members subjected to cyclic loading. The formulation includes low and high-order geometrically nonlinear stiffness matrices to account for P-Δ and P-δ effects, and an updated Lagrangian incremental/iterative formulation to evaluate the stiffness matrices during the analysis. Lateral-torsional buckling, flexural-torsional buckling, and the bowing effect are not modeled. Additional details of the CFT finite element formulation can be found in Hajjar et al. (1997a).

3. Nonlinear Material Models

Nonlinear material constitutive models are used to describe the stress-strain behavior of individual steel and concrete fibers at the member end cross sections. Both constitutive formulations are intended to model the full range of material stress-strain behavior commonly seen in CFT members, including capability to model repeated strain reversals under cyclic seismic loading.

The steel constitutive model used in the current formulation for structural steel wide-flange beams and for steel tubing is adapted from Shen et al. (1995). This bounding surface formulation permits accurate prediction of the material tangent modulus during cyclic loading. The formulation was modified for modeling cold-formed steel tubing by including the variation in material properties within the tube cross section, and accounting for the gradual rounding of the stress-strain curve due to plastic straining during cold-working.

The concrete constitutive model is adapted from Ameur-Moussa and Buyukozturk (1990), supplemented by an elastic tensile branch prior to cracking. The compressive cyclic model is a combined plasticity-damage model with a vanished elastic zone. The scalar damage parameter accounts for micro-cracking in compression. The compressive model exhibits all important concrete behavior including stiffness degradation, hysteretic loading-unloading loops, and a descending post-failure branch. The tensile model includes tensile cracking and crack opening and closing upon repeated loading. The slope of the post-failure branch of the stress-strain curve was adjusted to match experimental moment-curvature-thrust results from monotonically loaded short CFT specimens (Tomii and Sakino 1979). This variation in the descending branch of the compressive stress-strain curve accounts for the added ductility of the concrete due to confinement of the concrete core by the rectangular steel tube. Calibration and verification of the steel and concrete constitutive models are described in Hajjar et al. (1997b).

4. Calibration and Verification

Calibration of the slip model involved determining the appropriate values of k_{slip} and f_{bond} by utilizing the results from Dunberry et al. (1987) and Shakir-Khalil (1994) of CFT connection tests consisting of steel I-girders framing into CFTs with simple shear tabs. The initial stiffness k_{slip} = 10^4 MPa provided the best match to experimental results. This value results in computational solutions similar to analyses assuming perfect bond. However, modeling an accurate finite initial stiffness permits simulation of the gradual load transfer from the steel tube to the concrete core which takes place above and below the connection region. The calibration of bond strength resulted in a value of f_{bond} = 0.6 MPa. This value exceeds the design recommendations of both BS5400 (1979), which suggests a value of f_{bond} equal to 0.4 MPa, and AIJ (1980), which suggests a value of f_{bond} ranging from 0.1 MPa (for long term loading) to 0.15 MPa (for seismic loading). The difference in values may result from the use of connection tests in the current calibration, rather than push-out tests which were predominantly used for the development of these design codes. Connection tests were used for the current calibration rather than push-out tests because they are believed to represent more closely the conditions found in a CFT frame.

The current formulation has been verified against both monotonic and cyclic CFT experiments. The verification is presented in Hajjar et al. (1997a, b). Comparisons of two cyclic experiments with computational results are presented below together with the experiment schematics. Figure 1 shows a planar CFT specimen under constant axial load (P/P_0 = 0.2, where P_0 is the CFT axial strength) and cyclic shear loading (Sakino and Tomii 1981). Figure 2 shows a three-dimensional cruciform subassembly composed of steel wide-flange beams framing rigidly into a rectangular CFT column, with constant axial (P/P_0 = 0.15) and out-of-plane beam loading, and alternating antisymmetric in-plane beam loading to simulate seismic loads (Morino et al. 1993).

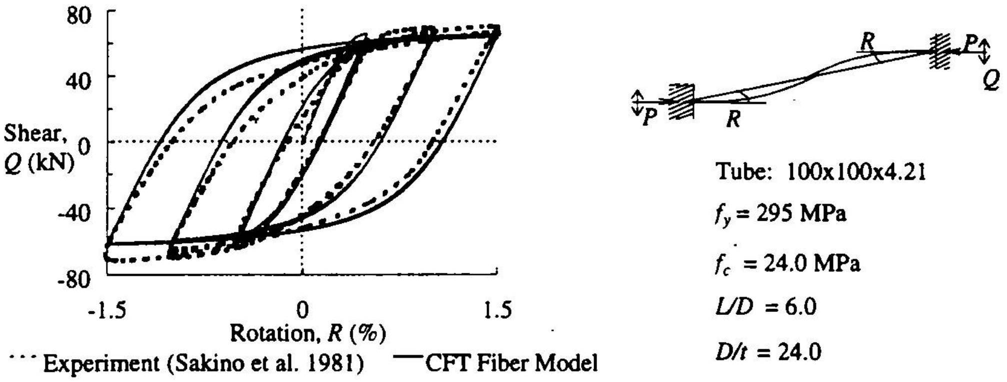


Figure 1: Comparison of Computational and Experimental Results (Sakino and Tomii 1981, Specimen CIVS3-2)

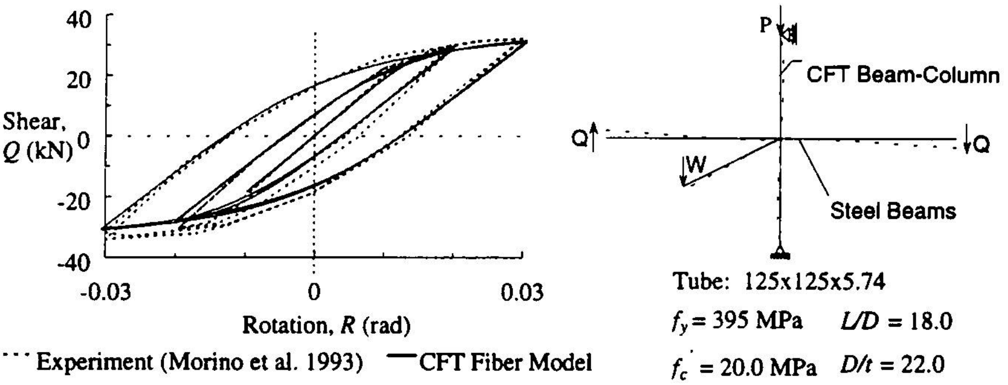


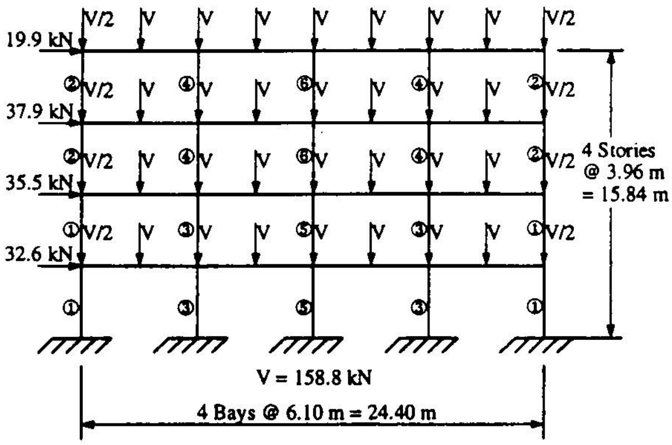
Figure 2: Comparison of Computational and Experimental Results (Morino et al. 1993, Specimen SCC-20)

5. Effect of Slip on CFT Members and Composite Frames

Only limited studies have been conducted on the effect that slip has on the load-deformation behavior and ultimate strength of CFT members (e.g., Dunberry et al. 1987; Shakir-Khalil 1994). The AISC LRFD Specification (1993) limits the ultimate flexural capacity of CFTs to the plastic moment capacity of the steel section alone, partially due to the lack of data on slip. This limitation reduces the economy of CFTs as the primary lateral load resisting elements in unbraced frames. The formulation in this work may be used to provide supplemental data for determining the effect of slip on CFT behavior.

A preliminary study of the effect of slip on CFT flexural capacity and moment-curvature behavior was conducted for three CFT cross sections with different tube width-to-thickness ratios by varying both f_{bond} and k_{slip} from the calibrated parameters. Reducing k_{slip} by two orders of magnitude slightly reduced the rigidity of these members, but had no perceptible effect on the ultimate moment capacity. Reducing f_{bond} to 0.1 MPa [e.g., a value in the range of that recommended by AIJ (1980)] reduced the computed moment capacity of the CFTs by 3% to 5%, suggesting that bond strength may have a small effect on the moment capacity of CFTs.

A second study was conducted to determine the effect of slip on frame behavior. Figure 3 shows a 4-story 4-bay frame subjected to factored gravity and wind loading. The loads are increased proportionally until the collapse of the frame is detected. Four cases were investigated to determine the effect of boundary conditions and slip parameters on the behavior of the frame. In Case I, the steel girder is assumed to engage the concrete directly through the connection, and no slip is permitted at the joints. In the other cases, the steel girder is assumed to engage only the tube, and load is transferred to the concrete through the slip interface. No perceptible difference in the global load-deformation response of the structure was observed between the four cases. An investigation of the interface stresses for Cases II, III and IV indicates that the values of both f_{bond} and k_{slip} affect whether bond strength is surpassed in a CFT frame. Bond loss is not detected for Cases II and III, although values close to 0.6 MPa are seen in Case II. However, Case III has interface stress values which are approximately 35% of the values for Case II, because for Case III the transfer of load at the connections occurs over a larger length of the CFT due to the lower stiffness. For Case IV, the bond strength is breached in several locations (first breach occurs at 19% of the design loading) resulting in localized slip in the connection regions that is approximately five times that seen in Case II (although the slip magnitudes remain small).



Beams:
W410x60; f_y = 248.2 MPa
CFT Sections:
① TS 177.8x177.8x6.35
② TS 152.4x152.4x4.76
③ TS 254.0x203.2x6.35
④ TS 203.2x152.4x6.35
⑤ TS 203.2x203.2x6.35
⑥ TS 152.4x152.4x6.35
f_y = 317.2 MPa, f_c' = 34.5 MPa
Load Cases:
Case I: No Slip Permitted
Case II: Slip Restrained at Bottom of Column Stacks; Calibrated Parameters
Case III: Case II, $k_{slip} = 10^2$ MPa
Case IV: Case II, f_{bond} = 0.1 MPa

Figure 3: Composite CFT Frame Model

6. Conclusions

The computational formulation presented in this paper is suitable for conducting parametric studies of individual CFT members and complete composite CFT frames. This formulation may also be used to determine the effect of slip stiffness and bond loss on rigidity, ultimate strength, ductility, and monotonic or cyclic behavior of composite CFT frames. A preliminary study demonstrates that the ultimate moment capacity of flexural specimens shows only slight change by lowering the bond strength. Variations in slip stiffness and bond strength are also seen to have virtually no effect on the global response of a CFT composite unbraced frame, although the slip parameters do have a small effect on the CFT behavior specifically in the connection region.

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