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Axial Compression Behavior of L-Shaped CFST Columns Enhanced by Fully Bolted Threaded-Rod Confinement: An Experimental Assessment

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Abstract

Special-shaped concrete-filled steel tube (CFST) columns are increasingly adopted as efficient vertical load-carrying members in integrated residential structural systems. However, their intrinsically nonuniform confinement promotes early local buckling and bulging of tube plates and limits deformation stability under axial compression. This study presents an experimental assessment of an L-shaped CFST column enhanced by a fully bolted threaded-rod transverse tie (RT) system, which is intended to strengthen confinement delivery and delay tube instability. Two 1500 mm-high specimens with identical cross-sectional dimensions (400 mm × 200 mm legs; 6 mm wall thickness) were fabricated using Q235 steel and C30 concrete: one conventional baseline (L1) and one RT-improved column (L2) with pre-drilled bolt holes at 150 mm spacing and installed threaded rods (10 mm nominal diameter) to provide a distributed transverse restraint. Monotonic axial compression tests were conducted under staged load control while recording the axial shortening, mid-height lateral deflection, and longitudinal and transverse steel strains. The RT detailing postponed the onset of visible local buckling, tightened the lateral deflection envelope, and increased the measured peak axial resistance from 4354 kN (L1) to 5354 kN (L2), corresponding to an increase of approximately 23%. The combined deformation and strain evidence indicates that the RT system improves the confinement effectiveness by stabilizing the tube dilation and promoting a more controlled instability evolution. Overall, the fully bolted RT approach offers a practical and fabrication-compatible pathway for enhancing the axial strength and deformation performance of L-shaped CFST columns.

Keywords: special-shaped CFST column; L-shaped concrete-filled steel tube; Threaded-rod confinement; axial compression; local buckling; composite action; confinement effectiveness



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1. Introduction

Concrete-filled steel tubular (CFST) columns are critical in structural engineering because of their strength, ductility, and constructability. Their widespread adoption is driven by a distinct composite advantage: the steel tube provides confinement that enhances the core concrete response, whereas the concrete delays steel instability and improves global compression performance [1–8]. Although this mutual restraint mechanism is well characterized in conventional circular and rectangular sections, the construction sector is increasingly migrating toward specially shaped CFST columns (e.g., L-shaped sections) to

accommodate space-efficient architectural layouts. However, these geometries are materially more complex from the standpoint of confinement and stability standpoint [9–14].

Literature consistently frames the axial behavior of special-shaped CFSTs as a challenge of “confinement management.” Unlike closed curvature-dominated sections, L-shaped tubes develop non-uniform confinement fields [15–17]. The corner and diagonal regions mobilize a favorable triaxial compression state in the concrete, whereas wider flat plates exhibit weaker lateral restraint and are highly susceptible to outward local buckling and bulging [18–20]. This nonuniformity drives asymmetric strain evolution and accelerates local plate instability, which often becomes the governing limit state under axial compression. Conceptually, the section functions as a composite of uniaxially and triaxially confined regions, with the restraint attenuating significantly toward the mid-plate zones [21–27].

Experimental programs on L- and T-shaped CFST stub columns consistently report the outward local buckling of steel plates as the primary damage signature, with non-uniform confinement leading to region-dependent strain growth [28–31]. To mitigate this, strategies such as local reinforcement (e.g., stiffeners or ribs) at the concave corner have been widely implemented to delay buckling initiation and stabilize the composite action [32–34]. However, a significant proportion of this literature has focused on stub columns (section-level behavior). Although valuable for understanding material interactions, design decisions in practice are often driven by member-level behavior. Recent studies have highlighted the need for evidence that extends beyond simple stubs to longer columns, ensuring that design models remain robust across different slenderness regimes [35–37].

Building on these findings, tie-based solutions using transverse connectors passing through the section have gained traction because they impose distributed restraints and directly suppress plate dilation, often more efficiently than external stiffeners do. However, this approach results in a persistent engineering trade-off: constructible tie layouts typically require drilling/openings that may reduce the net section capacity and create local stress concentrations. Consequently, despite the conceptual advantages of transverse restraint, the field still lacks design-ready, member-level experimental evidence that balances confinement enhancement with connection reliability and plate integrity [38–40]. From a structural integrity standpoint, the RT concept can be viewed as a mechanical-anchorage analog: a hardware-enabled restraint that provides a positive alternative load path when bond/friction-type mechanisms are insufficiently reliable under damage evolution. Related anchorage research in stone-clad façade systems similarly shows that mechanical anchorage can materially improve integrity and delay brittle loss of capacity relative to unanchored configurations, providing a useful comparative framing for the role of anchorage-type detailing in structural robustness [41,42].

To address this gap, this study operationalizes a fabrication-compatible, fully bolted threaded-rod transverse tie (RT) architecture for L-shaped CFST columns and evaluates its axial compression behavior through a controlled comparative test program. A conventional baseline specimen (L1) was tested alongside an RT-strengthened specimen (L2) with identical geometry and material specifications to isolate the structural contribution of the RT detailing. High-resolution instrumentation combining longitudinal and transverse steel strains with axial shortening and mid-height lateral deflection monitoring provides mechanism-grade evidence of how the RT system reshapes confinement delivery and instability progression in specially shaped CFST members.

Accordingly, this study presents a controlled experimental evaluation of a fully bolted threaded-rod transverse-tie (RT) confinement architecture for L-shaped CFST columns, benchmarked against an ordinary specimen with the same geometry and material properties. The program is structured to isolate the contribution of the RT system to the confinement effectiveness and instability governance using high-resolution measurements

(axial shortening, mid-height lateral deflection, and multi-face longitudinal/transverse steel strain histories). The resulting dataset provides deployment-oriented evidence of how a fabrication-compatible transverse tie system can shift the localization pattern of plate buckling and stabilize the composite working mechanism in specially shaped CFST members.

2. Experimental Program

2.1. Specimen Design

Two L-shaped CFST columns were designed (Table 1) as a controlled comparison set to evaluate the effect of the threaded-rod transverse-tie (RT) system. Both specimens shared the same geometric and material baseline to keep the test matrix “clean” and attributable: a column height of 1500 mm, L-section limb dimensions of 400 mm (long limb) × 200 mm (short limb), and steel tube wall thickness of 6 mm. The steel tube was specified as Q235, and the infill concrete as C30. An axial compression ratio of 0.75 was adopted as the target design-level benchmark for the loading program.

Table 1. Geometric parameters of specimens.

Specimen	Height (mm)	Leg Length (mm)	Leg Width (mm)	Tube Thickness (mm)	RT System
L1	1500	400	200	6	None
L2	1500	400	200	6	Through tie

Specimen L1 (Figure 1) was configured as the ordinary L-shaped CFST reference column, consisting of the L-shaped Q235 tube fully filled with C30 concrete and capped at both ends with loading plates to enable stable force introduction under end-bearing compression. To emulate a realistic boundary/load-transfer condition and mitigate end-localized stress artifacts, two Q235 loading plates of 400 mm × 400 mm × 40 mm were welded flush to the top and bottom ends of each specimen.

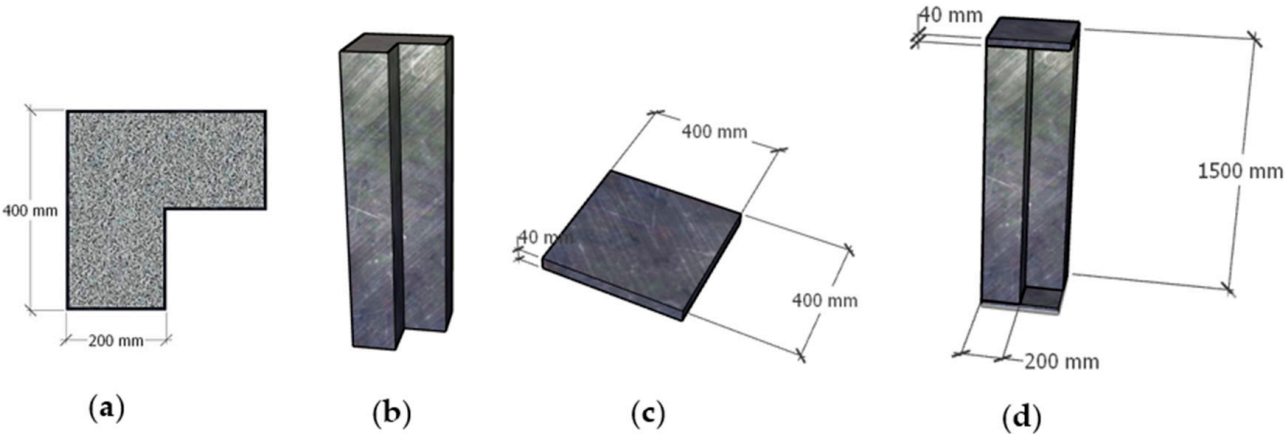


Figure 1. L-1 specimen geometry: (a) cross-section, (b) steel tube, (c) loading plate, and (d) integrated L-1 specimen.

Specimen L2 (Figure 2) adopted the same base geometry and end-plate detailing as L1 but incorporated an RT-improved confinement concept using fully bolted threaded rods acting as distributed transverse restraints. After the L-shaped tube was formed, threaded-rod holes were reserved at the midline of each face, with a vertical spacing of 150 mm between adjacent rows of holes and an end distance of 50 mm from the top/bottom reference planes to the nearest internal-hole row. The RT system included long rods (450 mm total length) and short rods (250 mm total length), each with a 10 mm rod diameter and a 20 mm nut height. The hole diameter was set to 12 mm to ensure assembly tolerance and mitigate

the risk of misalignment during installation. The design intent of this arrangement is to upgrade the confinement effectiveness and stability governance on flat-plate regions by providing repeatable, distributed transverse restraints without altering the primary section geometry.

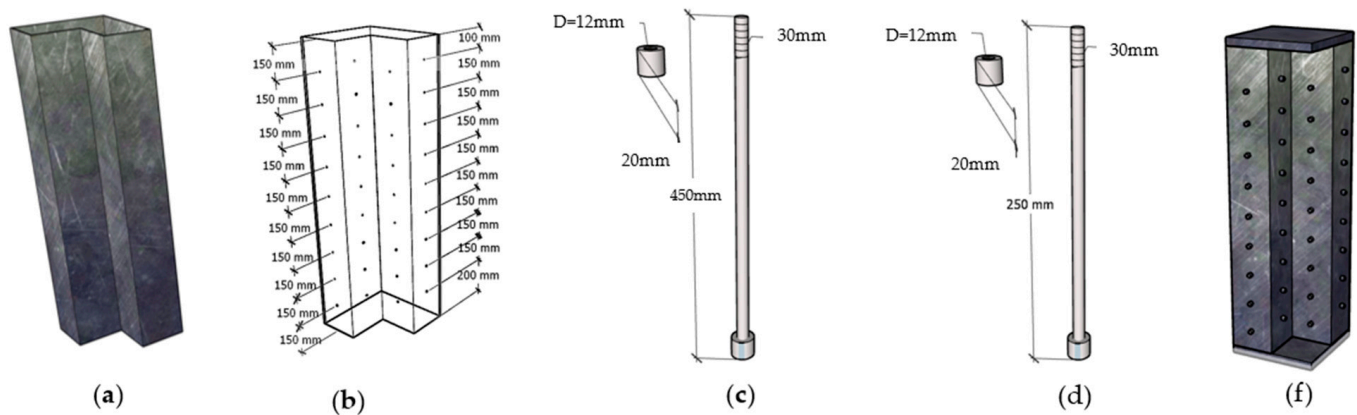


Figure 2. L-2 specimen geometry: (a) steel tube, (b) steel tube drilling, (c) long RT, (d) short RT, and (e) integrated L-2 specimens.

2.2. Materials

The mechanical properties of the steel were determined through tensile coupon testing of the Q235 steel (Figure 3). Two groups of standard specimens were tested, and their yield strength, ultimate strength, elastic modulus, Poisson's ratio, yield strain, and ultimate strain are presented in Table 2. The group-average values were 269 MPa yield strength and 393 MPa ultimate strength for Group 1 and 261 MPa yield strength and 358 MPa ultimate strength for Group 2. The measured elastic modulus was consistently approximately 205 GPa (205,883 MPa and 205,389 MPa for the two groups, respectively), with Poisson's ratio approximately 0.301–0.302. These measured properties were used as the material basis for interpreting the steel stress/strain development during axial loading.

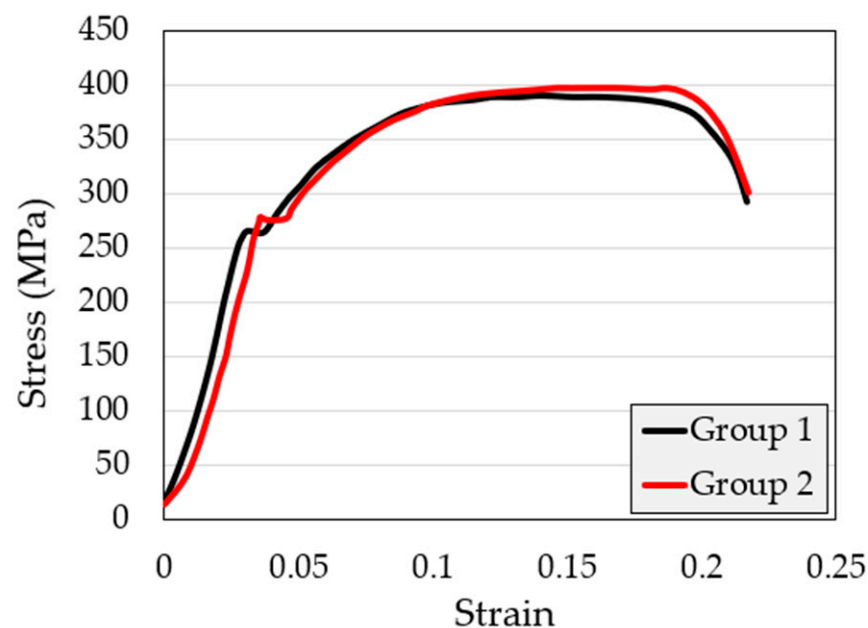


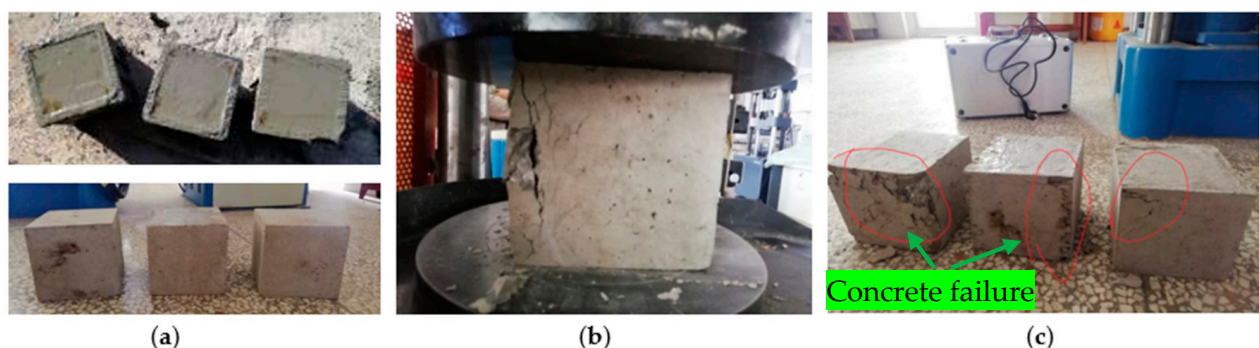
Figure 3. Steel stress–strain curve.

Table 2. Average mechanical properties of Q235 steel.

Group	Yield Strength (MPa)	Ultimate Strength (MPa)	Yield Strain	Ultimate Strength
1	269	393	0.0362	0.18–0.20
2	261	358	0.0341	0.18–0.20

Concrete of grade C30 was specified and characterized using standard cube-compression tests. The mixing proportion was 0.38:1:1.11:2.72 (water/cement/sand/coarse aggregate, with cement mass normalized to unity). The batch quantities used in the experimental program were water 31.8 kg, cement (P·C 45.5) 87.12 kg, sand 91.48 kg, and coarse aggregate (2–5 mm gravel) 226.5 kg.

To verify the concrete strength, 150 mm cubes were cast concurrently with the column infill and film-wrapped to simulate the confined curing condition inside the steel tube (Figure 4). After 28 days of standard curing, the cubes yielded compressive strengths of 27.9 MPa, 25.1 MPa, and 27.36 MPa, with an average value of $f_{cu} = 26.79$ MPa. The corresponding static elastic moduli were 29,038 MPa, 27,913 MPa, and 28,818 MPa, with a mean elastic modulus of 28,590 MPa. The constituent material tests (steel coupons and concrete cubes) were used to validate the baseline material properties and support the interpretation of the member-level response. A dedicated composite stub compression test (short length to suppress member-level instability) would be valuable for isolating the confinement-driven composite compressive behavior without buckling effects and for supporting future analytical model calibration. However, such stub testing was outside the scope of the present program, which prioritized the member-level instability–confinement interaction in 1500 mm columns.

**Figure 4.** Concrete cube test: (a) casting and curing cubes, (b) compressive strength testing, and (c) the post-failure condition of concrete cube specimens.

2.3. Fabrication Process: Welding, Drilling, Assembly, and Concrete Pouring

The fabrication sequence was designed using a constructability-oriented approach to minimize stress concentrations, control dimensional tolerances, and ensure procedural scalability. Both specimens followed a staged workflow comprising steel tube-forming, welding, assembly, concrete placement, and curing.

2.3.1. Steel Tube Fabrication

For both specimens, two 6 mm thick Q235 steel plates were cold-formed first into an L shape and then into a stepped profile using controlled bending operations. The abutting edges were joined using full-penetration, single-side V-groove butt welds (Figure 5). This configuration reduces the total weld length and associated residual stresses, thereby lowering the risk of stress concentration at the geometric transitions and improving the structural reliability.

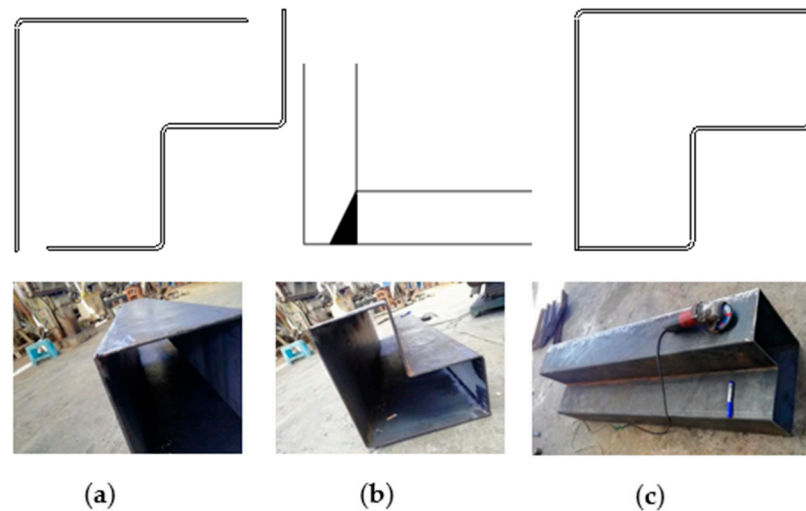


Figure 5. Steel tube fabrication: (a) L-shape, (b) welding, and (c) cleaning.

2.3.2. Drilling and Assembly of the RT System (Specimen L2)

To preserve dimensional accuracy and avoid cumulative tolerance errors, the threaded rod holes were drilled only after the L-shaped tube was fully welded. Holes ($\phi 12$ mm) were positioned along the midline of each face using a drilling template to ensure consistent vertical spacing (150 mm) and edge distances (50 mm from the end planes). This “fabricate-then-drill” sequence prevented misalignment during rod installation and eliminated forced-fit eccentricities.

After the bottom loading plate was welded to each tube, threaded rods (long: 450 mm; short: 250 mm) were inserted through the holes in L2 and secured with nuts, completing the transverse restraint assembly before concrete casting (Figure 6).

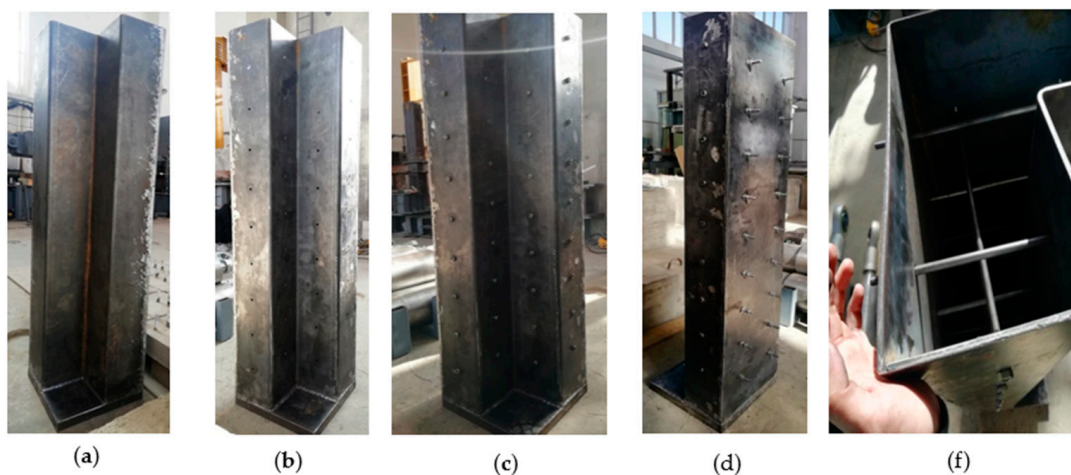


Figure 6. Drilling and assembly of the RT system: (a) L1 steel tube, (b) drilling, (c) RT installation, (d) RT tying, and (f) inside integrated L-2 specimens.

2.3.3. Concrete Preparation and Placement

A mechanical mixer was used to produce homogeneous C30 concrete with a proportion of 0.38:1:1.11:2.72 (water/cement/sand/coarse aggregate). During placement, the concrete was vibrated internally using a poker vibrator to ensure full compaction and mitigate segregation along the member height, which is a known concern for vertically casting composite sections (Figure 7).

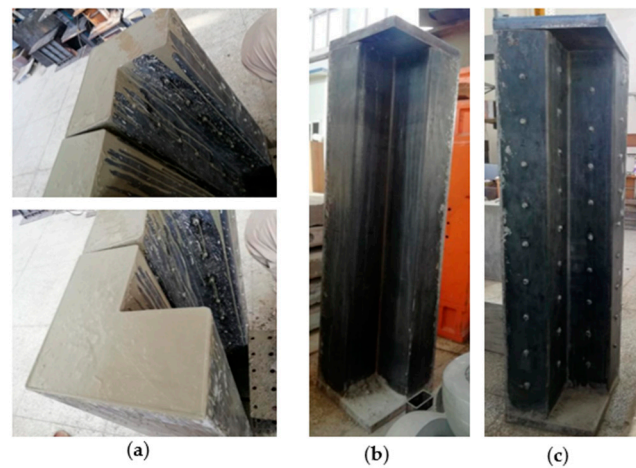


Figure 7. Specimen casting, curing, and final assembly: (a) casting, (b) L1 final, and (c) L-2 final.

2.3.4. Curing and Final Assembly

Both the column specimens and companion 150 mm cubes were film-wrapped and cured under identical ambient conditions for 28 days. After curing, a top-loading plate was welded to each specimen, and the test assembly was finalized with realistic load-transfer details (Figure 7).

This fabrication protocol ensured that the only variable between L1 and L2 was the presence of the threaded rod-restraint system, thereby isolating its effect on the structural performance.

2.4. Test Setup, Loading Protocol and Instrumentation

The experiment was conducted at the Structural Testing Laboratory of the Yunnan Earthquake Engineering Research Institute. All specimens were tested under a column-end axial compression configuration to replicate realistic boundary conditions and load-transfer mechanisms.

2.4.1. Test Setup

A 10,000 kN computer-controlled electrohydraulic servo pressure testing machine was used to apply axial compression. The overall test configuration, including the machine and specimen positioning, is illustrated in Figure 8. Prior to testing, each column was carefully aligned and centered within the testing frame to achieve a concentric loading path and minimize any unintended eccentricities in the loading path.

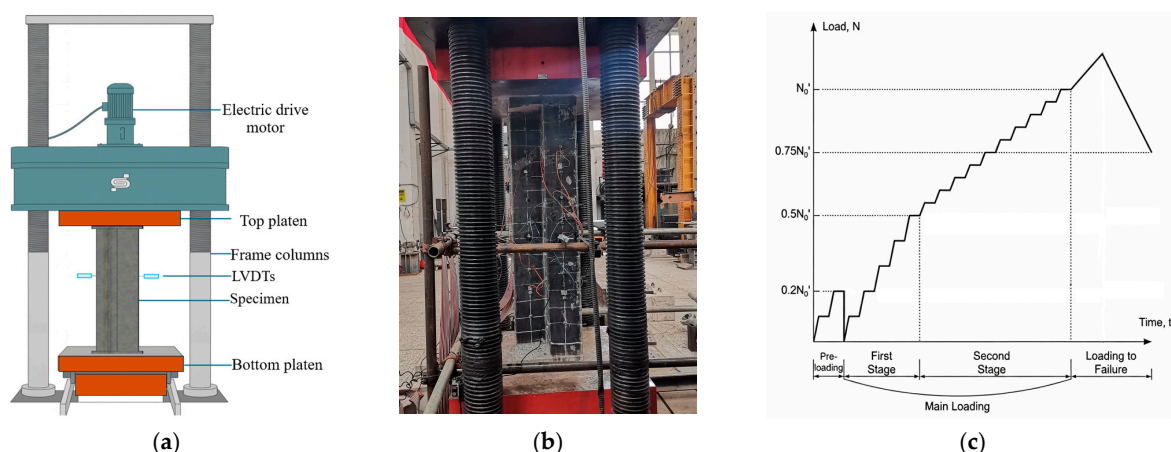


Figure 8. Test setup and loading history: (a) test setup, (b) test photograph, and (c) loading history.

2.4.2. Loading Protocol

A staged, force-controlled loading protocol was adopted to ensure operational safety and facilitate detailed observations of the damage progression. The complete loading regime is illustrated in Figure 8c and consists of three distinct phases:

- *Preloading phase:* A preload corresponding to 20% of the nominal design axial load was applied in three equal increments. Each increment was held constant for 3 min to eliminate the seating effects, verify the functionality of all the instrumentation, and confirm the physical alignment of the specimen.
- *Formal incremental loading phase:* After complete unloading, formal loading commenced in two stages.
- *Stage I ($0-0.5 N_0$):* The load was increased in increments of $0.1 N_0$ at a controlled rate of 5 kN/s. Each load level was maintained for 3 min to allow stable data acquisition and visual inspection.
- *Stage II ($0.5 N_0-0.75 N_0$):* Upon reaching $0.5 N_0$, the load increment was reduced to $0.05 N_0$, and the loading rate was set to 3 kN/s. The holding time at each level was extended to 5 min to closely monitor the behavior as the load approached a target design axial compression ratio of 0.75.
- *Continuation to failure:* After exceeding the design load level ($0.75 N_0$), monotonic loading was continued until specimen failure. The test was terminated when either of the following criteria was met: (i) the applied load dropped to 75% of the measured peak load, indicating substantial post-peak degradation, or (ii) excessive deformation was observed, compromising the specimen stability or the integrity of the data collected. This protocol provides a consistent and reproducible definition of the ultimate limit state for a comparative performance analysis.

2.4.3. Instrumentation

A comprehensive instrumentation scheme was implemented to capture the global force-deformation response and localized structural behavior.

- *Surface strain measurement:* To monitor the development of longitudinal and transverse strains on the steel tube, 36 electrical resistance strain gauges (18 longitudinal and 18 transverse) were bonded at three critical heights (mid-height, +375 mm, and −375 mm) across all six faces of the L-shaped section. The detailed layout of the strain gauges is shown in Figure 9.

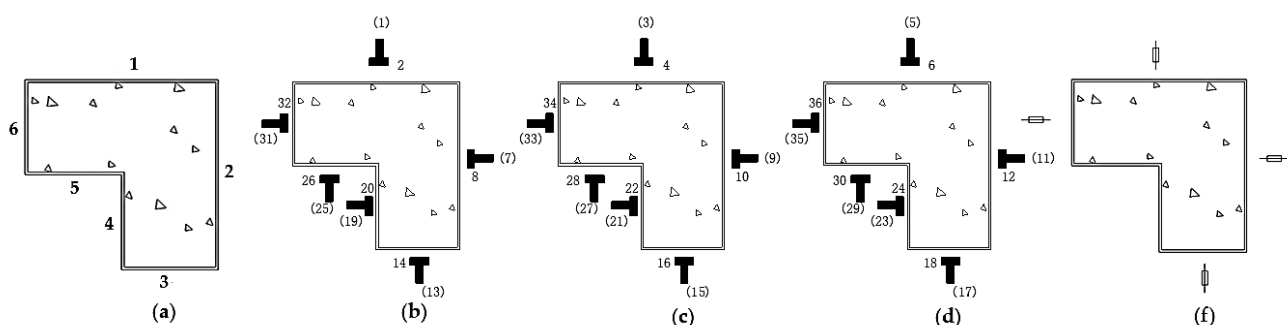


Figure 9. Instrumentation setup: (a) Faces, (b) at +225 mm, (c) middle, (d) at −225 mm, and (f) LVDTs.

- *Lateral displacement measurement:* Four YHD-100 type displacement transducers (LVDTs) were mounted at the mid-height of the column to measure out-of-plane lateral displacements, which are indicative of the initiation and progression of local buckling. The positions of the LVDTs on faces 1, 2, 3, and 6 are shown in Figure 9f.

- *Global response:* The axial load and corresponding axial shortening were recorded directly by the internal load cell and actuator displacement transducer of the testing machine.

All data channels were synchronized and recorded continuously using a digital data acquisition system throughout the test duration.

3. Results and Discussion

3.1. Failure Modes and Instability Progression

For benchmark specimen L1, the first clear instability signal was localized buckling and bulging at the upper region of the wide-leg face (Faces 1 and 2). At an axial load level of approximately 3350 kN, the initial bulge was recorded near the top end approximately 150–200 mm from the column top on Face 1 and approximately 200 mm from the column top on Face 2, whereas the remaining faces were still comparatively stable (Figure 10). With continued load build-up to approximately 4350 kN, the bulging on Faces 1 and 2 intensified, and synchronized bulging emerged on Faces 3–6 at a similar elevation (approximately 150 mm from the column top), indicating that the steel tube around the perimeter had broadly entered a yielding/buckling-dominated regime. As loading progressed, the upper steel tube segment exhibited a pronounced loss of effective axial stress contribution, and the deformation demand was concentrated around the top local-buckling band. After unloading, the post-test morphology showed that the damage localization was essentially top-dominated, with no meaningful bulging zones away from the column head.

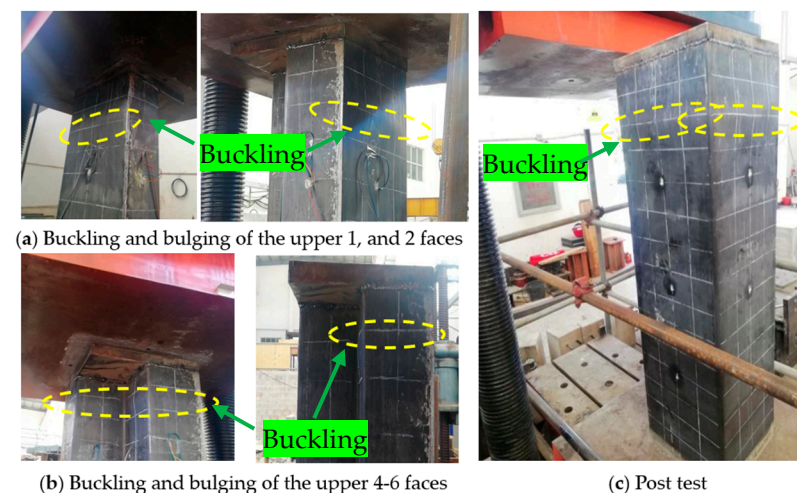


Figure 10. L1 Specimen failure mode.

For the L2 specimen, the failure mechanism remained local-buckling-led, but the risk profile was rebalanced by an additional restraint. In operational terms, the tie-rod system delayed the onset of visually obvious top-buckling and reduced its severity. The first slight bulging was reported at approximately 3600 kN on Faces 1 and 2 (Face 2 was marginally more pronounced), with the other faces remaining relatively unchanged at this stage (Figure 11). When the load increased to approximately 4630 kN, bulging became more evident on Faces 1 and 2 and initiated on Faces 3–6. Importantly, the characteristic bulging elevation was approximately 200 mm from the column top, that is, approximately 50 mm lower than the analogous concentration observed in L1. This downward migration is strategically consistent with the tie-rod system “sharing” confinement and perturbing the local instability zone rather than allowing an early single-band buckle to dominate.

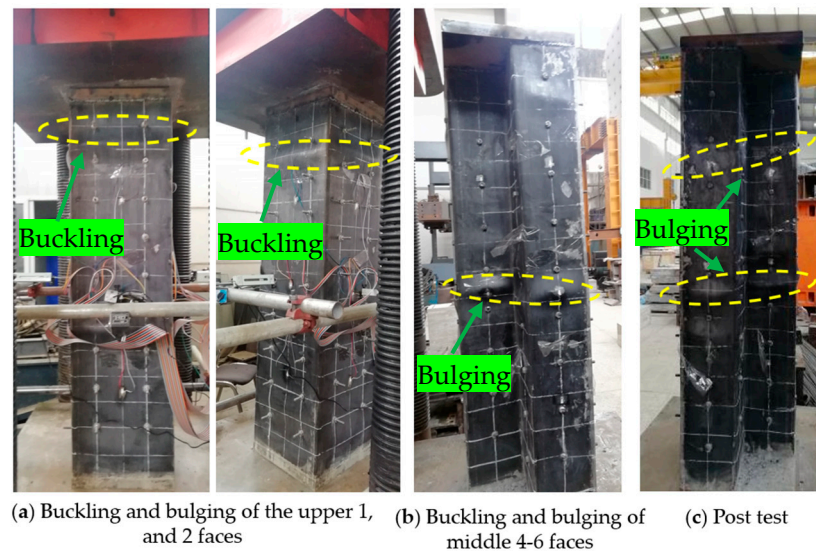


Figure 11. L2 Specimen failure mode.

As loading continued, L2 transitioned from a single-zone instability pattern to a multi-zone local buckling pattern. At approximately 4850 kN, the top bulging was further amplified, and additional bulging was initiated in the lower region, first on wide-leg Face 1, and then at approximately 4970 kN on wide-leg Face 2. Ultimately, the test progressed to failure/termination at approximately 5354 kN, by which point mid-height bulging was reported to be clearly developed with additional bulging elsewhere. A notable localized distress detail was that a bolt nut was squeezed off near the lower part of Face 5 (highlighted in the photographic record), underscoring that while the RT detailing delivers confinement and ductility upside, it can also introduce discrete local stress/interaction hotspots that require proactive detailing governance.

From a comparative benchmarking standpoint, the RT-improved solution postponed the onset of top-wall buckling by ~250 kN (3600 kN vs. 3350 kN) and converted the L2 response from a “single dominant buckle band” (L1) into a distributed buckling pattern involving the lower and mid regions as the loading escalated. In this study, the “first local failure” load was defined as the first visually observable local bulging/buckling event recorded during the staged loading protocol. Because local plate instability develops progressively and may initiate before it becomes visually evident, this observation-based threshold should be interpreted as a conservative reference point for comparative benchmarking rather than a sharply defined material limit state. This is a classic trade-off in composite-system optimization: the tie-rod restraint increases confinement effectiveness and delays the first instability trigger, but it also redistributes deformation demand across multiple zones, which can be beneficial for ductility and robustness, provided that local detailing (holes, nuts, and bearing zones) is engineered to manage concentrated secondary effects.

For the tested height and boundary conditions, the governing response was local-buckling-led rather than a classical global Euler mode. The macro-scale “global” signature in the dataset is expressed through the stiffness-degradation knee in the load–displacement curve and the growth of the mid-height lateral deflection as local bulging redistributes around the perimeter. The RT system does not change the governing limit-state category; it re-governs its progression by delaying early top localization and promoting a more distributed instability portfolio at higher loads, which has direct implications for the detailing. Connector-bearing reliability and hole-zone stress governance become design-critical as the system is enabled to carry higher loads deeper into the nonlinear regime.

3.2. Axial Load–Displacement Response and Capacity Uplift

The axial load–displacement curves of both L-shaped CFST specimens followed the classic composite compression trajectory, with an initial near-linear segment dominated by global elastic stiffness, followed by a nonlinear transition as the steel–concrete interaction intensified and local instability mechanisms began to govern the stiffness-retention pathway. In Figure 12, the early stage responses are closely aligned, indicating that before significant dilation and local plate effects emerge, the global stiffness is primarily controlled by the shared geometry and baseline material system rather than the presence or absence of RT restraint.

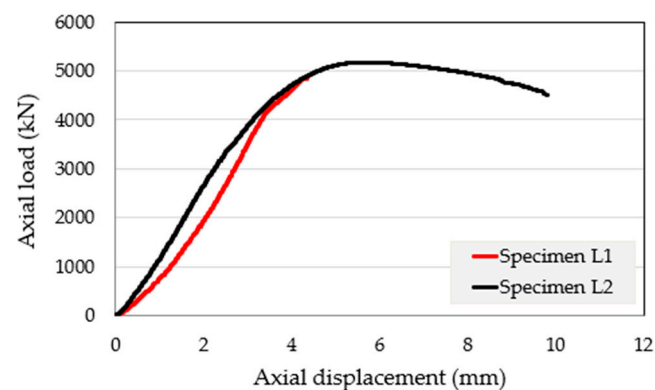


Figure 12. L1 and L2 specimen axial responses.

As loading progressed into the nonlinear range, the curves diverged in a structurally meaningful manner. The ordinary specimen L1 exhibited an earlier and more distinct “knee” (inflection), reflecting earlier stiffness degradation consistent with premature local effects (e.g., progressive wall bulging/buckling and associated redistribution of the axial stress contribution in the steel tube). In contrast, the RT-improved specimen L2 sustained a tighter displacement demand at comparable load levels, and its curve remained smooth with a delayed inflection. Mechanistically, this indicates that the threaded-rod system is not merely a peak-strength add-on; it actively reshapes the pre-peak response by suppressing tube dilation, strengthening the confinement effectiveness, and prolonging the more efficient composite-working stage.

From a capacity standpoint, the measured peak axial resistance increased from 4354 kN for L1 to 5354 kN for L2, representing an absolute uplift of 1000 kN and a relative enhancement of approximately 23%. This uplift is strategically significant for special-shaped CFST members because it is achieved without changing the primary section dimensions; that is, the gain is delivered through detailing-led confinement governance rather than through geometric upscaling.

Overall, the load–displacement evidence supports a clear performance narrative: the RT restraint system improves the “value chain” of the composite mechanism by delaying stiffness degradation, preserving load-carrying efficiency deeper into the loading history, and ultimately unlocking a higher peak capacity. In design terms (without invoking theory), this is the hallmark of an effective confinement intervention—one that upgrades both the strength ceiling and stability of the response path leading up to that ceiling, rather than simply shifting the peak point upwards.

3.3. Lateral Deflection and Buckling Control

The lateral response under concentric axial compression can be considered a direct “proxy signal” of steel tube dilation and the onset/progression of local wall instability. To capture this behavior, four horizontal displacement transducers (YHD-100) were installed

at the mid-height of each specimen on Faces 1, 2, 3, and 6, enabling a face-by-face profile of the lateral deflection development during loading.

Figure 13 shows that the mid-height lateral deflections on the monitored faces remained modest in the early (elastic) regime and then increased progressively as the confinement demand intensified, and the steel tube underwent outward expansion driven by the compressed core concrete. The curves were reported as positive on Faces 1, 2, 3, and 6, indicating outward deflection in the long-leg width direction, that is, a consistent dilation directionality associated with concrete compression and steel tube expansion.

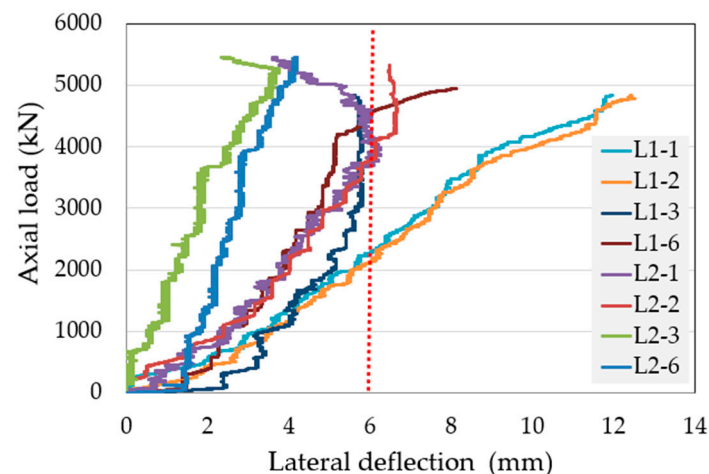


Figure 13. L1 and L2 lateral deflection response.

From a comparative standpoint, the RT-improved specimen (L2) exhibited a systematically “tighter” lateral deflection envelope than the ordinary specimen (L1) across all monitored faces. This explicitly noted that in the elastic stage, the mid-height deflection for both members was generally small (approximately within 12 mm), whereas after introducing the tie rods, it was “almost entirely” controlled within approximately 6 mm, demonstrating that the threaded-rod system was effectively engaged as a transverse restraint mechanism rather than acting only at the final stage.

This lateral deflection suppression aligns coherently with the observed buckling governance: the RT details delay the appearance of comparable steel-wall buckling in the upper region and, as loading advances, promote a more distributed buckling pattern (multiple bulging zones) rather than a single dominant localization band. In other words, the reduced mid-height lateral deflection in L2 is consistent with stronger confinement and improved stability retention of the tube plates, whereas the later-stage spread of bulging reflects a redistribution of instability demand under higher compression, which is an expected outcome when the transverse restraint elevates the confinement effectiveness and postpones early local failure concentration.

3.4. Steel Tube Strain Development and Confinement Effectiveness

Figure 14 consolidates the mid-height steel-tube strain histories on faces 1–6 for both specimens, which are reported in microstrain ($\mu\epsilon$). The solid curves represent the longitudinal strain (ϵ_L), which is dominated by axial compression (negative strain), whereas the dotted curves represent the transverse/hoop strain (ϵ_T), which primarily reflects the tube dilation under the lateral expansion of the confined concrete core (positive strain). The strain histories provide a mechanism-grade bridge between the global response and the observed buckling chronology. An acceleration in ϵ_T marks the transition into a confinement-engaged regime, where concrete dilation mobilizes the hoop demand. Concurrently, curvature changes or a reduced growth rate in ϵ_L on a given face can indicate

local plate efficiency loss (incipient out-of-plane deformation) and associated axial stress redistribution. Therefore, the face-to-face dispersion of $\epsilon L / \epsilon T$ is a proxy for localization risk: a larger dispersion implies that the confinement and axial contribution are concentrated into a subset of plates, increasing the likelihood of a dominant buckle band. In the present tests, L2 exhibited reduced face-to-face dispersion and a clearer mobilization of ϵT at higher loads, which aligned with the delayed onset of visible bulging and tighter mid-height deflection envelope.

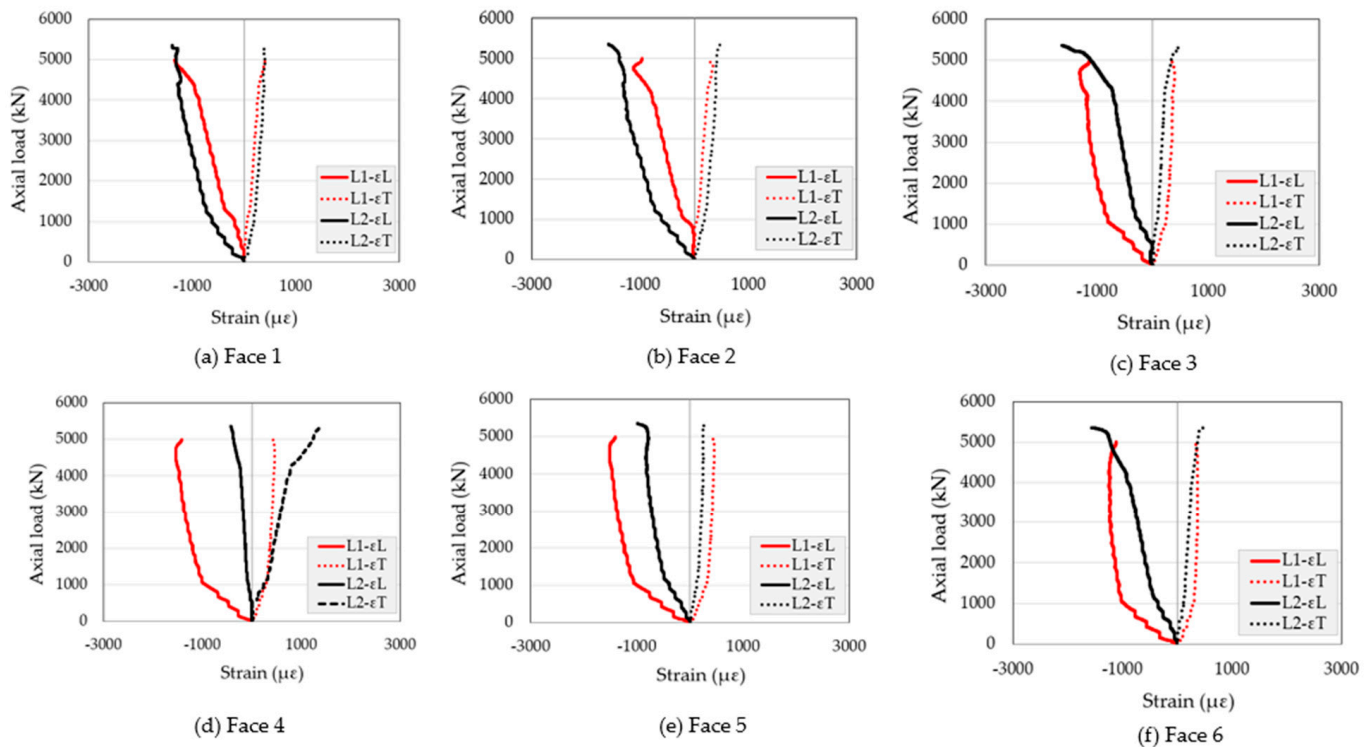


Figure 14. L1 and L2 mid-height strain responses.

Across all faces, the strain trajectories exhibited consistent two-regime behaviors. In the early stage, ϵL grew approximately proportionally with the axial load, indicating stable composite force transfer with limited dilation demand; during this phase, ϵT remained comparatively small, implying that confinement activation was still modest, and the tube behaved predominantly as an axial load-carrying shell. As the load increased, ϵT began to accelerate, and the ϵL curves deviated from their initial near-linear trend, indicating a transition into a more pronounced confinement-engaged regime, where the lateral expansion of the concrete intensified and the steel tube increasingly participated through hoop tension. This inflection-type behavior in ϵT is a key “trigger indicator” for the onset of significant dilation and local plate effects in tunnels.

The ordinary specimen (L1) exhibited stronger face-to-face non-uniformity in ϵL , with certain faces accumulating markedly larger compressive microstrains, while others developed less. This pattern is consistent with the inherent asymmetry of the L-shaped sections, where confinement and stiffness are not uniformly distributed, and the local buckling risk tends to concentrate in specific flat-plate regions. Importantly, on multiple faces, the L1 ϵL evolution becomes less stable at higher loads, manifesting as curvature changes and reduced growth rates, which is structurally consistent with progressive local buckling and stress redistribution within the tube (i.e., once local instability is initiated, the effective axial contribution of the affected plate segment is partially “de-rated,” and the load path reallocates).

In contrast, the RT-treated specimen (L2) demonstrated a more controlled strain development pathway. First, the ϵL histories on several faces remained more monotonic and less “knee-dominated,” suggesting that the steel tube preserved its effective axial role deeper into the loading history before the instability-driven redistribution became dominant. Second, the face-to-face dispersion in ϵL was generally reduced, indicating that the threaded-rod restraint improved the confinement delivery and helped flatten the strain-gradient risk across the section rather than allowing a small number of plates to become the sole instability hotspot. From a structural-governance perspective, this is precisely what an effective restraint system should accomplish: it does not just elevate strength; it improves load path reliability and delays the onset of strongly localized plate distress.

The ϵT results provide complementary evidence. On most faces, L2 developed a clearer and more sustained hoop-strain demand as the load increased, indicating that the tube was mobilized more decisively in hoop tension, which is consistent with a stronger confinement mechanism and a more robust triaxial compression state in the concrete core. In practical terms, this reflects a more efficient composite “value capture”: the confinement system (tube + threaded rods) is engaged earlier and more consistently, restraining lateral dilation and forcing the composite section to operate in a higher-quality confinement state rather than transitioning prematurely into local bulging-driven degradation.

Overall, Figure 14a–f supports a coherent conclusion on the mechanism effectiveness: RT detailing improves confinement governance by stabilizing the strain evolution across faces, sustaining the tube’s axial contribution, and enabling a more deliberate mobilization of hoop action as loading intensifies. This strain-based evidence aligns with the broader behavioral narrative observed in deformation and failure development, namely, that enhanced transverse restraint shifts the response from early localized instability toward a more controlled, confinement-led composite working regime.

3.5. Discussion

The results demonstrate that RT detailing does not simply “add strength”; it reoptimizes the failure pathway of the special-shaped CFST column by reshaping how confinement is delivered and how local instability is allowed to develop. For both specimens, the governing limit state remained steel tube local buckling driven by concrete lateral expansion, which is consistent with the mechanics of L-shaped CFST sections, where confinement is inherently non-uniform. Therefore, the differentiator is not the type of failure but the timeline, localization pattern, and stability retention as the member transitions from the elastic composite action into a buckling-governed regime.

The failure observations in Section 3.1 provide a clear contrast to the localization. In the ordinary specimen (L1), the first visible bulging occurred at 3350 kN on Faces 1 and 2 near the top (150–200 mm from the column head), and at 4350 kN, the bulging propagated to the other faces at a similar elevation, effectively forming a single dominant buckle band in the upper segment. This behavior is typical of asymmetric sections: once one region begins to dilate and loses plate stability, the axial load path rapidly reallocates, and the deformation demand concentrates in the weakest confinement corridor of the structure. In the RT specimen (L2), initial bulging was delayed to 3600 kN and was less severe in the early stages. More importantly, the characteristic top bulging zone shifted downward to approximately 200 mm from the column head, and at higher loads, bulging developed in multiple zones (top, middle, and lower regions). Mechanically, this indicates that the RT system “shares” the restraint demand and prevents the early formation of a single catastrophic localization band, thereby improving robustness, even though it simultaneously increases the need to govern connector-level stress concentrations (as evidenced by the nut squeeze-out recorded near the lower part of Face 5). The observed nut squeeze-out indicates that confinement

gains can shift the criticality from plate instability to connector bearing reliability if the bearing zones are under-designed. For robust deployment, the RT detail should be packaged with: (i) an enlarged bearing area via hardened large-diameter washers or local bearing plates to reduce contact pressure and pull-through sensitivity; (ii) a lock strategy (double-nut/jam nut or locknut) with verified thread engagement to reduce loosening and slip; (iii) reduced clearance and strict tolerance control using template-guided drilling and a fabricate-then-drill sequence; and (iv) where high restraint demand is anticipated, local doubler/stiffener plates around hole regions to mitigate stress concentration. These measures provide a practical pathway to de-risk connector distress while preserving the confinement value of the RT concept. Mechanism of confinement sharing and local stress governance. The RT system functions as a distributed transverse-compatibility constraint. Under increasing axial compression, the concrete core dilates laterally and pushes the tube plates outward; once the dilation demand becomes material, the threaded rods are mobilized in tension and provide discrete restraint points that suppress out-of-plane plate growth. Because the rods are installed on multiple faces at the same elevations (with reserved holes along face midlines and regular vertical spacing), the restraint demand is not absorbed by a single vulnerable plate; instead, it is redistributed through the rod network, which promotes a more uniform confinement delivery around the L-shaped perimeter and reduces the probability that one face becomes the sole instability “single point of failure.” Simultaneously, the restraint action necessarily introduces localized bearing and net-section effects at the hole and washer zones; therefore, RT should be treated as a system-level intervention, where confinement gains and connector stress concentrations are co-governed through detailing rules (bearing area, hole-edge distances, and tolerance control).

This local shift was consistent with the axial load–displacement response in Section 3.2. Both specimens exhibited closely aligned initial stiffness, confirming that the global elastic slope was dominated by the common geometry and material set rather than by the restraint hardware. The divergence occurs in the nonlinear transition: L1 develops an earlier and sharper inflection (knee), which is a macroscale signature of stiffness degradation triggered by local plate instability and stress redistribution. L2, in contrast, shows a smoother pre-peak path and reduced displacement demand at equivalent load levels, indicating that the RT system actively stabilizes tube dilation and extends the “high-efficiency composite-working” stage. This restructuring of the response path culminated in a measurable peak uplift from 4354 kN (L1) to 5354 kN (L2), an absolute gain of 1000 kN, and a relative enhancement of 23% achieved without changing the primary section dimensions. From a deployment standpoint, it is important to distinguish between (i) the modest increase in the first visually observed local buckling load ($\sim 3350 \rightarrow 3600$ kN) and (ii) the larger uplift in the peak resistance ($\sim 4354 \rightarrow 5354$ kN) and the associated stability retention. In practical design workflows, members are commonly proportioned to avoid early local instability under standard combinations; however, the value proposition of the RT system is primarily realized in instability governance and robustness margin, as evidenced by a tighter lateral-deflection envelope, a delayed stiffness-degradation inflection, and a shift from a single dominant buckle band toward a more distributed instability portfolio. These attributes are particularly relevant under construction tolerances, accidental eccentricity, second-order amplification, and abnormal/overload scenarios, where reserve capacity and stable response-path retention mitigate disproportionate failure risks. The RT configuration also introduces incremental fabrication steps (drilling and rod hardware); therefore, it is best positioned as a targeted reinforcement option for critical columns/high-demand zones, where risk-adjusted performance gains justify the incremental cost, rather than as a universal baseline detail.

The lateral deflection results in Section 3.3 provide an intermediate mechanism check between the global load–displacement curve and the local buckling observations. The mid-height lateral deflection, measured on Faces 1, 2, 3, and 6, remained modest in the early stage and increased as the dilation demand accumulated, as expected when the core concrete expansion drove the tube bulging. An important quantitative signal is the envelope tightening delivered by the RT. While the ordinary specimen exhibited mid-height deflections generally within 12 mm in the elastic-to-transition range, the RT specimen was reported to be controlled largely within 6 mm, indicating a materially stronger restraint against outward dilation. This deflection suppression aligns directly with the delayed buckling onset and redistribution of bulging zones: the RT system reduces uncontrolled local plate “runaway” behavior, but the price of improved stability is that higher load levels are sustained long enough for deformation to distribute across multiple regions rather than collapsing into one top band.

The mid-height strain evidence in Section 3.4 closes the loop by quantifying how the tube is mobilized in the axial–hoop coupling, which is the structural DNA of the confinement effectiveness. Across all faces, the longitudinal strain (ϵ_L) progressed in compression (negative $\mu\epsilon$) with a near-proportional relationship at low loads, whereas the hoop strain (ϵ_T) (positive $\mu\epsilon$) was initially modest and then accelerated as the confinement was engaged and dilation increased. The quality of this transition distinguishes the specimens: L1 exhibits stronger face-to-face non-uniformity and more pronounced curvature/irregularity at higher loads on several faces, consistent with local instability forcing sudden load-path redistribution. L2 exhibited a more stable monotonic strain evolution on multiple faces and a clearer mobilization of hoop demand, indicating that the tube was being driven more effectively into the intended confining role rather than losing efficiency early through local out-of-plane deformation. Even without over-claiming exact values from the plots, the practical takeaway is robust: the RT system improves confinement delivery consistency across the section and reduces the probability that one plate becomes the sole instability “single point of failure.”

A critical engineering implication is the trade-off embedded in the RT solution: by elevating confinement engagement and enabling the member to carry higher loads deeper into the nonlinear regime, the system also elevates the demand on connection details (holes, nuts, and bearing zones) and can introduce discrete distress points if not governed by the detailing rules. The nut squeeze-out event is therefore not an anomaly to ignore; it is a design signal that the RT concept must be packaged with connector-grade robustness (nut locking strategy, washer/bearing plate detailing, hole-edge distance governance, and tolerance control) to ensure that the confinement gain is not offset by local failures that could have been avoided. In short, the RT solution improves the structural “business case” by increasing capacity and stabilizing the response path; however, it must be treated as a system-level intervention, where member strength, local buckling control, and connection reliability are co-designed under the same performance envelope.

Generalization roadmap: The current findings are anchored to one geometry/material set (1500 mm height; 400 × 200 legs; 6 mm tube; Q235 steel; C30 concrete) and monotonic concentric loading. Expected RT performance trends can be framed through non-dimensional governance parameters, including plate slenderness (b/t), tie spacing ratio (s/b or s/t), rod stiffness/area ratio relative to tube stiffness, and concrete strength level (dilation demand). Under eccentric loading, the restraint engagement becomes asymmetric and may further elevate the connector demand on the highly compressed limb. Under cyclic actions, the primary risk shifts to connection durability (loosening, fatigue at the threads, and fretting at the holes). Accordingly, a targeted future matrix covering

RT spacing/diameter, plate slenderness, concrete strength, load eccentricity, and cyclic protocols is recommended to formalize the design rules and connector detailing envelopes.

4. Conclusions

This study presents a controlled experimental comparison between a conventional L-shaped CFST column (L1) and an RT-improved L-shaped CFST column (L2) incorporating a fully bolted threaded rod transverse restraint system. Based on the tested configuration and material grades, the following conclusions were drawn:

- Both specimens exhibited a local buckling-led response under monotonic axial compression, characterized by the outward bulging of the steel tube plates driven by concrete core dilation. The RT system did not change the governing limit state category; rather, it re-governed the progression by delaying early localization and reshaping the instability trajectory.
- The baseline specimen L1 developed an early top-dominated buckle band, whereas the RT specimen L2 exhibited a delayed onset of visible bulging and evolved toward a more distributed buckling portfolio (top–mid–lower regions) at higher loads. Mechanistically, the RT network operates as a distributed transverse compatibility constraint that shares the confinement demand across the perimeter, reducing the probability that a single face becomes the dominant localization band.
- The RT detailing delivered a measurable peak-load uplift from 4354 kN (L1) to 5354 kN (L2), that is, +1000 kN (~23%), without changing the primary section dimensions. The load associated with the first visually observed local bulging/buckling increased more modestly from ~3350 to ~3600 kN (~7–8%). This confirms that the primary value of the RT system is realized in peak capacity and response-path stability/robustness (delayed stiffness degradation and extended efficient composite-working regime), rather than solely shifting the first visible instability trigger (which is observation-based and can lag incipient local instability).
- Mid-height lateral deflection monitoring of multiple faces confirmed that the RT system provided an effective transverse restraint against outward dilation. Compared with L1, L2 maintained a tighter lateral-deflection envelope, indicating improved buckling control and more stable deformation under increasing axial demand.
- The mid-height strain results (ϵ_L – ϵ_T) indicate that RT promotes a more managed transition into coupled axial–hoop tube action. Relative to L1, L2 exhibited reduced face-to-face dispersion and clearer mobilization of hoop strain demand at higher loads, supporting the conclusion that RT improves the confinement delivery consistency across the L-shaped perimeter.
- Although RT improves global performance, the observed local connector distress (e.g., nut squeeze-out) demonstrates that RT should be treated as a system-level detailing package. Practical deployment should explicitly govern hole layout and edge distances, ensure adequate bearing area (e.g., large hardened washers or bearing plates), adopt robust nut-locking (double-nut/locknut with verified thread engagement), control tolerances (template drilling/fabricate-then-drill), and—where warranted—use local doublers/stiffeners to manage hole-zone stress concentrations and avoid avoidable local weaknesses.
- In terms of cost and constructability, RT introduces incremental fabrication/installation steps; therefore, it is best framed as a selective reinforcement option for critical members/high-demand zones, where risk-adjusted performance gains justify the added detailing. To avoid over-claiming beyond the present evidence base, this study intentionally focuses on experimental member-level behavior; formal design equa-

tions, theoretical modeling, and FEM-based generalization will be developed and reported in a follow-up study.

Limitations and future work: The findings are anchored to two monotonic axial tests on a single geometry and material set. Expanded experimental coverage is recommended across the RT spacing/diameter, plate slenderness, and concrete strength, and across broader loading domains (eccentric and cyclic demands). For long-term/cyclic deployment, connector durability and environmental effects (loosening, fatigue at threads, fretting around holes, and corrosion) should be addressed through locking/protection/inspection strategies and validated using cyclic protocols. In addition, composite stub compression testing is recommended to isolate confinement-driven composite compressive behavior without member-level instability and to support the calibration of planned theoretical and numerical models.

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