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Crack-Resistant Structural Systems Employing Nano-Composite Mortar–Filled Steel Tubes

Mohammed Sameer, Post Graduate Student, Dept. Civil Engg, Ghousia College Of Engineering, Ramanagara-562159
Syed Sharfuddin, Assistant Professor, Dept. Civil Engg, Ghousia College Of Engineering, Ramanagara-562159

Abstract
Concrete-Filled Steel Tubes (CFSTs) are widely adopted in advanced structural and civil engineering applications due to their high load-carrying capacity, excellent ductility, and effective composite interaction between the confining steel tube and the infilled concrete or mortar core. However, differential thermal expansion between steel and the mortar core under elevated temperatures can generate high interfacial stresses that lead to microcracking, debonding and reduced durability. This study develops a coupled thermo-mechanical finite element framework in ANSYS Workbench to analyze CFST columns filled with plain and nano-composite mortars (nano-silica and graphene-oxide modified). The model integrates steady-state and transient thermal analyses, nonlinear structural response, contact mechanics (TARGE170–CONTA174), and fracture modelling using XFEM/CZM. A parametric study varies steel yield strength, mortar compressive strength, and support–load spacing. Results show that nano-modified mortars reduce thermal mismatch, delay crack initiation, and improve confinement. A crack-free envelope is proposed to guide design under combined thermal and mechanical loading.

I. INTRODUCTION
CFSTs are widely adopted in advanced structural and civil engineering applications due to their high load-carrying capacity, excellent ductility, and effective composite interaction between the confining steel tube and the infilled concrete or mortar core. The tube provides continuous confinement that raises the compressive strength and ductility of the infill material, while the concrete or mortar core prevents local buckling of the tube and increases energy absorption capacity. This results in significantly superior behavior of CFST members compared to conventional reinforced concrete or pure steel structures in such uses as high-rise buildings, bridge columns, and critical load-bearing frameworks.

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But despite these structural advantages, the internal mortar or concrete core in CFSTs remains vulnerable to thermo-mechanical degradation. When these members are subjected to high temperatures, which could arise in cases of fire or rapid environmental temperature changes, there exists a differential thermal expansion between the steel tube and the mortar infill that generates high interfacial stresses. Moreover, restrained shrinkage, hydration-induced volume changes, and non-uniform heat transfer may lead to tensile cracking within the mortar, especially near the steel–mortar interface. Such microcracking compromises not only composite action between steel and mortar but also reduces member durability, stiffness, and long-term structural integrity. These defects, given time, may propagate into visible cracks, furthering corrosion, loss of bond, and reduced fire resistance.

Recent advances in nanotechnology have identified nano-composite mortars, where the cementitious matrix is significantly modified by the addition of nanoparticles including nano-silica (SiO_2), graphene oxide (GO), nano-alumina (Al_2O_3), or carbon nanotubes (CNTs). Such nano-additions enhance hydration kinetics and result in significant pore refinement, leading to a denser microstructure with higher tensile and fracture strengths. Moreover, nanoparticles can significantly modify the thermal expansion coefficient, thermal conductivity, and specific heat capacity of the mortar, resulting in reduced mismatch with steel and thereby helping to mitigate the resistance of the rebar-matrix system to thermal stresses. Improved ITZ between the steel and nano-modified mortar also contributes to improved adhesion and load transfer under combined thermal and mechanical loading.

This paper presents a coupled thermo-mechanical finite element simulation framework in ANSYS Workbench for systematic analysis of the behavior of CFST columns under realistic thermal and mechanical loading conditions. The approach incorporates steady-state and transient thermal analyses along with structural deformation and stress evaluation for full understanding of the interaction between temperature gradients, axial loads, and material properties responsible for cracking. Comparative studies have been carried out for CFSTs filled with plain mortar and nano-modified mortar, considering key outputs such as stress distribution, crack initiation time, crack propagation pattern, and load-displacement response.

A set of parametric analyses are carried out to explore the influence of the steel yield strength, mortar compressive strength, and support–load spacing on the general structural response. The advanced contact algorithms TARGE170–CONTA174 element pairs are implemented in the model to represent properly the frictional and thermal interface between steel and mortar. XFEM and CZM are utilized to simulate crack formation and propagation without remeshing through a modeling of fracture mechanics behavior.

Results from this study will define the "crack-free envelope," which is a set of thermal, material, and geometrical parameters that prevent crack formation in CFSTs. The envelope will set quantitative design guidelines for engineers in the selection of appropriate properties of nano-composite mortars and geometric configurations to assure superior performance under both service and fire conditions.

II. STATE OF THE ART

Research on Concrete-Filled Steel Tubes (CFSTs) has evolved significantly over the last two decades, transitioning from purely mechanical evaluations to comprehensive thermo-mechanical analyses aimed at preventing crack initiation and ensuring long-term durability. Traditional CFST studies have established the fundamental composite behavior under axial, bending, and cyclic loading, but recent investigations emphasize the need to address temperature-induced degradation and interfacial cracking within the steel–mortar composite.

Experimental studies indicate differential thermal expansion leads to interfacial microcracking under fire exposure. Nano-additives such as nano-silica and graphene oxide improve hydration, tensile strength and pore structure, reducing crack widths and delaying initiation. Analytical models capture global composite behavior but often neglect nonlinear fracture and temperature-dependent contact effects. Numerical FE studies using ANSYS, Abaqus and LS-DYNA with XFEM/CZM capture cracking phenomena, but parametric studies combining temperature-dependent material properties, advanced contact mechanics, and fracture models remain limited. This study fills that gap.

III. METHODOLOGY

A. Finite Element Model

A 3D quarter-symmetry model of a CFST column (steel tube with mortar core) was developed in ANSYS Mechanical APDL/Workbench. Geometry: 1500 mm length (modeled quarter), outer diameter 200 mm, steel thickness 4 mm. Symmetry planes applied to reduce computational cost. Loads and temperature profiles were applied on cut planes consistent with full-model behavior.

B. Elements and Contact

Steel tube: SHELL281; mortar core: SOLID186; mesh control: MESH200; contact: TARGE170–CONTA174. Contact includes friction (μ=0.5) and temperature-dependent heat transfer.

C. Material Properties

Steel: E=200 GPa, ν=0.3, α=12×10^-6/°C, density=7850 kg/m3, fy varied 275–355 MPa.
Mortar (plain vs nano): properties tabulated (E: 25→32 GPa, ρ:2300→2350 kg/m3, ft:3.0→4.2 MPa, fc:40→48 MPa, α:14→10×10^-6/°C, Gf:50→85 N/m). Dependent parameters computed per Eurocode relations.

D. Boundary Conditions and Loading

Quarter-model symmetry; bottom fully restrained; top allowed axial displacement; axial loads applied equal to 30–60% of steel yield capacity; thermal loading on steel outer surface (200–600°C) with convection h=25 W/m^2°C, ambient 30°C.

E. Mesh and Convergence
Meshes: 15, 25, 35, 45 mm. Convergence near 25 mm (≈4800 elements) chosen as compromise between accuracy and runtime.

F. Fracture Modelling
XFEM and Cohesive Zone Models used to capture crack initiation and propagation; fracture driven by tensile criteria and fracture energy.

G. Parametric Study
Parameters: Ls (600,675,750 mm), fy (275,297.69,355 MPa), fc (20,33.71,48 MPa). Seven simulations with one variable varied per run.

IV. RESULTS AND DISCUSSION

A. Mesh Study
Convergence observed near 25 mm mesh. Finer mesh increases Fmax but at a steep runtime cost.

B. Effect of Ls
Shorter Ls increases stiffness and Fmax. Regression: Fmax decreases ≈0.3903 kN per 1 mm increase in Ls (R^2=0.9975). Initial stiffness K reduces with increasing Ls.

C. Effect of fy
Fmax increases linearly with fy; relation ~0.6898 kN per 1 MPa (R^2=0.9989). Von Mises stresses increase with fy (~1.4955 MPa per 1 MPa fy). Buckling pattern location minimally affected.

D. Effect of fc
Third principal stress σ_3 increases linearly with fc (y=3.5801x-15.319, R^2=0.9896). Higher fc reduces failed areas and delays cracking; may shift local buckling.

E. Thermal Gradient (ΔT)
Optimal ΔT range 200–250°C for minimizing σ_{eq} and radial strain mismatch. ΔT >400°C raises σ_{eq} toward yield.

F. Crack Behavior
Plain mortar: early microcracks at interface; nano-mortar delays initiation, reduces crack width, and improves post-peak response. Crack-free envelope established: ΔT 200–250°C, fy 320–350 MPa, fc 45–50 MPa.

V. CONCLUSIONS AND FUTURE WORK

Nano-modified mortars improve thermal compatibility, increase fracture energy, and delay crack initiation in CFSTs. The FE framework with contact and fracture models accurately captures thermo-mechanical response. Recommended design envelope presented. Future work: experimental validation at elevated temperatures, nano-additive optimization, cyclic/seismic coupling, and fire-curve based studies.

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APPENDIX: Figures

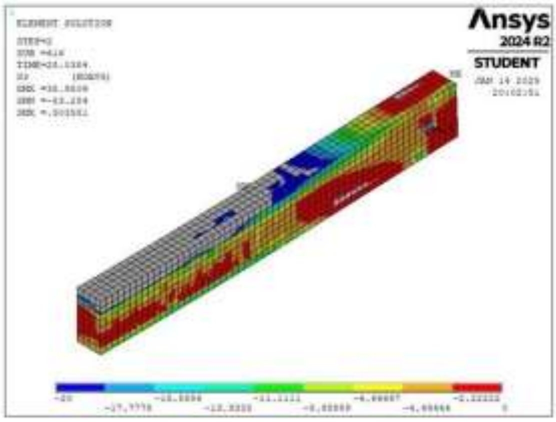

Fig. 37. Third principal stress for fc = 20 MPa.

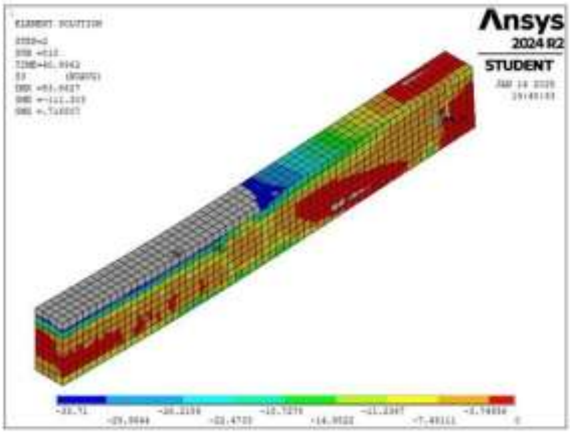

Fig. 38. Third principal stress for fc = 33.71 MPa.

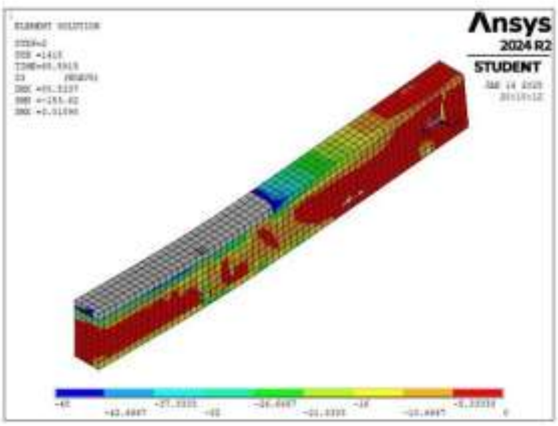

Fig. 39. Third principal stress for fc = 48 MPa.