



# A Comprehensive Review of Finite Element Analysis of Concrete-Filled Steel Tubular (CFST) Columns under Combined Loading

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## Abstract—

Concrete-Filled Steel Tubular (CFST) columns are widely recognized as efficient composite structural members due to their superior strength, stiffness, and ductility. The composite action between the outer steel tube and the inner concrete core provides enhanced confinement, resulting in improved load-carrying capacity and energy dissipation compared to conventional reinforced concrete or steel members. Owing to these advantages, CFST columns have been extensively studied under various loading conditions, including axial compression, bending, torsion, buckling, and their combined effects.

This paper presents a structured and critical review of the existing literature on CFST behaviour, systematically organized according to different loading regimes. Particular emphasis is placed on the diameter-to-thickness ( $D/t$ ) ratio, which plays a crucial role in governing confinement effectiveness, strength enhancement, and overall stability of the member. The review also highlights recent advances in nonlinear finite element modelling, with a focus on the application of the Concrete Damaged Plasticity (CDP) model in ABAQUS for accurately simulating the complex interaction between steel and concrete.

To strengthen the findings of the review, a finite element model is developed and validated against available experimental data. The

numerical results demonstrate good agreement with experimental observations, with deviations limited to within 5%, confirming the reliability of the adopted modelling approach.

Despite the substantial body of research, significant gaps remain, particularly in the limited understanding of combined axial–bending–torsion behaviour and the lack of comprehensive design provisions addressing such complex loading conditions. This study provides a comparative synthesis of existing findings and identifies key areas requiring further investigation. The outcomes are expected to contribute towards the development of more unified and reliable design methodologies for CFST structures.

**Keywords—** CFST; column; axial; bending; torsion; buckling; combined loading;  $D/t$  ratio; Concrete Damaged Plasticity; finite element analysis; confinement.



## I. INTRODUCTION

Modern structural engineering demands systems that simultaneously deliver high strength, ductility, constructability, and reliable performance under complex loading conditions. Concrete-Filled Steel Tubular (CFST) columns have emerged as one of the most efficient composite structural systems capable of meeting these requirements. Their superior performance is attributed to the synergistic interaction between the steel tube and the concrete core. The steel tube provides continuous lateral confinement, transforming the stress state of concrete from uniaxial to triaxial compression, thereby significantly enhancing compressive strength and post-peak ductility. Conversely, the concrete core delays local inward buckling of the steel tube, improving its stability and load-carrying efficiency.

The evolution of CFST systems has progressed from early applications driven by durability and fire resistance considerations to their widespread adoption as primary load-bearing members in modern infrastructure. Foundational experimental studies established their structural advantages and facilitated the development of design provisions in international standards. Today, CFST columns are extensively used in high-rise buildings, bridge piers, and offshore structures, where both strength and deformation capacity are critical.

Despite these advantages, the structural behaviour of CFST columns under realistic loading conditions remains an active area of research. While axial compression behaviour is well understood and codified, practical structural members are rarely subjected to purely axial loads. Instead, CFST columns are typically exposed to combined actions involving axial force, bending moments due to eccentricity or lateral loads, and torsional effects arising from geometric irregularities or asymmetric loading. These combined actions induce complex multi-axial stress states in both steel and concrete, leading to highly nonlinear responses that cannot be accurately captured using simplified analytical models.

Existing design standards, such as Eurocode 4 and AISC provisions, provide reliable guidance for axial and axial-flexural behaviour. However, they offer

limited or no provisions for torsion and combined axial-bending-torsion loading conditions. This creates a significant gap between design practice and actual structural demands, particularly in applications such as curved bridge columns, corner columns in irregular layouts, and members subjected to seismic torsional effects.

In this context, the present study provides a comprehensive and critical review of CFST column behaviour under various loading conditions, including axial compression, bending, torsion, buckling, and combined loading. Special emphasis is placed on the influence of the diameter-to-thickness ( $D/t$ ) ratio, which governs confinement efficiency, local stability, and overall structural performance. In addition, a validated nonlinear finite element modelling approach is incorporated to support the reliability of the reviewed findings. The study aims to synthesize existing knowledge, identify key research gaps, and propose directions for the development of unified design methodologies for CFST columns subjected to multi-axial loading. The present work integrates validated nonlinear finite element modelling with systematic literature synthesis, providing a more reliable and application-oriented understanding of CFST behaviour under realistic loading conditions.

## II. LITERATURE REVIEW

### 1. Axial Compression Behaviour

Axial compression represents the loading condition under which CFST columns exhibit their most pronounced composite advantage. Under increasing axial load, both steel and concrete initially share the load proportionally to their stiffness. As loading progresses, the concrete core undergoes lateral expansion, which is restrained by the steel tube, inducing circumferential tensile stresses in the steel. This confinement transforms the stress state of concrete into triaxial compression, significantly enhancing both strength and ductility.

The effectiveness of confinement is strongly influenced by cross-sectional geometry. Circular sections provide uniform confinement around the perimeter, resulting in substantial strength enhancement, whereas square and rectangular sections exhibit non-uniform confinement, primarily concentrated at the corners. Consequently, circular



CFST columns demonstrate superior performance in terms of strength and ductility.

Extensive experimental and numerical investigations have validated the superior performance of CFST columns. Studies on stub columns have demonstrated that circular CFST sections outperform square sections and equivalent reinforced concrete columns due to more effective confinement. Finite element simulations, particularly those developed using ABAQUS with the Concrete Damaged Plasticity (CDP) model, have consistently reproduced experimental load–displacement behaviour with high accuracy.

Research on alternative materials, such as rubberized concrete and recycled aggregate concrete, indicates that although peak strength may slightly reduce, ductility and energy absorption characteristics improve significantly. These findings highlight the robustness of CFST systems even with non-conventional materials.

Simplified numerical approaches, including fiber beam element models with modified constitutive laws, have also been developed to reduce computational effort while maintaining accuracy. Parametric studies further confirm that key parameters such as  $D/t$  ratio, concrete strength, and slenderness significantly influence axial capacity and deformation behaviour. Importantly, validated finite element results show close agreement with Eurocode-based predictions, reinforcing the reliability of both numerical modelling and design provisions.

## 2. Bending Behaviour

Under bending, CFST columns exhibit non-uniform stress distribution, with compression on one side and tension on the other. In the compression zone, composite action between steel and confined concrete governs behaviour, while in the tension zone, cracked concrete contributes minimally and the steel tube carries the majority of tensile forces.

The moment–rotation response typically consists of an initial elastic region, followed by a nonlinear stage due to cracking and yielding, and finally a post-peak softening region. Compared to conventional reinforced concrete sections, CFST columns demonstrate significantly improved

ductility due to confinement and the absence of cover spalling.

The  $D/t$  ratio plays a critical role in flexural performance. Lower  $D/t$  ratios (thicker tubes) enhance confinement, delay local buckling, and increase both flexural capacity and ductility. The interaction between  $D/t$  ratio and slenderness determines whether failure occurs through material yielding or instability.

Concrete strength influences compressive resistance and initial stiffness; however, its contribution under bending is less dominant compared to axial loading, as tensile behaviour is governed primarily by the steel tube.

Under combined axial load and bending, CFST columns exhibit interaction behaviour typically represented using  $P$ – $M$  diagrams. At low axial loads, confinement enhances moment capacity, whereas increasing axial load reduces flexural capacity due to compression dominance. Circular sections generally demonstrate higher moment capacity and ductility compared to rectangular sections. Existing code provisions provide simplified interaction models, which are often conservative for circular CFST columns.

## 3. Torsional Behaviour

Under torsional loading, the steel tube primarily resists shear stresses, while the concrete core contributes through confinement and interaction at the interface. The steel–concrete bond plays a critical role in transferring shear forces, particularly under combined loading.

The torque–rotation response typically exhibits elastic behaviour followed by gradual stiffness degradation and stable post-yield response. Unlike axial compression, torsional behaviour often shows less pronounced post-peak softening.

The interaction between axial compression and torsion is nonlinear. Moderate axial loads can enhance torsional capacity due to improved confinement, whereas higher axial loads reduce torsional resistance due to premature concrete crushing and reduced shear capacity of steel.



#### 4. Buckling and Stability

Local buckling is strongly influenced by the  $D/t$  ratio. Thin-walled sections are more susceptible to premature buckling, reducing confinement effectiveness. The presence of concrete delays inward buckling and improves performance compared to hollow steel sections.

For slender columns, global buckling governs behaviour. Composite action increases flexural stiffness and raises buckling resistance. Advanced numerical techniques, such as the Static Riks method, are widely used to capture nonlinear buckling behaviour and post-peak response.

The  $D/t$  ratio is the most critical geometric parameter influencing CFST behaviour across all loading conditions. It governs confinement effectiveness, local buckling resistance, and the relative contribution of steel and concrete. Lower  $D/t$  ratios enhance strength, ductility, and stability, whereas higher ratios increase susceptibility to buckling and strength degradation.

#### 5. Combined Loading Behaviour

Axial–bending interaction is well studied and represented through  $P$ – $M$  diagrams. Confinement enhances performance at low axial loads, while higher axial loads reduce flexural capacity.

Combined axial–bending–torsion loading represents the most complex and least explored scenario. The interaction between axial, flexural, and torsional stresses leads to nonlinear behaviour that cannot be captured through simple superposition. Existing studies indicate reduced strength and ductility under combined loading, highlighting the need for further research and improved design models.

Accurate modelling requires advanced constitutive models such as CDP for concrete and appropriate contact definitions for steel–concrete interaction. Nonlinear analysis methods, particularly the Static Riks approach, are essential for capturing post-peak behaviour under combined loading.

### III. NUMERICAL MODELLING AND VALIDATION

The developed finite element (FE) model was validated against experimental results available in the literature [1] for circular concrete-filled steel tubular (CFST) columns subjected to axial compression. The validation aimed to assess the accuracy of the modelling approach in capturing the load–deformation response, peak load capacity, and failure characteristics.

The numerical model was developed in ABAQUS using a three-dimensional nonlinear framework. The steel tube was modelled using an elastic–plastic material with isotropic hardening, while the concrete core was represented using the Concrete Damaged Plasticity (CDP) model to capture nonlinear compressive behaviour, tensile cracking, and stiffness degradation. Surface-to-surface contact interaction with hard contact in the normal direction and frictional behaviour in the tangential direction was defined between steel and concrete to simulate composite action. The boundary conditions and loading were applied in accordance with the experimental setup, with the base fully restrained and displacement-controlled loading applied at the top. The Static Riks method was employed to capture both pre-peak and post-peak response, ensuring stability in the nonlinear solution and enabling accurate prediction of the descending branch.

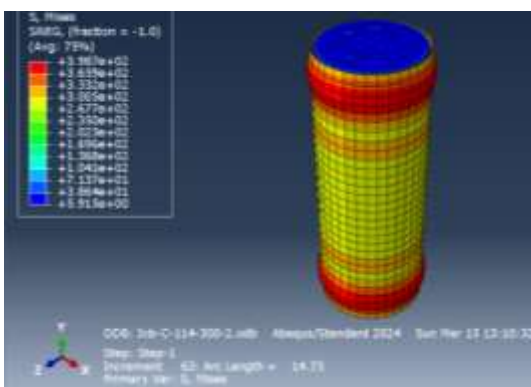
Table 1: Model Properties for FE validation study

Property	Value
Cross-section shape	Circular CFST
Steel grade	S235 ( $F_y = 235$ MPa)
Concrete grade	M40 (Normal Concrete)
Outer diameter (D)	114 mm
Concrete core diameter	107.6 mm
Column height (H)	300 mm
Steel tube thickness (t)	3.20 mm
$D/t$ ratio	35.6



The comparison between numerical and experimental results demonstrated excellent agreement. The FE model predicted the ultimate load with a deviation of approximately 3–5%, indicating high accuracy. The load–displacement curves obtained from the simulation closely matched the experimental response in terms of initial stiffness, peak load, and post-peak softening behaviour. Minor deviations in the post-peak region were observed, which can be attributed to idealizations in material modelling and boundary conditions. In addition to load capacity, the deformation pattern and failure modes predicted by the FE model were consistent with experimental observations. The model successfully captured key behavioral features, including steel yielding, confinement-induced strength enhancement, and

Figure 1 Deformed configuration of CFST column under axial compression obtained from finite element analysis



progressive concrete damage.

Overall, the validation confirms that the adopted modelling approach, including the use of the CDP model for concrete and nonlinear contact interaction, is capable of accurately simulating the behaviour of CFST columns. This provides confidence in the use of the developed FE model for further parametric studies involving bending, torsion, and combined loading conditions

#### IV. RESULTS AND DISCUSSION

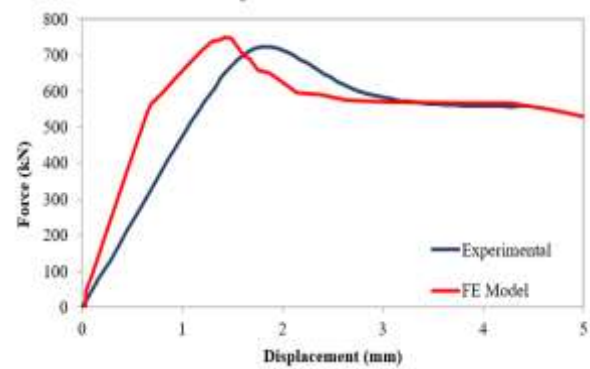


Figure 2 Comparison of experimental and FE load–displacement curves for validation

Table 2 summarizes the structural behaviour of CFST columns under different loading conditions, highlighting governing parameters and observed trends.

Table 2: Summary of Key Research Findings on CFST Columns

Loading Condition	Structural Behaviour	Key Influencing Parameters
<b>Axial Compression</b>	Composite action with strong confinement; triaxial stress in concrete	D/t ratio, concrete strength, steel yield strength
<b>Axial (Alternative Materials)</b>	Modified composite behaviour with non-conventional materials	Concrete type (rubberized, recycled), interface bond
<b>Axial (Numerical / Simplified Models)</b>	Behaviour captured using FE and reduced-order models	CDP parameters, mesh size, modelling assumptions
<b>Bending (Flexural)</b>	Non-uniform stress distribution; tension governed by steel	D/t ratio, steel strength, neutral axis shift
<b>Axial–Bending Interaction</b>	Combined compression and flexure (P–M interaction)	Axial load ratio, D/t ratio, geometry
<b>Torsion</b>	Steel tube carries primary shear; concrete contributes via	Wall thickness, interface friction, axial load level



	interaction	
<b>Axial–Torsion Interaction</b>	Nonlinear interaction between axial force and shear	Axial load ratio, D/t ratio
<b>Buckling (Local)</b>	Local instability of steel tube	D/t ratio, confinement level
<b>Buckling (Global)</b>	Flexural instability governed by slenderness	Slenderness ratio (L/D), stiffness (EI)
<b>Combined Loading (Axial + Bending + Torsion)</b>	Multi-axial stress state with complex interaction	D/t ratio, load combination ratios, material properties
<b>Stiffened CFST</b>	Improved confinement and buckling resistance using internal stiffeners	Stiffener spacing, equivalent D/t ratio

## V. CONCLUSION

This study presents a comprehensive review of the structural behaviour of Concrete-Filled Steel Tubular (CFST) columns under axial compression, bending, torsion, buckling, and combined loading conditions, with particular emphasis on the influence of the diameter-to-thickness (D/t) ratio and the role of advanced finite element modelling.

The review confirms that the superior performance of CFST columns is primarily governed by the confinement mechanism, wherein the steel tube induces a triaxial stress state in the concrete core, significantly enhancing strength and ductility while simultaneously stabilizing the steel against local buckling. This effect is most pronounced under axial compression, particularly for circular sections, which provide uniform confinement and optimal composite interaction. Under bending, the behaviour is characterized by steel-dominated tensile resistance and confined concrete in compression, resulting in improved ductility but reduced confinement effectiveness compared to axial loading.

Under torsional loading, the steel tube acts as the principal load-resisting component, while the concrete core contributes indirectly through interaction and confinement. The axial–torsion interaction is inherently nonlinear, with moderate axial compression enhancing torsional capacity,

whereas higher axial levels lead to premature degradation. Buckling behaviour, both local and global, is strongly influenced by geometric parameters, particularly the D/t ratio and slenderness, which govern stability, stiffness, and failure mode.

A key outcome of this review is the identification of the D/t ratio as the most influential parameter governing CFST behaviour across all loading regimes. It controls confinement efficiency, local buckling resistance, torsional stiffness, and overall structural response. Lower D/t ratios consistently improve strength, ductility, and stability, particularly under complex loading conditions.

Under combined axial–bending–torsion loading, CFST columns exhibit highly nonlinear interaction behaviour, with significant reductions in strength and stiffness compared to individual loading cases. This loading condition remains insufficiently explored in both experimental and numerical studies and is inadequately addressed in current design standards, representing the most critical gap between analytical understanding and practical design.

Although the behaviour of CFST columns under individual loading conditions is well established, their response under realistic multi-axial loading remains insufficiently understood. The incorporation of validated nonlinear finite element modelling, particularly using the Concrete Damaged Plasticity (CDP) framework, provides a robust and reliable approach for capturing this complex behaviour and extending analysis to scenarios beyond current experimental limitations.

Future research should focus on the development of unified interaction-based design models for CFST columns under combined loading, supported by comprehensive experimental validation and advanced numerical simulations. The establishment of design-oriented P–M–T interaction frameworks and their integration into existing codes will be essential for bridging the gap between research and practice, thereby enabling safe, efficient, and performance-based design of CFST columns in modern structural systems.



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