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Hybrid Composite Behavior of Concrete-Filled Steel Tube (CFST) Columns: Review of Collapse Mechanisms and Polymer-Based Enhancements

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Abstract

Concrete-Filled Steel Tube (CFST) columns are an advanced hybrid composite system where the steel tube's confinement and the concrete core's load capacity work together to improve structural performance. While commonly used in civil engineering, CFSTs can also be understood within the framework of composite materials, similar to polymer- and fiber-reinforced composites, in which interactions between phases determine strength, ductility, and failure modes. This review compiles experimental and numerical research on the collapse of CFST columns under various boundary conditions, focusing on how steel–concrete interactions affect load capacity, deformation, and failure. Recent innovations, including fiber-reinforced polymers (FRP), nanomaterials, rubberized concrete, and sustainable fillers, are discussed to expand CFST applications into polymer-composite fields. The role of advanced finite element analysis (FEA) and machine learning in predicting collapse behavior, especially with hybrid or polymer-based materials, is also covered. By viewing CFSTs as multifunctional composite systems, this work connects structural mechanics with polymer science, highlights gaps in current knowledge, and suggests future research into incorporating polymers, fibers, and recycled fillers to develop next-generation, high-performance, sustainable composite columns suitable for extreme conditions. Investigations into the long-term behavior of CFST columns, including creep, concrete core shrinkage, and steel tube corrosion, especially under variable environmental and loading conditions, are needed. The behavior of CFST columns at high temperatures and their residual strength after post-fire exposure are other critical areas requiring further experimental and numerical exploration.

Keywords: Concrete-filled steel tube (CFST) columns, confined concrete columns, dynamic increase factors (DIFs), fibre-reinforced polymers (FRP), finite element analysis (FEA), polymer-modified binders

INTRODUCTION

Concrete-Filled Steel Tube (CFST) columns have become important in modern construction because they combine the benefits of two materials into a single hybrid system. The steel tube offers high tensile strength, ductility, and confinement, while the concrete core provides compressive strength, energy absorption, and helps prevent local buckling. This synergy reflects the principles of composite materials, where multi-phase components collaborate to achieve superior properties that individual materials cannot provide.

Historically, CFST research has primarily focused on structural engineering aspects, including load capacity, end conditions, and

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collapse behavior. However, when viewed as composites, CFST systems resemble polymer- and fiber-reinforced composites. Both rely on effective stress transfer, confinement, and crack-bridging mechanisms. This broader perspective allows CFSTs to be studied as advanced hybrid composites, which can be further improved with polymer-based modifications.

Recent progress includes the incorporation of fiber-reinforced polymers (FRP), carbon and glass fiber jackets, nanomaterials, rubberized concrete, and polymer-modified binders into CFST. These innovations enhance performance under extreme conditions, boost durability, and promote sustainability by using recycled or waste materials as fillers. Additionally, advanced simulation techniques, such as finite element analysis (FEA) and machine learning, offer predictive insights into collapse mechanisms, enabling the optimization of hybrid and polymer-enhanced CFST designs.

However, there are still significant gaps in understanding how principles of composites, especially polymer reinforcement, long-term durability, and multifunctionality, can be methodically applied to CFST systems.

Recent comprehensive reviews have systematically summarized CFST behavior from structural, material, and analytical perspectives. However, limited attention has been paid to integrating polymers and sustainable fillers into CFST systems and to their implications for collapse mechanisms. This review addresses this gap by consolidating findings across experimental, analytical, and numerical studies and identifying opportunities to advance CFSTs as multifunctional hybrid composites suitable for extreme and sustainable construction environments.

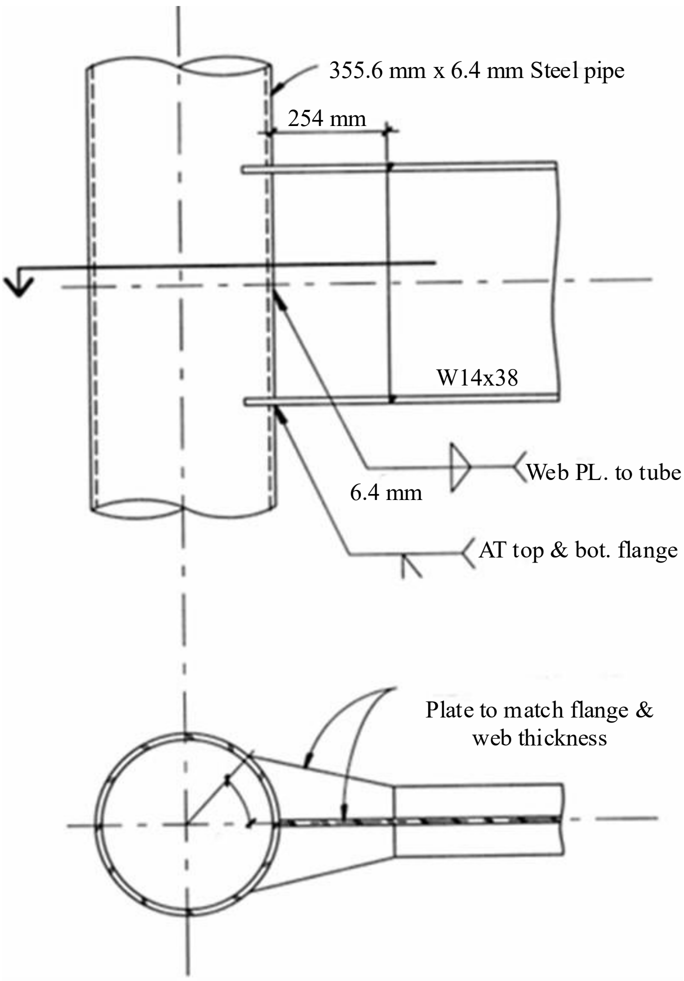

Figure 1. Simple connection of concrete-filled steel tube columns (schneider et al., 1998) [4].

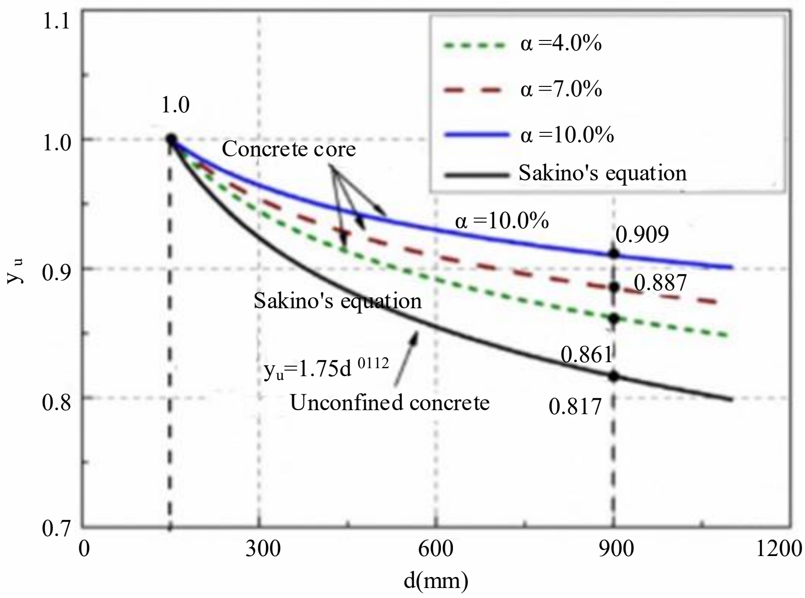

Figure 2. Core diameter increase (150–900 mm) cuts unconfined strength by 18.3%, and confined strength by 13.9%, 11.3%, and 9.1% for 4%, 7%, and 10% steel ratios. (Wang et.al., 2017) [1]

This review aims to address these gaps by analyzing CFST column collapse behavior under different boundary conditions, emphasizing material interactions, and exploring the potential of polymer and sustainable composites to advance next-generation hybrid structural systems. Figure 1 represents the simple connection of Concrete-Filled Steel Tube columns.

Wang et al[1]. These findings collectively illustrate that while increasing steel content enhances confinement and reduces size effects, it may not linearly translate into higher ductility across all scales. This suggests that the effectiveness of confinement depends on both geometric ratios and material compatibility – an essential aspect for hybrid CFST design. Experimental tests were conducted on thirty-six short circular concrete-filled steel tube (CFST) columns, with diameters ranging from 150–460 mm and steel content ratios between 4.0%–10.0%, to evaluate the influence of the size effect under axial loading. The results demonstrated that with an increase in column diameter, there was a decrease in maximum axial stress, ultimate axial strain, and the ductility factor. At the same time, the composite modulus of elasticity remained relatively stable. Furthermore, the magnitude of the size effect on the peak compressive stress decreased with increasing steel ratio. A modification factor was introduced to account for the size effect, revealing that the steel tube's confinement considerably mitigates the size effect compared to plain concrete columns without confinement. Figure 2 represent the Core diameter increase (150–900 mm) cuts unconfined strength by 18.3%, and confined strength by 13.9%, 11.3%, and 9.1% for 4%, 7%, and 10% steel ratios.

Eladly et al[2]. The above numerical and experimental insights show how connection geometry and end-plate detailing directly affect the moment-rotation response and ductility. This understanding is essential for designing CFST joints that balance stiffness and energy dissipation during cyclic or seismic loading. A detailed numerical study was conducted on 180 configurations of stainless-steel extended-end-plate beam-to-column joints using a validated shell-based finite element model. The research investigated the impact of various geometric parameters on initial rigidity, maximum moment capacity, rotational deformation, energy absorption, and ductility performance. An efficient analytical approach was formulated and verified to estimate the moment–rotation (M-Φ) response with high precision, achieving a mean deviation of less than 4%. Connections incorporating end-plate stiffeners demonstrated enhanced ductility and load-bearing capacity, highlighting their suitability for earthquake-resistant design. Mou et al[3]. Numerical simulations were conducted to examine the elastoplastic response and localized behavior of panel zones in unequal-depth steel beams to concrete-filled steel tube (CFST) column joints featuring external annular stiffeners. A three-dimensional nonlinear finite element model, validated through experimental data, was utilized in the study. Parametric analyses indicated that the beam depth ratio (Db2/Db1) had a pronounced effect on the failure mechanisms. At the same time, the central panel zone, outer ring stiffener, column face, and core concrete collectively contributed to the overall shear resistance. In contrast, the secondary panel exhibited a negligible impact. Both the beam depth ratio and the diameter-to-thickness ratio (D/t) were identified as critical parameters influencing the yielding and peak shear capacities. Schneider et al[4]. performed quasi-static loading tests on six full-scale connection assemblies, consisting of connection stubs that were shop-welded and bolted on-site. The test results revealed that direct welding of the stub to the steel tube exterior induced significant wall deformation and increased the likelihood of fracture. Incorporating external diaphragm plates improved the inelastic cyclic response by ensuring a more even transfer of flange forces. Embedded reinforcement elements – notably deformed bars affixed to the beam flange and anchored within the concrete core – delivered over 1.5 times the nominal plastic moment capacity while sustaining stable and symmetric hysteretic behavior. In contrast, joints using only continuous flange plates showed limited strength unless additional anchorage features were provided. A through-type connection-stub, extending across the entire concrete-filled tube (CFT) column, achieved full plastic moment development and exhibited superior cyclic performance. Wang et al[5]. A thorough literature review was carried out to examine the compressive performance of circular concrete-filled steel tube stub columns (CFST-SCs), emphasizing material characteristics, confinement effects, and identifying failure modes. The assessment included experimental data from 367 specimens to evaluate the precision and dependability of six international design codes. Results indicated that all standards conservatively predicted axial compressive strength, with AS/NZS 2327 and CAN/CSA S16–01 providing the most cautious estimates. In contrast, Eurocode 4 (EC4) exhibited greater predictive accuracy, especially for smaller-scale CFST stub columns, while maintaining an acceptable level of reliability. Furthermore, the review examined methods to mitigate buckling-related failures and assessed the suitability of existing design provisions for axial load-bearing capacity. Chua et al[6]. A study was undertaken to analyze the progressive collapse response of laterally supported steel modular buildings under various column removal scenarios. Due to the distinct structural layout of modular systems, in which individual floor slabs are typically interconnected only at module corners, the performance of inter-module joints is critical to structural robustness. Both nonlinear static and dynamic simulations were conducted for buildings ranging from 5–30 stories. Findings revealed that employing static analysis with a dynamic amplification factor (DAF) often results in an overprediction of displacement behavior. The research explored load redistribution paths, evaluated the influence of column loss on interconnection performance, and investigated design strategies, including the minimum tie force criteria necessary for enhanced structural continuity and collapse resistance. Jin et al[7]. The size-dependent behavior of CFRP-confined square concrete columns was examined using both experimental testing and numerical modeling. A total of 30 CFRP-wrapped specimens, with a maximum cross-sectional width of 600 mm, were subjected to repeated axial loading. The research investigated the effects of loading conditions, geometric scale, and reinforcement layout on failure modes. A three-dimensional mesoscale finite element model, incorporating concrete material heterogeneity and the behavior of the CFRP-to-concrete interface, was employed to assess the influence of structural size further. An improved size effect law (SEL) was formulated, demonstrating strong agreement with both experimental observations and numerical predictions, and offering an accurate representation of the scaling behavior in CFRP-confined concrete columns. Wang et al[8]. A novel T-head Square-neck One-side Bolt (TSOB) was examined through tensile testing of TSOB connections (TSOBCs) designed for T-stub to Hollow Square Steel Tube (HSST) joint applications. The experimental program involved six TSOBC specimens and three Standard High-strength Bolt Connections (SHBCs), identifying four dominant failure mechanisms: plastic deformation of the column wall, combined wall yielding with bolt hole tearing, yielding of the T-stub flange, and bolt rupture. Under certain failure conditions, TSOBCs demonstrated lower yield and ultimate tensile capacities compared to SHBCs. The flexural yield capacity of TSOBCs was assessed using adapted formulations of the Gomes and Yeomans models, which showed strong correlation with the observed test data. The study concludes that the modified Gomes model is particularly suitable for predicting performance in cases involving combined column wall yielding and bolt hole distortion. Alostaz et al[9]. A nonlinear three-dimensional finite element analysis (FEA) was conducted to assess various connection schemes for concrete-filled steel tubes (CFSTs) subjected to seismic loading, with a specific focus on circular steel tubes due to their complex connection detailing. The numerical models employed eight-node shell elements for the steel components and 20-node solid brick elements for the concrete infill, incorporating both material nonlinearities and geometrical imperfections. The simulation outcomes were validated using experimental results, considering key parameters such as the diameter-to-thickness (D/t) ratio and axial load intensity. The analysis revealed that connection systems designed to transmit forces directly into the concrete core exhibited enhanced seismic behavior. Among the evaluated configurations, those featuring full-penetration connections into the composite column demonstrated the highest stiffness and most robust girder connection performance. Yang et al[10]. An experimental study was carried out to evaluate the rotational performance of bolted I-beam connections to concrete-filled elliptical steel tubular (CFEST) columns. A total of ten joint specimens were subjected to a constant axial compressive force on the column, combined with concentrated upward loading applied at the beam ends. The investigation focused on the influence of column orientation and the arrangement of stiffening plates. Analysis of the moment–rotation relationships and observed failure mechanisms highlighted the positive contribution of both the core concrete and stiffeners in improving the structural behavior of the connections. The results indicated significant enhancements in both load-bearing capacity and rotational ductility across the tested configurations. Yiyan Lu et al[11]. focused their research on the axial load response of short concrete-filled steel tube (CFST) columns, incorporating both plain concrete and steel fiber-reinforced concrete (SFRC). A total of thirty-six specimens were examined, with variations in steel fiber volume fractions (0%, 0.6%, 0.9%, and 1.2%), steel tube wall thicknesses (3 mm, 4 mm, and 5 mm), and concrete compressive strengths ranging from 50–70 MPa. The findings demonstrated that introducing steel fibers effectively delayed local buckling of the outer steel tube and improved the shear-friction interaction within the concrete core. This resulted in noticeable gains in both ductility and energy absorption capacity of the CFST members. However, the influence of steel fibers on the ultimate axial load capacity was found to be minimal. Additionally, the study developed design formulas to estimate both load-carrying strength and ductility, which showed a strong correlation with the experimental data. Together, these investigations highlight the interaction between reinforcement configuration, concrete confinement, and joint stiffness. They show that both internal reinforcement and external diaphragm strengthening can effectively delay local buckling and improve post-peak stability. Figure 3 represent the Test setup of LVDTs.

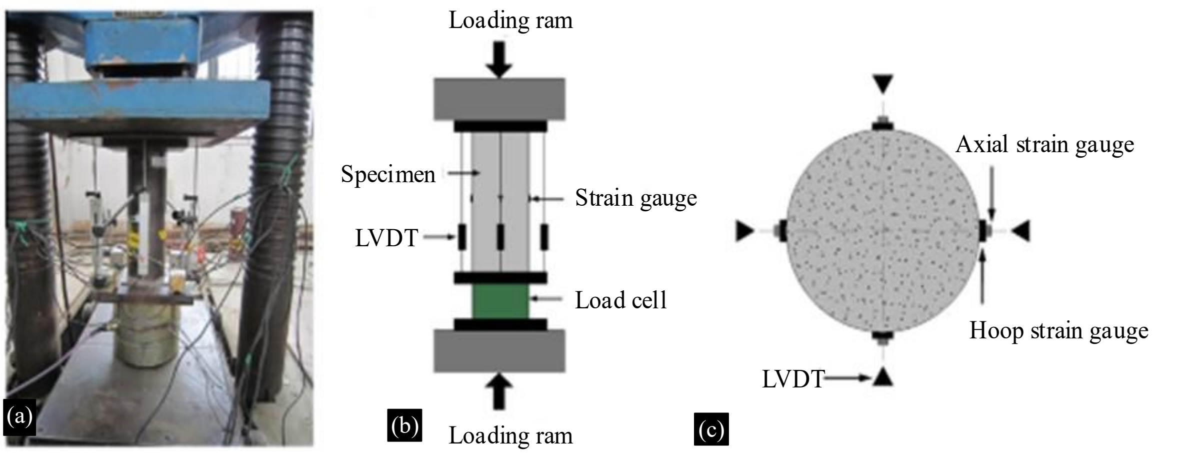

Figure 3. Test setup includes: (a) photograph; (b) schematic diagram; (c) placement of strain gauges and LVDTs. (Yiyan Lu et al., 2015) [11].

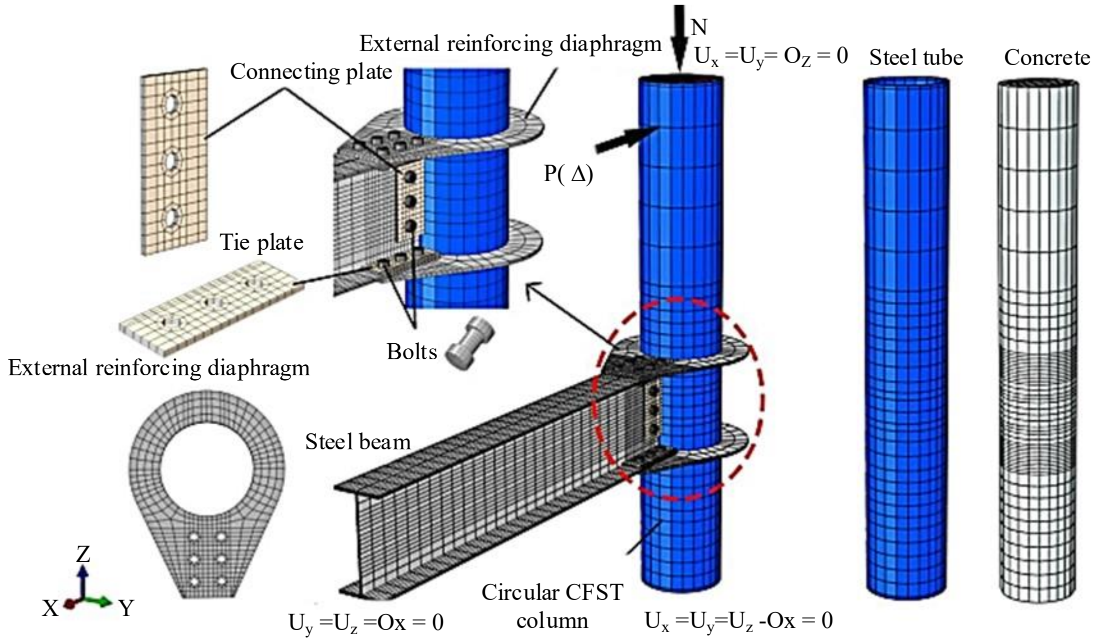

Figure 4. The joint specimen was modelled in the finite element analysis (F. Xing Ding et al., 2021) [12].

Ding et al[12]. A study was conducted on three configurations of concrete-filled steel tubular (CFST) column-to-steel beam bolted connections reinforced with external diaphragm plates, using half-scale specimens subjected to cyclic loading. The investigation focused on the impact of steel beam dimensions and the inclusion of high-strength bolt tie plates on the failure patterns. Finite element models developed in ABAQUS were validated against the experimental data. Results revealed that these bolted diaphragm-reinforced joints behaved as semi-rigid connections, delivering stiffness and load-carrying capacity similar to fully welded rigid joints, especially when equipped with four rows of bolts and web stiffeners. Furthermore, the bolted joints demonstrated over 80% of the plastic energy dissipation potential of welded connections, with the steel beam playing the dominant role in absorbing and dissipating cyclic energy. Figure 4 represent the joint specimen was modeled in the finite element analysis.

Zheng et al[13]. investigated the progressive collapse resistance of concrete-filled steel tubular (CFST) column-to-composite beam fabricated joints through a combination of experimental tests and numerical analyses. The study assessed three distinct connection configurations along with two shear connector types to evaluate failure mechanisms, load-bearing and deformation behavior, and strain–displacement responses. Additionally, the analysis considered bending moments and axial force distributions within the steel beam, along with the individual contribution of each component to the overall vertical load resistance. The study quantified nonlinear collapse resistance, benchmarking results against the DoD guidelines and FEMA 350 provisions, and calculated Dynamic Increase Factors (DIFs) using experimental data, finite element simulations, and the energy balance method. Elghazouli et al[14]. This study explored the structural response of circular steel tubes infilled with concrete incorporating recycled rubber particles under lateral cyclic loading, with, and without an applied axial force. A total of twelve specimens were evaluated, with rubber replacement levels reaching up to 60%, and axial loading applied at up to 30% of the nominal compressive capacity. While increased rubber content led to a notable reduction in concrete compressive strength, the confinement effect provided by the steel tube helped to offset the loss in capacity. Specimens with rubberized concrete exhibited enhanced ductility and greater energy dissipation, showing improvements of approximately 10% and 17%, respectively, compared to standard CFSTs. The study also developed simplified analytical models for predicting key performance indicators, offering practical insights for structural design and evaluation. The integration of polymers, fibers, and nanomaterials into CFST concrete cores demonstrates a new dimension of hybridization. Rubberized concrete improves ductility and energy absorption, while nanomaterial additives such as nano-silica and CNTs enhance stiffness and confinement efficiency. These polymer-based interventions bridge the gap between traditional CFST systems and modern, multifunctional composites, offering improved performance under both static and cyclic loading conditions.

Abendeh et al[15]. The study focused on the development of innovative self-compacting concrete (SCC) mixes designed to enhance interfacial bond strength in concrete-filled steel tubes (CFSTs) at both 30-day and one-year curing periods. The mixes incorporated waste steel slag aggregates (SSA) as partial substitutes for both coarse and fine aggregates. A total of 36 circular and square CFST specimens were prepared, featuring SSA replacement levels of 0%, 25%, and 50%. The results indicated that the inclusion of SSA improved the bond strength for both tube shapes and mitigated long-term reductions in interfacial performance. Furthermore, a three-dimensional nonlinear finite element simulation was conducted to model the bond-slip interaction at the concrete–steel interface. Isleem et al[16]. investigated the axial compressive performance of concrete-filled steel tube (CFST). They reinforced concrete-filled steel tube (RCFST) columns using a combination of finite element analysis (FEA) and machine learning (ML) techniques. A dataset comprising 85 previously tested column specimens was utilized, and multiple ML algorithms were applied to predict the ultimate load-bearing capacity. The findings showed that improvements in compressive strength, ductility, and structural toughness were achieved through the optimization of reinforcement layouts and steel tube properties. The FE models accurately replicated the structural behavior of RCFST columns. Among the evaluated ML models, gradient boosting yielded the highest predictive accuracy and consistency, underscoring its effectiveness as a reliable tool for estimating ultimate loads in both CFST and RCFST systems. Pengfei et al[17]. investigated the axial compressive behavior of concrete-filled steel tube (CFST) columns through experimental testing. The study considered two groups of specimens – columns with and without foundation support – with variations in steel tube wall thickness and the presence of longitudinal reinforcement. Results indicated that bar-reinforced CFST columns exhibited greater load-carrying capacity, improved plastic deformation, and enhanced toughness. Furthermore, the mechanical properties of the steel tube and the embedment depth of rock-socketed foundations were found to influence the ultimate axial strength significantly. Numerical simulations further revealed that the actual failure loads exceeded the predicted values provided by current design standards. Lianqiong et al[18]. examined the axial compressive performance of concrete-filled steel tubular (CFST) hybrid columns using finite element analysis (FEA), with the results validated against experimental data. The study confirmed that the strain distribution along the column height, prior to peak loading, adheres to the plane section assumption, indicating uniform deformation behavior. The ultimate load capacity was primarily influenced by the bearing strength of the reinforced concrete (RC) connecting plate. Additionally, the CFST hybrid columns exhibited enhanced ductility beyond the peak load, signifying superior energy dissipation and deformation tolerance. These results highlight the significant influence of both steel tube wall thickness and RC plate configuration on optimizing the structural efficiency of CFST hybrid columns. Elghazouli et al[19]. The research evaluated the structural response of circular steel tubes infilled with rubberized concrete under lateral cyclic loading, both with and without concurrent axial loading. A total of twelve specimens were tested, incorporating rubber content ranging from 0%–60%, to assess key parameters such as stiffness, load-bearing capacity, ductility, energy absorption, and failure characteristics. Despite the reduction in compressive strength caused by increased rubber content, the overall structural performance remained largely unaffected due to the confinement and strength contribution of the steel tube. Compared to standard concrete-filled tubes, the rubberized variants achieved up to 10% enhancement in ductility and 17% improvement in energy dissipation. Additionally, the study developed predictive analytical models to estimate critical performance indicators, offering practical tools for structural design and assessment. Ghazijahani et al[20]. The research examined the structural performance of concrete-filled steel tubes (CFST) incorporating recycled redwood timber chips under axial compressive loading. A total of eighteen short columns with varying timber chip content and steel tube configurations were experimentally evaluated to analyze failure patterns, axial load-bearing capacity, self-weight reduction, and energy dissipation characteristics. Findings indicated that the inclusion of wood waste in concrete provides an eco-friendly approach to converting timber residues into economically viable construction materials. An analytical model that accounted for confinement effects was formulated and validated using data from 100 previously published specimens. The proposed model accurately estimated axial strength and demonstrated high consistency with design guidelines such as Eurocode-4, AISC-LRFD, DL/T, and ACI standards. Zhao et al[21]. This study aimed to estimate the load-bearing capacity and confinement pressure of rectangular concrete-filled steel tube (CFT) columns through the application of artificial neural networks (ANNs). Given the challenges associated with direct measurement of confining pressure and the inherent limitations of finite element analysis, the research utilized a newly developed experimental dataset to train ANN models based on five critical input variables. The model's predictive accuracy was verified using data from existing literature, demonstrating high reliability. Furthermore, parametric studies were conducted to explore the influence of geometric configurations and material characteristics on the load capacity and confinement behavior, offering a deeper understanding of the composite interaction between the steel casing and concrete core in rectangular CFT elements. Singh et al[22]. This study examined the axial compression behavior of a novel stiffening configuration in concrete-filled steel tube (CFST) columns, termed the catty-cornered propped CFST, incorporating concrete enhanced with nanomaterials. The influence of nano-silica (NS), carbon nanotubes (CNT), and nano-titanium dioxide (NT) on ultimate load capacity, load–strain characteristics, ductility index, secant stiffness, and composite interaction efficiency was systematically evaluated. Findings revealed that the innovative stiffening technique improved the ultimate axial capacity by approximately 14%, with the addition of nanomaterials contributing an additional 7% increase. While nanomaterial inclusion enhanced stiffness, it was associated with a reduction in ductility. Overall, the synergy between the modified CFST configuration and nanomaterial-infused concrete substantially enhanced the structural response under compressive loads. Isleem et al[23]. This study investigated the axial compressive performance of concrete-filled steel tube (CFST) and reinforced concrete-filled steel tube (RCFST) columns using a combination of finite element modeling (FEM) and machine learning (ML) approaches. A dataset comprising 85 column specimens from prior literature was utilized to simulate structural responses through FEM and to train various ML algorithms for predicting ultimate load capacity. Results demonstrated that reductions in transverse reinforcement spacing, increased longitudinal bar ratios, and enhancements in steel tube thickness and yield strength significantly improved compressive strength, ductility, and toughness. Among the ML models evaluated, the gradient boosting algorithm exhibited superior predictive accuracy, achieving coefficient of determination (R^2) values of 99.925% and 99.863%, and root mean square errors (RMSE) of 0.00708 and 0.00717 in the training and test phases, respectively. These outcomes underscore the effectiveness of gradient boosting as a robust predictive tool, offering a reliable alternative to extensive experimental investigations for estimating the load-carrying capacity of CFST and RCFST columns. Figure 5 represents the configuration of diagonally braced CFST.

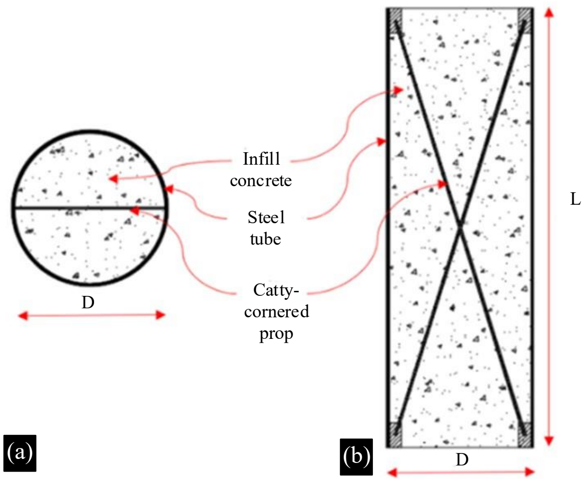

Figure 5. Configuration of diagonally braced CFST: (a) Plan view, (b) Elevation view. H. F. Isleem et al. (2023) [23].

Tao et al[24]. This study evaluated the bond behavior at the steel–concrete interface in concrete-filled steel tube (CFST) systems through an extensive series of push-out tests on circular and square specimens. Key parameters investigated included cross-sectional dimensions ranging from 120–600 mm, steel types (carbon and stainless), concrete types (standard, recycled aggregate, and expansive), concrete ages spanning from 31–1176 days, and various interface enhancement methods such as standard surfaces, welded shear studs, and internal steel rings. Results indicated that CFST specimens fabricated with stainless steel exhibited lower bond strength than those with carbon steel. Furthermore, bond strength decreased with increasing cross-sectional size and concrete age. Among the enhancement strategies, the incorporation of welded internal rings yielded the greatest improvement in bond strength, followed by welded shear studs and expansive concrete. These findings provide valuable insights into optimizing composite interaction and improving load transfer efficiency in CFST applications. Wang et al[25]. reported that removing a corner column resulted in localized deformation concentrated near the failure zone. In contrast, the removal of a middle column induced varying degrees of damage in the adjacent beams. In both scenarios, collapse was initiated by the fracture of a steel beam. Notably, the structural system demonstrated greater resistance to collapse following middle column removal, attributed to the synergistic contribution of flexural and catenary actions developed in the surrounding beams. Chen Fang et al[26]. This research investigated the seismic performance of a ring-beam connection system linking reinforced gangue concrete (RGC) beams to coal gangue concrete-filled steel tubular (GCFST) columns. Two connection specimens – interior and exterior – were tested under fully reversed cyclic loading applied at the beam ends. Finite element models were developed in ABAQUS to simulate the structural response under combined axial and cyclic loads, with validation against experimental results. Key performance indicators, including load capacity, deformation resistance, stiffness, and strength degradation, energy dissipation, and ductility, were analyzed. A parametric study assessed the impact of various material and geometric parameters on connection behavior. Based on the results, a restoring force model for the connection's backbone curve was proposed, offering practical guidance for seismic design and application of such connection systems. Jiaqi Sun et al[27]. The study revealed that both arches were subjected to significant confining pressure, which greatly influenced their ultimate load capacity and ductility under central and half-span loading conditions, highlighting the need to consider this effect in analyses. The shear stress in the steel tubes was found to be minimal, allowing its interaction with normal stress to be disregarded in finite element (FE) models. Additionally, residual stress showed negligible impact on the load-bearing capacity of the CFST arches and was therefore omitted from the simulations. FE models employing both solid and beam elements effectively predicted buckling behavior, with maximum deviations from experimental ultimate load capacities limited to 1.2% and 0.9%, respectively. Aditya Kumar Tiwary et al[28]. The axial load-bearing capacity of concrete-filled double-skin steel tubular (CFDST) columns is strongly influenced by the thickness and diameter of the steel tubes. A reduction in the diameter of the inner steel tube led to a 15.7% increase in load capacity. Additionally, increasing both the thickness and diameter of the outer steel tube significantly enhanced the columns' ultimate axial strength. Analysis of the load–strain (P–ε) curves indicated that the sandwich concrete core contributed approximately 50%–55% of the total load-carrying capacity, while the outer and inner steel tubes accounted for about 30%–40% and 10%–15%, respectively. Zi-Ming Yang et al[29]. This study examined the seismic performance of circular concrete-filled steel tube (CFST) columns reinforced internally with latticed steel angles under combined axial compression and reversed cyclic lateral loading. Eight specimens were tested, including two conventional CFST columns and six columns incorporating internal latticed steel reinforcement. The investigation considered key variables such as the diameter-to-thickness (D/t) ratio of the steel tube, the cross-sectional area of the internal reinforcement, and the axial compression ratio. Experimental evaluation included load–displacement and load–strain responses, with a focus on identifying failure modes, hysteretic behavior, backbone curves, stiffness degradation, ductility, and energy dissipation characteristics. Jiuyang Li et al[30]. found that incorporating coal gangue as aggregate does not alter the typical failure mode of CFST columns with low slenderness ratios. Failure typically occurs through circular bending at the steel tube ends and mid-span, accompanied by crushing of the concrete core, consistent with conventional CFST behavior. As the slenderness ratio increases, lateral deflections become more significant, causing failure to transition from material failure to instability. Increasing the coal gangue replacement percentage leads to a reduction in the ultimate load capacity of the columns. Moreover, both the load-carrying capacity and ductility tend to decrease with higher slenderness ratios but show improvement with increased steel content. Zhihua Chen et al[31]. In unconfined specimens, failure initiated with local buckling of the steel tube, followed by the development of vertical cracks along the welded joints and lateral cracking at the corners. The progression of damage culminated in the tensile rupture of the steel flange and the complete crushing of the core concrete, ultimately leading to a total loss of load-bearing capacity. Long Zheng et al[32]. The welded beam (WB) connection demonstrated a higher initial load-bearing capacity compared to the bolted connection. However, premature fracture of the bottom welded flange impeded the development of catenary action (CA), thereby limiting its deformation capacity and overall structural resistance. In contrast, the reduced welded beam (RWB) and bolted connections exhibited enhanced rotational performance due to plastic deformation in the bolted regions, which promoted the formation of CA and improved vertical load resistance under large deformations. Xin Nie et al[33]. The large-scale steel–concrete–ECC (Engineered Cementitious Composite) composite frame demonstrated superior seismic performance, with strength, stiffness, energy dissipation capacity, and degradation trends comparable to those of conventional steel–concrete composite frames. Notably, the inclusion of ECC significantly reduced crack widths and tensile strains in the slab. Under vertical loading, ECC-enhanced frames exhibited a reduction in crack widths ranging from 18%–40% relative to traditional composite frames. Yun Zou et al[34]. Have shown that concrete-filled composite steel tube columns with polygonal steel tubes (CFCST-PST) exhibit superior mechanical performance and enhanced constructability. Experimental results showed that the strength index (SI) of PST specimens exceeded that of conventional standard tube (ST) specimens by 16.67%, while the ductility index (DI) was 8.28% higher. Finite element simulations supported these findings, demonstrating that the polygonal geometry provides improved confinement to the core concrete, thereby substantially increasing the axial load-carrying capacity of the columns. Yudong Ma et al[35]. Both high-strength concrete-filled steel tube (HSCFST) and fiber-reinforced polymer (FRP)-confined HSCFST stub columns predominantly exhibited shear failure modes. Specimens confined with a single layer of CFRP or fewer than two layers of GFRP developed diagonal cracks extending from top to bottom at approximately a 60° angle. In contrast, columns wrapped with more than two CFRP layers or three GFRP layers experienced vertical fractures concentrated in the central FRP region. Increasing the number of FRP layers significantly enhanced the ultimate load-bearing capacity, axial strain, and deformation at the FRP strengthening stage. CFRP was more effective in improving strength and overall deformability, whereas GFRP demonstrated better ductility characteristics. Harpreet Singh et al[36]. reported that the ultimate axial load capacity of the proposed stiffened concrete-filled steel tube (CFST) columns exceeded that of unstiffened CFST columns by approximately 15%, 20%, and 25% for binary, tertiary, and quaternary propped configurations, respectively. Stiffened sections reached their peak loads at lower strain levels, reflecting reduced deformation at ultimate capacity. Additionally, the inclusion of diagonal stiffeners led to a more gradual post-peak load decline, indicating improved ductility and enhanced post-peak stability compared to their unstiffened counterparts. Shan Gao et al[36]. Under repeated impact loading, all specimens displayed overall flexural damage along with localized indentation at the impact site. As the number of impacts increased, total deformation continued to grow; however, the deformation added with each successive impact gradually diminished. Ultimately, the accumulated plastic displacement approached a steady value, suggesting the attainment of a saturation point in the damage progression. Yong Fang et al[37]. demonstrated that the incorporation of an external thin-walled helical concrete-filled steel tube (CFCST) substantially enhances the cyclic torsional performance of reinforced concrete (RC) columns. This addition leads to significant improvements in torsional strength, deformability, and ductility. With only a 2% increase in the steel ratio, the ultimate torque capacities increased by factors of 5.0 and 2.61 in the positive and negative directions, respectively, relative to the unconfined RC column. Additionally, the maximum torsional angles achieved were nearly three times greater than those of the RC specimen. Benhao Gao et al[38]. Under repeated lateral loading, the tested joint assemblies exhibited three distinct types of structural failure: combined compression and bending collapse in the column, shear failure within the joint core region, and bending-induced failure at the plastic hinge zone of the beam. The predominant failure pattern was primarily influenced by the flexural strength ratio between the beam and column. Notably, joints that experienced flexural yielding at the beam's plastic hinge zone demonstrated superior seismic resilience, evidenced by the highest ductility index (exceeding 3.72) and a slower deterioration rate in both load-bearing capacity and stiffness. Moreover, enhancing the compressive strength class of lightweight high-performance concrete (LC-HPC) from C60–C100 significantly improved the joints' deformation capacity, maximum load resistance, and ability to dissipate energy under cyclic loading. Faxing Ding et al[39]. Connections with single-side bolts between SCFST columns and composite beams usually fail due to beam-end bending, column-end compression-flexure, or joint core cracking. Their hysteresis response tends to follow one of two forms, depending on whether bidirectional stirrups are included. When present, these stirrups improve seismic efficiency, preserving both strength and ductility under heavy axial pressure and significant lateral drift. Sun-Hang Ji et al[40]. The constructed finite element models provide an accurate depiction of the performance of concrete-filled steel tubular columns subjected to fire loading after lateral impact events. The simulation outcomes suggest that damage from impact significantly diminishes thermal stability and intensifies deflection rates during fire, thereby increasing the potential for sudden structural failure. Xi Lan et al[41]. When the initial failure mode involves brittle net section fracture of the flange plate or bolt rupture, the system cannot engage alternative load paths, resulting in limited rotational capacity of the connection (typically under 12°) – inadequate for mitigating progressive collapse. In contrast, if the primary failure mode is bearing deformation in the flange or web plates, secondary load paths become active. Under high-temperature conditions, these mechanisms enable substantially greater rotational capacities – surpassing 20° when flange bearing failure occurs before web bearing, and approximately 15° when the sequence is reversed. Guo-Qiang Wei et al[42]. The detrimental impact of seismic damage on the fire resistance of circular concrete-filled steel tube (CFST) columns diminishes as the axial load ratio increases. At a lower axial load ratio ($n = 0.284$), the fire endurance decreases from 21.7 minutes in the undamaged state to 20.6 minutes at a drift ratio of 2.67%, and further declines to 16.2 minutes when the drift reaches 4.48%. In comparison, for a higher axial load ratio ($n = 0.431$), no loss in fire resistance is detected at a drift of 2.63%, and only a marginal reduction is observed – from 14.2–13.7 minutes – when the drift reaches 4.42%. Gosala Sai Ram Reddy et al[43]. Experimental and finite element load–displacement curves for circular and square CFST and RCC stub columns show strong agreement, validating the accuracy of the material models used in the simulations. The structural response is characterized by a load increase with axial shortening until a peak (ultimate load) is reached, followed by a reduction in load-carrying capacity. Wei Xian et al[44]. A comparative study of the impact behavior of square steel-reinforced concrete-filled steel tubular (SRCFST) and concrete-filled steel tubular (CFST) members reveals that SRCFST specimens demonstrate superior impact resistance, despite having equivalent cross-sectional dimensions. The incorporation of an internal steel profile in SRCFST members results in a 27.3% reduction in peak displacement and a 29.3% decrease in residual displacement, with a modest 7.6% increase in total mass. Shiye Wang et al[45]. reported that the CFST specimen exhibited relatively stable tensile strength throughout loading, with only minimal deterioration. Conversely, the compressive strength decreased significantly following the onset of local buckling in the steel tube. While the tensile unloading stiffness decreased slightly with increasing load levels, the compressive unloading stiffness decreased substantially. Both post-buckling and tensile stiffnesses declined progressively as the loading advanced. Haijia Huang et al[46]. investigated the axial compressive behavior of circular CFST columns featuring notches and externally reinforced with CFRP. A total of thirteen specimens were tested to assess the influence of notch length and the number of CFRP layers on the efficiency of the strengthening technique. Finite element models were developed and calibrated against experimental results. Subsequent parametric studies using these models explored the effects of various parameters on structural enhancement. The inclusion of vertical notches in the steel tubes significantly compromised the load-bearing capacity of the CFST columns [46]. However, despite a marginal reduction in ductility compared to unnotched counterparts, CFRP reinforcement effectively enhanced overall structural performance. Shuhong Lin et al[47]. Under horizontal impact from a rigid body, CFST columns with fixed-base and free-top boundary conditions showed predominant bending-induced failure. The columns experienced considerable lateral displacement, forming an oblique deflection shape. Near the column base, local buckling appeared distinctly on the face opposite the impact direction, primarily due to compression generated by flexural deformation. Raed M. Abendeh et al[48]. New SCC mixes incorporating 0%, 25%, and 50% steel slag aggregate (SSA) were designed to enhance bond strength in CFST columns at 30 days and one year. Thirty-six circular and square CFST specimens were tested, showing improved interfacial bond performance with SSA. Although bond strength declined over time, SSA reduced the rate of degradation. A 3D nonlinear FE model was also developed to replicate the bond–slip behavior between the concrete core and the steel tube. Zaiyu Zhang et al[49]. The finite element (FE) models demonstrated high predictive accuracy in simulating the load–displacement behavior, failure mechanisms, and ultimate capacity, with peak load deviations remaining within 5% of the experimental results. The steel tube offered substantial lateral confinement to the ECC, leading to a relatively uniform distribution of contact pressure along its inner surface. This confinement effect markedly enhanced the compressive strength of the ECC material. Yu-Hang Wang et al[50]. Recognized for its superior damping characteristics, energy absorption, and ductility, rubberized concrete (RuC) is being explored as a sustainable alternative in structural systems. Its integration into CFST columns represents a promising eco-conscious strategy for current construction practices. However, the lack of comprehensive data on RuC's behavior after fire exposure presents a critical limitation. Bridging this gap is key to enabling fire-resilient design of RuC-based CFST structures. Ruitian Xu et al[51]. A strong confinement synergy was found between the CFRP–PVC tube and the I-section steel. Increasing the hoop coefficient improved peak strength and confinement but reduced ductility. When the hoop coefficient remained constant, more steel content lowered confinement efficiency, with ductility showing an initial drop followed by a rise. Section steel enhanced overall confinement beyond earlier reported levels. For hoop coefficients ≤ 0.68, steel content should stay below 6.53%. In weak confinement, extra steel reduced axial stiffness, but under strong confinement, it proved beneficial. The optimal hoop coefficient range was 0.4–0.68. Qiuying Chang et al[52]. The research focuses on the mechanical behavior of concrete-filled double-skin tubular columns, which consist of a steel outer tube, a UPVC inner tube, and a concrete infill. Through experimental testing, the study evaluates how variations in the diameter ratio, steel tube thickness ratio, and inner tube material impact axial compressive strength. The outcomes serve as a design reference for selecting appropriate dimensional parameters and materials to achieve enhanced load-bearing capacity.

Aref A. Abadel et al[53]. The findings revealed that the outer steel tube provided significantly stronger confinement to the core concrete compared to PVC tubes and CFRP sheets. Among all specimens, the CFST column demonstrated the highest ultimate axial strength, with an increase reaching up to 233.8%. However, pronounced inward local buckling in the inner steel tube was observed, which compromised the effectiveness of the encased shell concrete and limited the full yield potential of the inner steel component. Additionally, the inclusion of inner steel tubes led to a reduction in axial load capacity. The axial capacity decreased by 33.53% for CFST-Ann, 25.81% for CFPVC-Ann, and 9.52% for CFFRPT-Ann when compared to their respective counterparts without internal steel tubes (CFST, CFPVC, and CFFRP). Qingxuan Shi et al[54]. The failure modes observed in the tested specimens predominantly fell into two categories: horizontal shear cracking along the joint's central horizontal axis and axial instability resulting from buckling of the inclined columns. The buckling behavior was attributed to second-order effects induced by differential displacements occurring above and below the joint during the loading process. Additionally, due to the influence of the axial compression ratio, the specimens remained largely in a state of compressive stress throughout the axial cyclic loading. As a result, the hysteresis response was primarily confined to the compressive zone, where most of the energy dissipation occurred. Xing Gao et al[55]. An experimental investigation was undertaken to assess the structural behavior and load-bearing capacity of an innovative concrete-anchored slip-critical blind bolt (CASCBB) system using pull-out tests on concrete-filled steel square hollow sections (SHS). Three primary failure mechanisms were identified: formation of a concrete cone or anchorage rupture, cracking at the steel tube corners, and bolt extraction. In several cases, anchorage failure was subsequently followed by either bolt withdrawal or corner fracture, contingent on factors such as the bolt's edge distance and the thickness of the steel tube flange. Notably, these failure types did not always align with the peak load capacity. In comparison to the conventional slip-critical blind bolt (SCBB) system – typically constrained by premature loss of bond with the concrete and absence of cone failure – the CASCBB system demonstrated significantly greater rigidity and load resistance. Under equivalent conditions, the CASCBB system attained tensile strengths up to twice those of the SCBB. Additionally, the existence of threading on the anchor stud had minimal influence on the overall connection strength. Ahmed A. Hamoda et al[56]. The dominant failure pattern in the columns was characterized by global flexural deformation coupled with concrete crushing. Enhancing the reinforcement ratio and increasing the embedment depth of the steel bars effectively postponed the initiation of cracking. Columns with shorter embedment lengths – approximately 15 times the diameter of the reinforcing bar – typically experienced failure at the ECC/SHCC interface, whereas longer embedment depths shifted the failure location away from this junction. Columns featuring ECC or SHCC joints consistently demonstrated higher stiffness than conventional counterparts. This stiffness was further improved with greater reinforcement and deeper steel bar embedment. Specifically, columns incorporating ECC joints exhibited a stiffness enhancement of nearly 150%, while those with SHCC joints achieved an improvement of around 93%. Xipeng Ma et al[57]. All tested steel–concrete–steel foam-filled tubular energy-absorbing structures (SSEASs) exhibited a consistent failure mechanism: the central polyurethane foam-filled steel tubes (PUFFST) experienced global collapse, while the surrounding steel–concrete–steel sandwich panels (SCSSPs) developed localized indentation. The impact response was characterized by two distinct phases – loading and unloading. During the initial loading phase, localized denting occurred, accompanied by a sharp increase in impact force. Xin Tang et al[58]. Special-shaped concrete-filled steel tubular (SCFSTF) elements incorporating outer diaphragm linkages exhibit remarkable adaptability and enhanced energy absorption, contributing to robust seismic resistance. These linkages promote effective force transmission, with plastic hinges typically initiating at the beam extremities and subsequently at the base of the columns. At the same time, the joint zones generally stay within the elastic range. This structural response is consistent with capacity-based design concepts, which emphasize greater strength in columns and joints compared to beams, thereby enabling controlled, ductile failure. Shaozhen Chen et al[59]. Integrating stiffeners into large rectangular concrete-filled steel tubular (RCFST) columns postpones the onset of local buckling in the steel shell until after yielding occurs, thereby enhancing structural strength and boosting the maximum load-bearing capacity of the column. Yong Yang et al[60]. The newly developed segmented high-strength concrete-filled steel tubular (CFST) column, integrated with a precast reinforced concrete beam frame, achieved a peak displacement of 133 mm, equating to an inter-story drift ratio of 1/36. This behavior exceeds the seismic code threshold of 1/50 under major earthquake conditions, highlighting its exceptional seismic resistance. Moreover, the frame complies with the "strong column–weak beam" design concept and demonstrates efficient energy dissipation capabilities. Kai Wang et al[61]. In specimen PC1, which incorporated a bolted flange joint, the primary load-carrying mechanism was flexural-compressive arch action (F-CAA), reflecting the rigid nature of the connection. Cracking appeared near the extremities of the precast concrete beam, while the internal reinforcement bars and connectors remained within the elastic range. However, following the attainment of peak load, the structure experienced out-of-plane instability, which hindered further assessment of its post-peak response during the experiment. Rosette Niyirora et al[62]. Recent investigations have predominantly focused on the seismic behavior of columns and isolated structural components. However, research concerning the connections in centrally-embedded concrete-filled steel tubular (CE-CFST) columns remains relatively limited. Moreover, the finite element analysis (FEA) models and analytical methods developed so far can be adapted for column bases with diverse CFST configurations and varying levels of concrete confinement. Aref A. Abadel [63] The external steel tube provided substantially superior confinement to the concrete core relative to the PVC tube and CFRP wrap. Among all tested column types, the CFST column demonstrated the highest axial load capacity, achieving enhancements of up to 254.7%. Nevertheless, all specimens exhibited inward local buckling of the inner steel tube, which reduced the confinement efficiency on the core concrete and restricted the inner tube from attaining its full yield potential. Mohammed Jalal Al-Ezzi et al[64]. The flexural performance and failure mechanisms of pultruded GFRP tube beams are greatly affected by the type of infill concrete.

Incorporating high-strength concrete enhances both the load-bearing capacity and flexural rigidity; however, it may also induce brittle failure modes such as flange crushing and wide crack propagation. In contrast, normal-strength concrete improves ductility and mitigates the likelihood of abrupt failure. The use of seawater sea-sand concrete (SWSSC) contributes to delaying local buckling and enhances bending behavior, although early flange crushing can still occur under elevated loading conditions. Recycled aggregate concrete demonstrates comparable performance to natural aggregate concrete, underscoring its viability for sustainable structural applications. Junchang Ci et al[65]. Both experimental results and finite element analyses demonstrate that square concrete-filled double-skin tubular (CFDST) columns incorporating an inner square hollow section (SHS) exhibit enhanced ultimate strength and ductility compared to conventional CFST and double CFST (DCFST) columns. Moreover, the parametric analysis highlights that the compressive strength of the concrete, particularly in the core (sandwiched) layer, is a critical factor influencing the axial load-bearing capacity of the columns. Xiang Li et al[66]. In the CTRC frame, a column-to-beam strength ratio (η) of 3.0 resulted in failure occurring at the beam's plastic hinge, while a ratio of 0.9 shifted the failure to the column's plastic hinge. In both scenarios, the joint core regions remained largely intact, demonstrating that the novel joint configuration effectively achieved the desired "strong joint–weak member" performance objective. Chen Fang et al[67]. The ring-beam connection linking RGC beams to GCFST columns exhibited a characteristic full spindle-shaped hysteresis curve, indicating strong performance and a gradual reduction in stiffness. Failure occurred when a plastic hinge developed in the RGC beam, consistent with the "strong column–weak beam" design concept. Overall, this connection demonstrated satisfactory seismic behavior. According to Alireza Khaloo et al., replacing normal concrete with expansive concrete increased strength by up to 15% and enhanced ductility by 70%. The expansive agent helped minimize concrete shrinkage and strengthened the bond between the steel tube and the concrete core. Additionally, increasing specimen height from 220 mm to 660 mm resulted in reductions of 7%–26% in peak load and 14%–17% in axial strain. Cun Hui et al[68]. Based on the ultimate balance theory, the calculated values rise with an increase in the lateral pressure coefficient (k1). When k1 ranges from 3–4, these calculated results align well with experimental data. However, for values of k1 greater than 4, the accuracy of the calculations decreases, potentially leading to unsafe predictions. Alireza Khaloo et al[69]. Replacing regular concrete with expansive concrete led to a strength increase of up to 15% and a notable 70% improvement in ductility. The expansive agent played a key role in minimizing concrete shrinkage and enhancing the bond between the steel tube and the concrete core. Additionally, as the specimen height grew from 220 mm to 660 mm, the peak load and the associated axial strain declined by 7%–26% and 14%–17%, respectively. Salih K. Alrebeh et al[70]. The results indicated that using high-strength steel bolts enhanced the compressive strength by as much as 25.3%, 9.0%, and 3.5% for short, medium, and long columns, respectively, compared to the control samples. Additionally, the tests showed that decreasing the steel bolt spacing, as well as the (L/D) and (D/t) ratios, led to improvements in the columns' compressive capacity, stiffness, and ductility. Harpreet Singh et al[71]. reported that the uniaxial ultimate load capacity of the proposed orbicular CFDST columns exceeded that of the unstiffened ones. Specifically, positioning the orbicular anchorage at lengths L=5, L=4, and L=3 resulted in approximately 3%, 6%, and 15% increases in the ultimate capacity of the CFDST columns, respectively, compared to the unstiffened versions. Among these, placing the orbicular ring at L=3 had the greatest effect on enhancing the ultimate load capacity. Qiang Wang et al[72]. The load–displacement behavior of the columns typically progressed through five distinct stages: elastic, elastic-plastic, post-yield, sudden drop, and residual. During the elastic stage, the concrete and steel tube independently resisted the axial load. The steel tube's confinement effect became noticeable in the elastic-plastic stage, whereas the FRP sheets contributed significantly only after yielding, during the post-yield stage. Figure 6 represent the failure modes of different joints.

The analyzed studies reveal a clear trend: combining CFSTs with polymeric or recycled fillers improves both their mechanical and environmental qualities. Although enhancements in confinement and stiffness are well-supported, research on long-term durability and fire resistance remains limited. Additionally, variations in testing configurations and boundary conditions across studies complicate direct comparisons. Employing unified modeling frameworks and standardized testing setups will help enhance future design guidelines for CFST systems.

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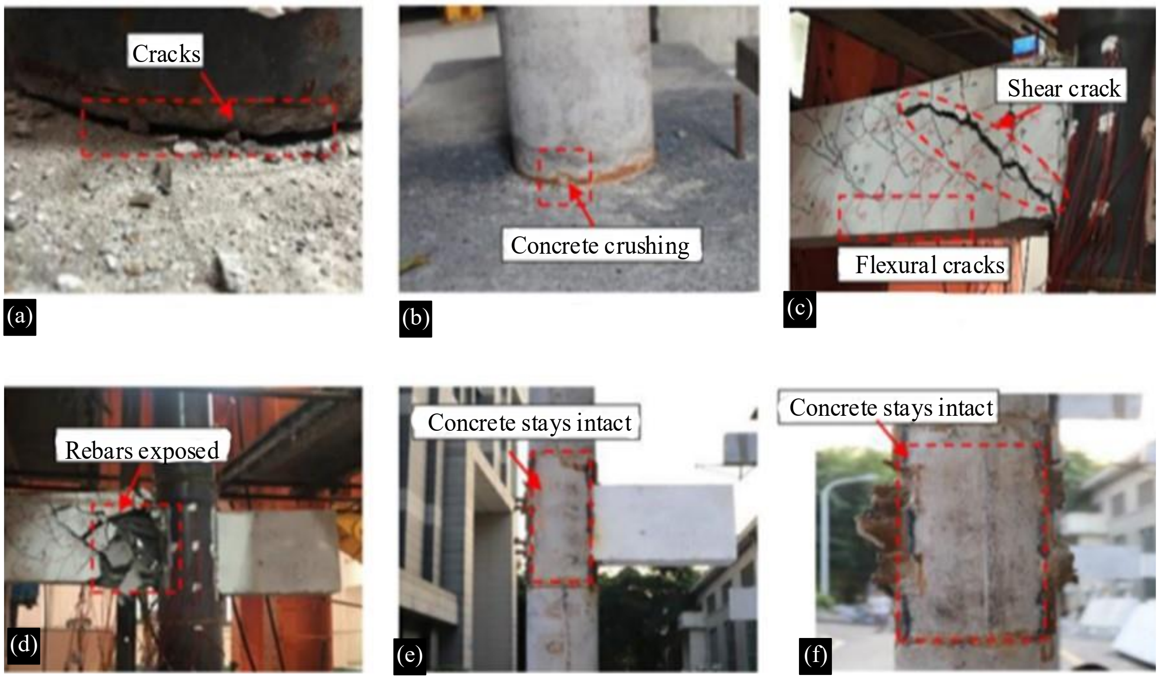

Figure 6. Failure modes of CTRC-40-0.6-2-r: (A) column base damage; (B) core exposed without steel tube; (C, D) RC beam at Δ = 90 mm and 150 mm; (E) edge joint distress; (F) middle joint failure (Wang et al., 2022) [72].

CONCLUSION

This review highlights the essential role of end conditions in controlling the structural behavior and collapse performance of Concrete-Filled Steel Tube (CFST) columns. Experimental studies consistently indicate that boundary conditions significantly affect the axial load capacity, deformation patterns, and failure modes of CFST elements. Similarly, numerical simulations, especially finite element models, have proven to be effective tools for accurately predicting these behaviors, as long as the interaction between the steel tube and concrete core is modeled properly. Among different end conditions, fixed–fixed supports typically provide the highest load resistance, whereas pinned–pinned supports tend to have lower stiffness and reach instability earlier. Despite considerable progress, important gaps still exist in understanding CFST behavior under complex loading conditions, dynamic effects, and non-uniform end restraints. Future research should focus on exploring these areas, refining constitutive models, and developing comprehensive design guidelines that consider a wider range of practical boundary conditions. Overall, improving our understanding of CFST columns under various end constraints will greatly contribute to safer and more efficient structural systems in both normal and extreme environments.

Recent advances in simulation and data-driven modeling have significantly impacted CFST research. Finite element analysis (FEA) successfully models nonlinear confinement behavior. At the same time, machine learning (ML) techniques, such as gradient boosting and neural networks, can predict ultimate strength and ductility with very high accuracy ($R^2 > 0.99$). These approaches reduce experimental costs and assist in creating design guidelines for hybrid CFST systems.

The studies reviewed reveal a clear trend: increased confinement, an ideal steel-to-concrete ratio, and the application of polymer or FRP composites significantly enhance ductility and resistance to collapse. Nevertheless, their effectiveness heavily relies on the geometric layout and interface bonding, highlighting the importance of optimizing hybrid designs via combined experimental and numerical approaches.

FUTURE SCOPE

- Future reviews should adopt standardized analytical frameworks that combine materials science, structural engineering, and AI-based prediction models. This integrated approach will accelerate the transition from traditional CFST systems to next-generation multifunctional hybrid composites, aligning with global goals for resilience and sustainability in infrastructure design.
- Despite the extensive research on Concrete-Filled Steel Tube (CFST) columns, several critical areas remain underexplored and offer promising avenues for future investigation:
- *Dynamic and seismic loading conditions:* Most existing studies focus on static loading. Research into the performance of CFST columns under dynamic, seismic, and blast loads – especially with varying end conditions – remains limited and should be expanded.
- *Non-uniform and realistic boundary conditions*: Real-world structural systems often present boundary conditions that do not fall neatly into idealized pinned or fixed categories. Studies incorporating semi-rigid or partially restrained end conditions could offer more practical insights.
- *Long-term performance and durability*: Investigations into the long-term behavior of CFST columns, including creep, shrinkage of the concrete core, and corrosion of the steel tube, especially under variable environmental and loading conditions, are needed.
- *Advanced material combinations*: The use of high-performance concrete, self-compacting concrete, and fiber-reinforced concrete in CFST systems warrants further study to assess their influence on overall performance.
- *Hybrid modeling techniques*: Integration of artificial intelligence, machine learning, and probabilistic modeling with traditional finite element approaches could enhance the predictive capabilities of numerical models.
- *Fire resistance and post-fire behavior*: The behavior of CFST columns under high temperatures and their residual strength post-fire exposure is another critical area requiring further experimental and numerical exploration.

REFERENCES

1. Wang Y, Chen P, Liu C, Zhang Y. Size effect of circular concrete-filled steel tubular short columns subjected to axial compression. *Thin-Walled Struct.* 2017;120:397–407. doi:10.1016/j.tws.2017.09.010.
2. Eladly MM, Schafer BW. Numerical and analytical study of stainless-steel beam-to-column extended end-plate connections. *Eng Struct.* 2021;240:112392. doi:10.1016/j.engstruct.2021.112392.
3. Mou B, Li X, Bai Y, He B, Patel VI. Numerical evaluation on shear behavior of irregular steel beam-to-CFST column connections. *J Constr Steel Res.* 2018;148:422–435. doi:10.1016/j.jcsr.2018.06.002.
4. Schneider SP, Alostaz YM. Experimental behavior of connections to concrete-filled steel tubes. *J Constr Steel Res.* 1998;45(3):321–352. doi:10.1016/S0143-974X(97)00071-0.
5. Wang X, Fan F, Lai J. Strength behavior of circular concrete-filled steel tube stub columns under axial compression: A review. *Constr Build Mater.* 2022;322:126144. doi:10.1016/j.conbuildmat.2021.126144.
6. Chua YS, Pang SD, Liew JYR, Dai Z. Robustness of inter-module connections and steel modular buildings under column loss scenarios. *J Build Eng.* 2022;47:103888. doi:10.1016/j.jobe.2021.103888.
7. Jin L, Chen H, Wang Z, Du X. Size effect on axial compressive failure of CFRP-wrapped square concrete columns: Tests and simulations. *Compos Struct.* 2020;254:112843. doi:10.1016/j.compstruct.2020.112843.
8. Wang P, Sun L, Zhang B, Yang X, Liu F, Han Z. Experimental studies on T-stub to hollow section column connections bolted by T-head square-neck one-side bolts under tension. *J Constr Steel Res.* 2021;178:106493. doi:10.1016/j.jcsr.2020.106493.
9. Schneider SP. Experimental behavior of connections to concrete-filled steel tubes. *Struct Congr Proc.* 1997;2:954–958.

10. Yang J, Sheehan T, Dai XH, Lam D. Experimental study of beam to concrete-filled elliptical steel tubular column connections. *Thin-Walled Struct.* 2015;95:16–23. doi:10.1016/j.tws.2015.06.009.
11. Lu Y, Li N, Li S, Liang H. Behavior of steel fiber reinforced concrete-filled steel tube columns under axial compression. *Constr Build Mater.* 2015;95:74–85. doi:10.1016/j.conbuildmat.2015.07.114.
12. Ding FX, et al. Hysteretic behavior of CFST column–steel beam bolted joints with external reinforcing diaphragm. *J Constr Steel Res.* 2021;183:106729. doi:10.1016/j.jcsr.2021.106729.
13. Zheng L, Wang WD, Xian W. Experimental and numerical investigation on the anti-progressive collapse performance of fabricated connections with CFST columns and composite beams. *Eng Struct.* 2022;256:114061. doi:10.1016/j.engstruct.2022.114061.
14. Elghazouli AY, Mujdeci A, Bompa DV, Guo YT. Experimental cyclic response of rubberised concrete-filled steel tubes. *J Constr Steel Res.* 2022;199:107622. doi:10.1016/j.jcsr.2022.107622.
15. Abendeh RM, Salman D, Al Louzi R. Experimental and numerical investigations of interfacial bond in self-compacting concrete-filled steel tubes made with waste steel slag aggregates. *Dev Built Environ.* 2022;11:100080. doi:10.1016/j.dibe.2022.100080.
16. Isleem HF, Chukka NDKR, Bahrami A, Oyebisi S, Kumar R, Qiong T. Nonlinear finite element and analytical modelling of reinforced concrete-filled steel tube columns under axial compression loading. *Results Eng.* 2023;19:101341. doi:10.1016/j.rineng.2023.101341.
17. Li P, Zhang T, Wang C. Behavior of concrete-filled steel tube columns subjected to axial compression. *Adv Mater Sci Eng.* 2018;2018:4059675. doi:10.1155/2018/4059675.
18. Zheng L, Yang H. Numerical study on the axial compression performance of concrete-filled steel tubular hybrid columns. *IOP Conf Ser Mater Sci Eng.* 2018;392:022032. doi:10.1088/1757-899X/392/2/022032.
19. Elghazouli AY, Mujdeci A, Bompa DV, Guo YT. Experimental cyclic response of rubberised concrete-filled steel tubes. *J Constr Steel Res.* 2022;199:107622. doi:10.1016/j.jcsr.2022.107622.
20. Ghanbari-Ghazijahani T, Azandariani MG, Vimonsatit V, Sulong NHR. Experiments and design of concrete-filled steel tubes with timber chips under axial compression. *Thin-Walled Struct.* 2023;186:110679. doi:10.1016/j.tws.2023.110679.
21. Zhao B, et al. Artificial neural network assisted bearing capacity and confining pressure prediction for rectangular concrete-filled steel tube (CFT). *Alexandria Eng J.* 2023;74:517–533. doi:10.1016/j.aej.2023.05.031.
22. Singh H, Tiwary AK, Eldin SM, Ilyas RA. Behavior of stiffened concrete-filled steel tube columns infilled with nanomaterial-based concrete subjected to axial compression. *J Mater Res Technol.* 2023;24:9580–9593. doi:10.1016/j.jmrt.2023.05.135.
23. Isleem HF, Chukka NDKR, Bahrami A, Oyebisi S, Kumar R, Qiong T. Nonlinear finite element and analytical modelling of reinforced concrete filled steel tube columns under axial compression loading. *Results Eng.* 2023;19:101341. doi:10.1016/j.rineng.2023.101341.
24. Tao Z, Song TY, Uy B, Han LH. Bond behavior in concrete-filled steel tubes. *J Constr Steel Res.* 2016;120:81–93. doi:10.1016/j.jcsr.2015.12.030.
25. Wang JX, Shen YJ, Zhou K, Yang Y. Experimental and numerical study on progressive collapse of composite steel–concrete frames. *Steel Compos Struct.* 2024;50(5):531–548. doi:10.12989/scs.2024.50.5.531.
26. Fang C, Li GC, Zhang L, Yang ZJ. Experimental and numerical investigation on seismic performance of ring-beam connection to gangue concrete-filled steel tubular columns. *Adv Steel Constr.* 2022;18(1):506–516. doi:10.18057/IJASC.2022.18.1.9.
27. Sun J, Geng Y, Zhang H, Yin H, Wang Y. Experimental and numerical study on slender concrete-filled steel tubular arches subjected to tilting loads. *Thin-Walled Struct.* 2022;179:109701. doi:10.1016/j.tws.2022.109701.
28. Tiwary AK. Experimental investigation into mild steel circular concrete-filled double skin steel tube columns. *J Constr Steel Res.* 2022;198:107527. doi:10.1016/j.jcsr.2022.107527.
29. Yang ZM, Chen J, Wang F, Wang J. Seismic performance of circular concrete-filled steel tube columns reinforced with inner latticed steel angles. *J Constr Steel Res.* 2023;205:107908. doi:10.1016/j.jcsr.2023.107908.

30. Li J, Luo J, Chen L, Fan X, Zhu Y, Wang X. Axial-compression performance and numerical-simulation analysis of steel tube coal gangue concrete column. *J Constr Steel Res.* 2024;216:108612. doi:10.1016/j.jcsr.2024.108612.
31. Chen Z, Dong S, Du Y. Experimental study and numerical analysis on seismic performance of FRP-confined high-strength rectangular concrete-filled steel tube columns. *Thin-Walled Struct.* 2021;162:107560. doi:10.1016/j.tws.2021.107560.
32. Zheng L, Wang WD, Xian W. Experimental and numerical investigation on the anti-progressive collapse performance of fabricated connection with CFST column and composite beam. *Eng Struct.* 2022;256:114061. doi:10.1016/j.engstruct.2022.114061.
33. Nie X, Duan L, Zhuang L, Ding R, Fan J. Experimental and numerical study on steel–concrete composite frames with engineered cementitious composites. *Eng Struct.* 2022;265:114489. doi:10.1016/j.engstruct.2022.114489.
34. Zou Y, Wang L, Sun Z, Pan J, Chen M, Wu Y. Experimental and numerical studies of concrete-filled corrugated steel tubular column under axial compression. *Eng Struct.* 2023;276:114813. doi:10.1016/j.engstruct.2022.114813.
35. Ma Y, Ma K, Han X, Yao T. Experimental investigation of FRP-confined HSC-filled steel tube stub columns under axial compression. *Eng Struct.* 2023;280:115670. doi:10.1016/j.engstruct.2023.115670.
36. Singh H, Tiwary AK. Experimental and numerical investigation on concrete-filled steel tube columns reinforced with diagonal stiffeners under axial loading. *Eng Struct.* 2023;292:116602. doi:10.1016/j.engstruct.2023.116602.
37. Fang Y, Yang H, Chan T, Wang Y. Experimental investigation on seismic behaviour of concrete-filled corrugated steel tubes under cyclic torsional loads. *Eng Struct.* 2024;309:118062. doi:10.1016/j.engstruct.2024.118062.
38. Gao B, Xu L, Huang L, Chi Y, Yu M, Wen S. Seismic performance of a novel concrete-filled steel tube column to continuous reinforced concrete beam joint with multiple openings in the core region. *Eng Struct.* 2024;319:118775. doi:10.1016/j.engstruct.2024.118775.
39. Ding F, Zhang S, Pan Z, Lei J, Wang L, Duan L. Seismic performance of square concrete-filled steel tubular column–composite beam single-side bolted joints: Experimental and numerical study. *Eng Struct.* 2025;322:119035. doi:10.1016/j.engstruct.2024.119035.
40. Ji S, Wang W, Shi Y, Wang J. Numerical analysis on fire behaviour of concrete-filled steel tubular columns after lateral impact. *Eng Struct.* 2025;327:119632. doi:10.1016/j.engstruct.2025.119632.
41. Lan X, Wang Y, Zhang Y, Tan B. Complete failure behaviour of bolted diaphragm connections to concrete-filled tubes at elevated temperatures. *Eng Struct.* 2025;328:119698. doi:10.1016/j.engstruct.2025.119698.
42. Wei G, Wang W, Zhou K, Mao W. Experimental and numerical investigation of circular concrete-filled steel tubular columns subjected to post-earthquake fires. *Eng Struct.* 2025;332.
43. [Abendeh RM, Salman D, Al R. Comparative study on structural behaviour of circular and square section concrete-filled steel tube (CFST) and reinforced cement concrete (RCC) stub column. *Structures.* 2021;29:2067–2081. doi:10.1016/j.istruc.2020.12.078.
44. Xian W, Chen W, Hao H, Wang W. Experimental and numerical studies on square steel-reinforced concrete-filled steel tubular members subjected to lateral impact. *Thin-Walled Struct.* 2021;160:107409. doi:10.1016/j.tws.2020.107409.
45. Wang S, Wang W, Xie Z. Nonlinear cyclic behavior of steel tube in concrete-filled steel tube members including local buckling. *Thin-Walled Struct.* 2023;191:111055. doi:10.1016/j.tws.2023.111055.
46. Huang H, Guo L, Zhao O, Gao S. Experimental and numerical investigation into locally corroded circular concrete-filled steel tubular stub columns strengthened by CFRP. *Thin-Walled Struct.* 2023;192:111174. doi:10.1016/j.tws.2023.111174.
47. Lin S, Zhang B, Zhang S, Zhang Y, Hu X. Dynamic responses of concrete-filled steel tubes impacted horizontally by a rigid vehicle. *Thin-Walled Struct.* 2024;199:111826. doi:10.1016/j.tws.2024.111826.

48. Abendeh RM, Salman D, Al R. Experimental and numerical investigations of interfacial bond in self-compacting concrete-filled steel tubes made with waste steel slag aggregates. *Dev Built Environ.* 2022;11:100080. doi:10.1016/j.dibe.2022.100080.
49. Zhang Z, Wu X, Hu G, Sun Q. Numerical study on triaxial compressive behavior of engineered cementitious composites confined by circular steel tubes. *Constr Build Mater.* 2022;345:128285. doi:10.1016/j.conbuildmat.2022.128285.
50. Wang Y, Zeng W, Ayough P, Ren W, Wang W. Axial compression performance of rubberized concrete-filled steel tubular stub columns after fire exposure. *Constr Build Mater.* 2024;438:137129. doi:10.1016/j.conbuildmat.2024.137129.
51. Xu R, Chen Z, Ning F. Axial compression mechanism and numerical analysis of CFRP–PVC tube and I-shaped steel composite confined concrete column. *Constr Build Mater.* 2025;461:139931. doi:10.1016/j.conbuildmat.2025.139931.
52. Chang Q, et al. Concrete-filled double steel tube columns incorporating UPVC pipes under uniaxial compressive load at ambient and elevated temperature. *Case Stud Constr Mater.* 2022;16:e00907. doi:10.1016/j.cscm.2022.e00907.
53. Abadel AA, Khan MI, Masmoudi R. Experimental and numerical study of compressive behavior of axially loaded circular ultra-high-performance concrete-filled tube columns. *Case Stud Constr Mater.* 2022;17:e01376. doi:10.1016/j.cscm.2022.e01376.
54. Shi Q, Ying Y, Wang B. Experimental investigation on the seismic performance of concrete-filled steel tubular joints in diagrid structures. *Structures.* 2021;31:230–247. doi:10.1016/j.istruc.2021.01.089.
55. Gao X, Wang W, Teh LH. Experimental and numerical investigations of tensile behavior of slip-critical blind bolts anchored in concrete-filled steel tubes. *Structures.* 2023;55:354–369. doi:10.1016/j.istruc.2023.06.041.
56. Hamoda AA, Ahmed M, Abadel AA, Ghalla M, Ishvarbhai V, Quan Q. Experimental and numerical studies of circular precast concrete slender columns with intermediate connection filled with high-performance concrete. *Structures.* 2023;57:105204. doi:10.1016/j.istruc.2023.105204.
57. Ma X, et al. Experimental and numerical study on the impact response of the steel–concrete–steel–foam-filled-tube energy absorbing structure. *Structures.* 2024;62:106278. doi:10.1016/j.istruc.2024.106278.
58. Tang X, Yang Y, Yang W, Lanning J, Frank Y. Experimental and numerical investigation on the seismic behavior of plane frames with special-shaped concrete-filled steel tubular columns. *J Build Eng.* 2021;35:102070. doi:10.1016/j.jobe.2020.102070.
59. Chen S, Liu Y, Luo J, Gao S. Experimental and numerical analysis on rectangular concrete-filled steel tubular columns with T-shaped stiffeners. *J Build Eng.* 2022;45:103510. doi:10.1016/j.jobe.2021.103510.
60. [Yang Y, Xue J, Liu Z, Wang J, Wang X. Experimental and numerical study on seismic behavior of spliced high-strength concrete-filled steel tubular column to precast RC beam frame. *J Build Eng.* 2025;104:112301. doi:10.1016/j.jobe.2025.112301.
61. Wang K, Xiong J, Xiong M, Chen L, Yao C. Experimental and numerical study on progressive collapse resistance of novel fully assembled concrete beam–column connections. *J Build Eng.* 2025;105:112516. doi:10.1016/j.jobe.2025.112516.
62. Niyirora R, et al. Behavior of concrete-encased concrete-filled steel tube columns under diverse loading conditions: A review. *Cogent Eng.* 2023;10(1). doi:10.1080/23311916.2022.2156056.
63. Abadel AA. Structural performance of strengthening of high-performance geopolymer concrete columns utilizing different confinement materials. 2023.
64. Al-Ezzi MJ, Ayamsir A, Supian ABM, Beddu S. Flexural behavior and failure modes of pultruded GFRP tube concrete-filled composite beams: A review. 2024.
65. Ci J, Ahmed M, Jia H, Chen S. Experimental and numerical investigations of square concrete-filled double steel tubular stub columns. *Proc Inst Mech Eng Part L.* 2021. doi:10.1177/13694332211004111.
66. Li X, Zhou X, Wang X, Chen YF. Experimental and numerical investigations on seismic behavior of circular tubed reinforced concrete column to RC beam frames. 2022;1224–1244. doi:10.1002/eeqe.612.

67. Fang C, Zhang L. Experimental and numerical investigation on seismic performance of ring-beam connection to gangue concrete-filled steel tubular columns. *Adv Steel Constr.* 2023. doi:10.18057/IJASC.2022.18.1.9.
68. Hui C, Li K, Li Y, Bian Y, Hai R, Li C. Experimental study and analysis on axial compression performance of high-strength recycled concrete-filled steel tube column in corrosive environments. *Int J Steel Struct.* 2022;22:450–471. doi:10.1007/s13296-022-00584-4.
69. Khaloo A, Borhani MH, Habibi O. Experimental and numerical investigation on the performance of GFRP-confined expansive concrete-filled PVC tubes. *J Reinf Plast Compos.* 2024;37(3):983–1011. doi:10.1177/08927057231190558.
70. Alrebeh SK, Ahmed AD, Al AK, Talha A. Experimental performance evaluation of concrete-filled steel tube columns confined by high-strength steel bolts. *Int J Steel Struct.* 2023;23(4):1135–1147. doi:10.1007/s13296-023-00755-x.
71. Singh H, Tiwary AK. Axial compression behaviour of concrete-filled double skin steel tube columns anchored with orbicular rings. *J Struct Eng.* 2023;26(15):2830–2861. doi:10.1177/13694332231205054.
72. Wang Q, Liu K, Zhang M. Numerical studies on the performance of circular FRP–concrete-filled steel tube stub columns under axial compression. 2022. doi:10.1177/07316844211051707.

