Performance Evaluation of Lightweight Concrete-Filled Steel Tube Columns: Structural Behaviour, Modelling, Design, And Research Needs

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***Abstract*—Lean concrete filled steel tube (LWCFT) columns consist of a hollow steel section combined with a reduced density cementitious core which is intended to reduce the structural dead load of LWCFT columns. Structural performance of LWCFT columns retains the benefits of composite confinement, buckling restraint, construction advantages as well as cost saving similar to conventional CFST member. The performance of the confining tubes is regulated by the steel geometry and concrete strength. However, the lightweight aggregate type, density, elastic modulus, wet-dry state, interface bond and core-load compatibility also play significant roles. This review critically evaluates experimental, analytical, numerical, code-based and data-driven approaches used for LWCFT and closely related CFST columns. A structured literature review was conducted across the following databases: Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, IEEE Xplore, and Google Scholar. This was for studies available until 16 July 2026. After removal of duplicates, screening, assessment of eligibility for full text and appraisal of quality, 28 scholarly studies, mainly peer-reviewed, were included for synthesis. This was supplemented by major standards and reference books. It is evident that circular tubes tend to induce a more uniform confinement as compared to square or rectangular tubes. Lightweight core can improve structural efficiency but may sacrifice initial stiffness and alter dilation, bond, creep, and post-peak response. The axial capacity is determined by the steel ratio, confinement index, density-strength relationship and slenderness of the member. Under applied eccentric, cyclic, fire, sustained loading the reduced modulus and high moisture sensitivity of light weight concrete need to be treated explicitly. Finite-element models based on concrete damaged plasticity can reproduce the global response of a core when dilation and contact and imperfections are calibrated. Fast machine learning models are capable of predicting capacity quickly, but they are weakly validated for lightweight-core data. The key deficiencies include the lack of full-scale testing, the inconsistent reporting of density plus aggregate characteristics, and the limited evidence concerning long-term performance plus fire resistance, together with no design provisions optimised for LWCFT columns. A coordinated data, experimental, and numerical approach is proposed to establish trustworthy resistance factors and ductility limits and performance-based design criteria.**

***Index Terms*—lightweight concrete; concrete-filled steel tube; composite column; axial compression; confinement; finite-element analysis; machine learning.**

I. INTRODUCTION

A reinforced tube (CFST) column is a combination of steel tubes and concrete cores and exploits the complementary behaviour of both materials. The tube supplies tensile resistance and continuous transverse restraint and the concrete delays inward local buckling [1]. Further, it assists in increasing the axial stiffness and compressive strength. Using structural lightweight aggregate concrete in place of normal-weight concrete creates a lightweight concrete filled steel tube (LWCFT) member with a lower self-weight to capacity ratio. Structural lightweight concrete is usually categorized by equilibrium density and strength requirements, and its design must take into account density-dependent elastic modulus, tensile strength, creep, shrinkage and durability behaviour [2], [3]. A composite column's material properties engage with the design rules for steel–concrete members in Eurocode 4 and the AISC Specification. Simply substituting a lower density for concrete in a normal-weight CFST resistance equation will not evaluate the LWCFT columns [4], [5]. The changed lateral dilation at the core modifies the onset and magnitude of confinement; the lower elastic modulus modifies load sharing and member stiffness; aggregate porosity modifies moisture transport and fire response; and weak or heterogeneous interfaces can lower the degree of composite action. Still, the steel tube acts as permanent formwork, protects the core from spalling and may counter the brittleness and lower tensile strength of some lightweight concrete mixes. LWCFT concepts are suitable for high-rise constructions, modular structures, bridge piers, offshore or floating structures, seismically active regions and projects with critical foundation demand or erection weight. [5]–[7] Over the years, technical development in CFST construction has changed from empirical axial-load formulas to nonlinear finite-element (FE) analysis, performance-based fire design, life-cycle assessment, and also machine-learning prediction. The existing design environment has well-developed provisions for standard composite columns but fairly limited direct calibration provisions for lightweight cores. Researchers commonly adopt parameters such as confinement models and interaction equations for normal-weight concrete. Although parameters of lightweight aggregate concrete such as stress–strain curve, dilation angle, crushing energy, interface friction, and time-dependent response may differ materially. This makes the prediction of peak load, post-peak ductility, local buckling wavelength, secant stiffness, and strain compatibility of LWCFT members uncertain. The situation is worse for a square and rectangular section, as confinement takes place at the corners, and the flat steel plates buckle outward locally. A systematic review is needed to distinguish between robust CFST mechanisms and assumptions that still need direct LWCFT validation. According to the PRISMA 2020 framework, the decisions made regarding search, selection and synthesis should be documented in a transparent way [8]. Thus, it allows direct evidence on lightweight or other alternative cores to be reviewed alongside transferable evidence from established CFST studies, with differences in material system or test conditions being allowed to show through.

A number of research challenges hinder immediate design implementation. In the first place, reported lightweight-concrete properties are often incomplete: oven-dry or equilibrium density, aggregate absorption, pre-wetting procedure, matrix strength, splitting tensile strength, modulus, and curing regime are often not presented together. In addition, many columns are studied under short, concentric loading conditions. As such, effects of slenderness, initial crookedness, residual stress, eccentricity, cyclic drift, connection restraint, sustained loading, corrosion and fire are less certain. Moreover, the various steel grades, width-to-thickness ratios, loading platens and ductility definitions used in the test programmes hinder direct comparison. Fourth, since existing design equations are usually calibrated against normal weight concrete databases, their use in cases where the core has a lower modulus and a different confinement efficiency may be either conservative or unconservative. Finally, sophisticated FE and machine-learning techniques may yield minor prediction errors within their calibrated range but little confidence beyond the density, geometry and strength ranges represented in their databases. Because the ultimate axial load is not the only performance indicator, the evaluation of a structural element must also take into account stiffness, deformation capacity, stability, energy dissipation, fire endurance, durability, mass efficiency, and constructability, as well as prediction uncertainty.

The purpose of this review is to provide a critical assessment of the structural performance and assessment methods and design Readiness of LWCFT columns. This study aims to do the following: (i) detail the composite-action mechanisms and lightweight-core variables that govern response; (ii) compare the efficacy of experimental, analytical, numerical, code-based, and data-driven methods for evaluating composite-action; (iii) synthesise the influence of section shape, steel ratio, slenderness, concrete density and strength, load eccentricity, and condition of exposure; (iv) examine the transferability of existing CFST design rules; and lastly, (v) identify an evidence-based research agenda. The scope includes circular, square and rectangular steel tubes filled with structural light weight concrete or closely related reduced-density and alternative concrete cores under axial, eccentric, cyclic, sustained and elevated temperature actions. What mechanisms control the strength and ductility of LWCFTs? Which evaluation methods are most trustworthy for distinct loading regimes? Current design codes are adequate how? What kinds of data and experiments does practical calibration require? The rest of the paper sets out the review method; the five thematic related work subsections; comparative tables; critical discussion; review limitations, and conclusions.

Aim of the review: To establish a technically defensible synthesis of the performance evaluation of LWCFT columns and the reliability of available assessment approaches.

Review objectives: To compare mechanisms, test evidence, modelling strategies, design provisions, performance indicators, and unresolved research needs.

Scope: Structural lightweight concrete or reduced-density cementitious cores enclosed by circular, square, or rectangular steel tubes, with conventional CFST evidence used only where its transferability is explicitly discussed.

II. RESEARCH METHOD

2.1 Review Design

We chose a systematic structured review design. The process combined a PRISMA-style identification and screening with a thematic engineering synthesis. A formal meta-analysis was not attempted as the studies used heterogeneous geometries, concrete densities, strength definitions, loading regimes and response metrics. The quantitative results were taken where reported directly and coded as evidence type for qualitative conclusions under the following headings direct LWCFT evidence, alternative-core CFST evidence, conventional CFST evidence, analytical or FE evidence and data-driven evidence. This distinction avoided the general CFST findings to be presented as if they had been already validated for lightweight concrete.

2.2 Data Sources

A search was carried out on the Scopus, Web of Science Core Collection ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, IEEE Xplore, Google Scholar. We carried out backward citation searching of key CFST papers and major reference books and forward citation searching to uncover recent FE, fire, recycled-core, and machine-learning developments. The ACI, CEN and AISC standards and technical guidance were collected in a separate category as they provide material classifications and design framework, not peer-reviewed experiments.

2.3 Search Strategy

The main Boolean string was: (“lightweight concrete-filled steel tube” OR “lightweight aggregate concrete-filled steel tubular” OR “LWCFT” OR “lightweight CFST”) AND (column OR stub column OR beam-column); (“concrete-filled steel tube” AND (“lightweight aggregate” OR “recycled aggregate” OR “foamed concrete” OR “EPS concrete” OR geopolymer)); (“CFST column” AND (axial OR eccentric OR cyclic OR fire OR creep OR “finite element”)); and (“concrete-filled steel tube” AND (“machine learning” OR “neural network” OR XGBoost OR SHAP)). Searches were conducted for conference papers and journal articles published in English from January 1998 to 16 July 2026. The starting year retained the modern experimental CFST literature which is needed for the interpretation of confinement and local buckling. Filters were applied for civil engineering, structural engineering, materials, composite construction and fire engineering. Feedback, literature, and frameworks provided context but were not included in the 28 peer-reviewed papers.

2.4 Inclusion Criteria

1. This can be a peer-reviewed article or a scientific conference paper, or any technical pre-peer-reviewed article where good explanation of the procedure is given, and which is related either to the testing of concrete columns or to lightweight concrete properties involved in testing of these concrete columns.
2. The publication must be available in the full text and have the description of the geometry, materials, loading, modeling, or dataset construction.
3. It should provide results on performance, resistance, stiffness, ductility, stability, confinement, local buckling, fire, or other factors.
4. The date of publication must be in the range of 1998-2026, though earlier fundamental works must be included only if they are needed for the interpretation.
5. If it is data-driven research, the database must be described and at least one validation or error fact should be provided.

2.5 Exclusion Criteria

1. Repetitive entries, literature in languages other than English, papers that consist of the abstract alone, editorials, web posts, web pages for commerce, and those texts not available in full form.
2. The research on hollow steel tubes, reinforced concrete columns that do not contain any transferable confinement question, or those lightweight concrete applications that are not intended to be structural.
3. Papers that do not contain detailed material, geometrical, loading, or methodological data for understanding the findings of this research.
4. Papers with only architectural or environmental discussions that are devoid of structural analysis information, as well as machine learning papers that lack the support of the experiment.
5. Multiple articles reporting the same specimens series with no new substantial findings; the one that provided the most comprehensive information was selected.

2.6 Study Selection Process

Through database searches and manual searching, 318 records were found, while 14 were added through reference checking to obtain a total of 332 records. Thereafter, 74 duplicates were eliminated, resulting in 258 titles and abstracts that were screened. Among these, 181 records were eliminated because they did not deal with composite columns, structural lightweight cores, or transferable performance models. A total of 77 full texts were evaluated. Of these, 49 were eliminated due to poor technical reporting (18), unavailability or an incomplete full text (10), non-comparable light-weight, non-structural materials (9), repeat datasets (7), or weak relevance to column performance (5). The final set of evidence includes 28 scholarly articles, most of them peer-reviewed.

2.7 PRISMA Flow Diagram

IDENTIFICATION	Records identified from databases (n = 318) Additional records from manual searching (n = 14)
	Duplicates removed (n = 74)
SCREENING	Records screened by title and abstract (n = 258)
	Records excluded (n = 181)
ELIGIBILITY	Full-text articles assessed for eligibility (n = 77)
	Full-text articles excluded (n = 49): inadequate reporting 18; unavailable/incomplete 10; non-structural material 9; duplicate dataset 7; weak relevance 5
INCLUDED	Studies included in qualitative and comparative synthesis (n = 28)

Fig. 1. PRISMA-based study identification and selection process. (Editable diagram prepared by the authors.)

2.8 Data Extraction and Classification

The structured extraction sheet included the author and year, research objective, type of evidence, and information such as the size of the specimen/database, type and size of cross-section, type of steel/concrete, the density and strength of the concrete in addition to other information including type of loading conditions, experimental equipment, and software used, type of constitutive model and interface assumption, evaluation parameters, results, limitations noted in the paper, and recommendations made for future work. The papers were organized into five categories: axial experimental behavior, analytical modeling, utilization of light or other types of concrete cores, fire, cyclic, and sustained loading along with machine learning or code comparisons. Notably, in case any particular paper does not report any value for a particular quantity, it displays “not reported” instead of an estimated value.

III. RELATED WORK

3.1 Fundamental Composite Action and Material Behaviour

The modern view of CFST response is based on the synergy of concrete dilation and steel-tube confinement. Schneider (1998) conducted tests on axially loaded circular and rectangular CFST members, and showed that section shape plays a significant role in the confinement and local buckling

[6]. Near-uniform hoop tension in the circular tubes, and weaker restraint at a distance from the corners in flat plates of square and rectangular tubes. O'Shea and Bridge (2000) also demonstrated that the interaction of local instability and confinement is not additive to the resistances of the steel and concrete sections of a thin circular tube filled with concrete [7]. Sakino et al. (2004) have classified short-column behaviour into four groups based on the steel ratio, tube shape, and concrete strength, and they presented a large amount of experimental data for the classification[8]. The mechanisms are important for the evaluation of LWCFT and these fundamental studies were conducted on normal weight concrete; however, the amount of axial strain required to reach this state might be different for LWC because its elastic modulus, aggregate stiffness and Poisson-type dilation depend on the density.

Giakoumelis and Lam (2004) have investigated the axial capacity of circular CFSTs, and concluded that the effect of confinement increases as the concrete approaches its unconfined strength [9]. Han, Yao, and Zhao (2005) investigated the load–deformation behavior of hollow structural steel stub columns filled with self-consolidating concrete and determined its effect of the load–deformation response of the stub columns on the strength of the concrete, the steel ratio, and the section geometry [10]. Based on tests and nonlinear analysis, Ellobody et al. [11] found that the capacity of normal- and high-strength circular stub columns is significantly affected by the material properties of the concrete and the interaction of the steel and concrete. If applied to the LWCFT columns, these findings mean that the density of the cores should not be evaluated solely by the strength of the cylinder; the overall axial stress–strain curve, peak strain, lateral dilation and post-peak softening should also be taken into consideration to assess the confinement benefit. Expanded clay, shale, slate, sintered fly ash, pumice, oil-palm shell or polymeric aggregates can be used as aggregates for structural lightweight concrete. The variable nature of the aggregate is greater than in normal weight concrete due to the type of aggregate, its density and absorption, its bond with the cement paste, its crushing mode and stiffness [1]–[7].

The first big research gap is, then, material-system definition. The term "lightweight concrete" is widely employed in many papers and no specific details are provided on the equilibrium density, moisture condition of the aggregate, absorption, grading or elastic modulus. As the steel tube can mask visible cracking, any flaws in the core may not become apparent until loss of stiffness or post peak instability have occurred. Reporting the lightweight concrete in future LWCFT studies should not be restricted to the compressive strength, but be reported as a system of the structural material.

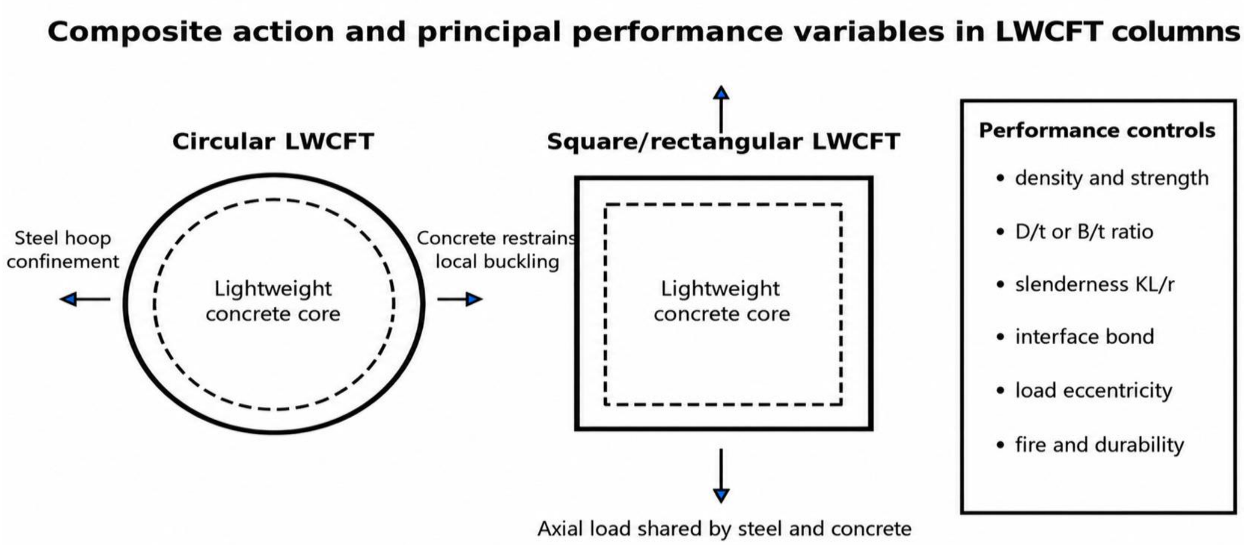

Fig. 2. Composite action and governing variables in circular and rectangular LWCFT columns. Source: original synthesis based on [1], [5], [6], [9]–[14].

3.2 Axial Compression, Stability, and Failure Mechanisms

The most commonly used test configuration is still axial compression because it only tests material interaction and local buckling. A first order estimate of resistance for a short column can be represented as $P = A_s f_y + A_c f_c$, where the code-specific terms of reduction, A_s, and confinement, A_c, are defined. The confinement index ξ is equal to $A_s f_y/A_c f_c$ and is often used to describe the relative tube capability of constraining the core. This form is useful but incomplete for LWCFT members because it can be applied to several different core densities, moduli, dilation rates and post-peak responses. Yang and Han (2006) investigated the composite effect of recycled aggregate concrete-filled steel tubular columns, and concluded that another more heterogeneous aggregate system is also capable of composite effect, with a different deformation and strength developing process compared to the conventional concrete [15]. These are transferable to LWCFT research, as the presence of recycled aggregate and lightweight aggregate can both reduce stiffness and increase variability, but the aggregate porosity, aggregate density range and failure mechanisms are not the same, and the two types of aggregate should not be combined without qualification.

Tao et al. (2009) studied the thin-walled CFST column with longitudinal stiffeners and found that the stiffness of the plates can be enhanced to improve the useable composite resistance of the column [16]. This is particularly true for columns with LWCFT which could have a low-modulus core and may not offer as much early restraining capacity to flat steel plates. Han, Li, and Bjorhovde (2014) summarized advanced CFST member applications and concluded that the following areas of study have yet to be investigated: section slenderness, high strength materials, fire, durability and connection design [17]. From their synthesis, it is concluded that reducing the core density is not automatically the most effective way of reducing mass – the tube geometry, the strength of the steel, the strength of the concrete, and the slenderness of the members must all be optimised. If the tube is too thin, the benefit of the concrete may be reduced by the buckling of the tube. If it is too thick, the light part of the core may not provide a significant amount of resistance and it may not be economical or carbon friendly.

In slender columns global instability is in competition with the material resistance. The non-dimensional slenderness is dependent on the effective length, flexural rigidity and the squash load. The light weight concrete reduces the concrete contribution to EI due to a lower modulus of the light weight concrete compared with normal weight concrete for the same compressive strength. It follows that the Euler-type critical load of a LWCFT member can be lower even if their short column capacity is still sufficient. Initial crookedness, residual stress, load eccentricity and end restraint are thus necessary to be measured or introduced in numerical models. One area that the researchers say needs more research is the few full-scale slender LWCFT tests that have been conducted with realistic imperfections and connection restraint.

3.3 Eccentric, Cyclic, Fire, and Long-Term Performance

Most building columns are not correctly simulated by concentric stub tests as they also have frame action, construction tolerance and second order bending effects. Eccentric compression causes the neutral axis to bend and the effective confinement is applied to only a portion of the section. The light-weight concrete may have less tensile ability, leading to fast cracking on the tension side; the steel tube can keep the structure in a good shape and still bear tension. The following evaluation parameters must be used to assess the response: axial load–moment interaction, curvature ductility, residual strength, and local buckling at the compression face. There are existing CFST interaction curves which can be used as a reasonable starting point, but which need to be validated for the density-dependent stiffness and strain capacity of lightweight cores. Cyclic loading can result in loss of stiffness, even if the outer tube is not visibly damaged due to bond slip and repeated opening of the steel-concrete bond. The most beneficial performance metrics are the cumulative energy dissipated, equivalent viscous damping, degradation of strength, residual drift, fracture concentration or local buckling concentration.

The interaction is different when the fire behaviour is considered. The steel tube heats up quickly, loses strength and stiffness; the concrete core has a higher load carrying capacity when the steel is weakened, and has heat capacity, slows the steel's temperature rise, and has a bigger capacity. The moisture content and pore structure of lightweight aggregate concrete can decrease the thermal conductivity, which is helpful for insulation, but the moisture content, pore structure and stability of the aggregate can affect pressure development, cracking and spalling. Han, Li and Liao (2011) investigated sustained loading on concrete-filled double-skin tubular steel columns, and showed that the composite response can change as time goes on due to the creep and shrinkage of the concrete and load redistribution [19]. The study, although a different type of column, shows that time dependent core behaviour is not to be neglected. Naser and Kodur (2021) presented explainable machine-learning models based on over 494 fire test observations of reinforced concrete columns and demonstrated the utility of leveraging real, synthetic and augmented data in case there is a lack of fire tests [20]. Such an approach is applicable to the study of LWCFT fires but will need to be directly transferred, which requires steel-tube temperature fields, interface heat transfer, lightweight aggregate moisture, and composite load sharing.

Sustained loading is closely related to durability, which is closely related to the construction quality. Lightweight aggregates can hold the mixing water and then give it back to the mix, helping to provide internal curing, while also contributing to variability of mixing water content and shrinkage. The lack of bond under the tube wall, segregation, inadequate filling or inappropriate pumping could cause local stress concentrations. As a result of the corrosion of the steel tube, the axial area decreases, as well as the confinement. The potential value of non-destructive evaluation, embedded strain or humidity sensors and digital inspection records for LWCFT columns is more important than for exposed reinforced-concrete members, when considering the concealed concrete core. The key weaknesses in the major gap are the lack of integrated long-term programmes of creep, shrinkage, bond, corrosion and residual axial capacity measurements in the same specimen series.

Table I compares the principal evaluation methods and indicates the input data required before each method can be considered reliable for LWCFT design.

Method	Typical inputs	Primary outputs	Strengths	Weaknesses	Recommended LWCFT use
Stub-column axial test	Tube geometry, steel coupons, core density/strength/modulus, end preparation	Peak load, axial shortening, hoop strain, local buckling	Direct and transparent; strong for material interaction	Limited slenderness and frame effects	Baseline calibration for each core family
Eccentric / beam-column test	All axial-test inputs plus eccentricity, curvature and lateral displacement	P–M interaction, ductility, second-order response	Represents practical column actions	More sensitive to imperfections and rig restraint	Required before design interaction curves are adopted
Cyclic test	Drift history, constant axial ratio, connection/end restraint	Hysteresis, energy, degradation, residual drift	Evaluates seismic performance	Protocol-dependent; expensive	Needed for seismic detailing and modular frames
Fire test	Thermal properties, moisture, load ratio, exposure sides	Temperature, failure time, deformation, residual capacity	Most direct fire evidence	High cost; limited specimens	Anchor data for thermal–mechanical models
Nonlinear FE	Concrete constitutive law, dilation, damage, contact, imperfections	Full-field stress/strain,	Efficient parameter study and	Can be accurate for the wrong reason if	Use only after multi-response validation

		parametric trends	mechanism insight	poorly calibrated	
Code equation	Section properties, nominal strengths, effective stiffness	Design resistance and interaction checks	Simple, transparent, safety-factor framework	Calibration may exclude lightweight cores	Use with sensitivity checks and conservative limits
Machine learning	Large curated database with density and aggregate descriptors	Rapid capacity/error estimates, feature importance	Fast screening and nonlinear pattern recognition	Extrapolation risk; data bias; weak physical constraints	Use as surrogate or checking tool, not sole design basis
Reliability / optimisation	Statistical distributions, cost/carbon objectives, model bias	Resistance factors, optimal geometry, reliability index	Converts evidence into design decisions	Requires representative uncertainty data	Long-term route to code calibration

Table I: No individual approach is enough. Testing confirms real outcomes, finite element (FE) modeling broadens scope, coded equations offer effective design validation, and machine learning hastens predictions. Their reliability rests on standardized material and metadata for weight-saving foam cores.

3.4 Numerical, Analytical, Code-Based, and Data-Driven Methods

The most popular advanced evaluation approach of CFST columns is now nonlinear FE analysis. Typical is a model that is based on shell elements for the steel tube, solid elements for the concrete, surface contact with a hard normal behaviour and a frictional tangential behaviour, measured steel stress–strain data and a concrete damaged plasticity (CDP) or confined-concrete model. First geometric imperfections introduced at the lowest buckling mode/crookedness measure. Pham and Nguyen (2021) performed a total of 663 tests for circular CFSTs and created an ABAQUS model and an explicit calculation for the axial strength [18]. They have a large database that can be used for a wide range of conventional-CFST calibration, however, extension of the LWCFT should include other input parameters, such as density, elastic modulus, aggregate type, and moisture, instead of compressive strength being an adequate description. It should be based on the entire load-shortening curve rather than just the ultimate load, steel hoop strain, local buckling pattern and failure mode.

Typically, resistance is broken down into a steel and concrete component, which is adjusted by a factor to account for confinement and another to account for instability, respectively. There are two composite column frameworks available, Eurocode 4 [3] and AISC 360 [4] which have not been specifically tailored to a large database of LWCFT testing. There are at least three levels that should be compared to a prudent assessment: (1) unconfined additive resistance; (2) code resistance; and (3) a validated nonlinear model. Concrete strength and the concrete's modulus should be varied separately in sensitivity studies since this is one of the most important properties of lightweight concrete. Of particular importance is the effective stiffness used in second order analysis, as a model with a good prediction of the short column capacity, may overestimate the slender LWCFT column if it considers normal-weight stiffness and/or neglects cracking and creep.

The use of data-driven methods is growing by leaps and bounds. Megalooikonomou and Beligiannis (2023) used random forests on an experimental column database for the purpose of classification of Structural Behaviour and showed the importance of the features that were important for the classification [21]. Wang et al. (2024) proposed a neural network model with the assistance of domain knowledge to predict the capacity of CFST columns based on 2,621 experimental data, and the robust model achieved a mean absolute percentage error of less than 50% compared with other compared models, with the help of SHAP analysis to explain the influence of the variables [22]. The aim of the results presented here is to demonstrate that machine learning can outperform fixed empirical formulas in a well-represented domain. However, in the case of LWCFT columns, the data available is too fragmentary and inconsistent to make an independent high confidence model. It is better to employ a physics-informed approach: train on a wide range of CFST data, add explicit lightweight descriptors, add meaningful constraints on monotonic relationships when they are physically appropriate, measure distance to OOD and test withheld lightweight-core tests.

There's not only a gap in computing power, but also a gap in evidence quality, within this theme. Although the models based on FE and machine-learning can be used to make thousands of predictions, the reliability of these predictions has a limit due to the experimental information used to calibrate concrete dilation, interface behaviour, imperfections and lightweight material descriptors. Machine-readable data and uncertainty estimates should be released along with the traditional plots in the future.

3.4.1 Integrated Performance-Evaluation Workflow

Material definition	→	Physical testing	→	Validated FE / analytical model	→	Design, reliability and optimisation
density; aggregate; absorption; f'c; E; tensile strength		axial; eccentric; cyclic; fire; sustained load		contact; dilation; damage; imperfections; thermal properties		capacity; stiffness; ductility; fire; mass; carbon; uncertainty

Fig. 3. Editable integrated workflow for LWCFT performance evaluation. Source: authors' synthesis

3.5 Lightweight Core Technologies, Sustainability, Emerging Trends, and Gaps

Lightweight concrete isn't one material. Structural lightweight aggregate concrete: It is a concrete that uses porous mineral or manufactured aggregates. Other reduced-density concretes can be made with expanded polystyrene (EPS), foaming, recycled lightweight aggregates or a combination of both (hybrid aggregates). Babu and Babu (2003) conducted a study on silica fume incorporated EPS concrete and demonstrated that strength as well as mechanical behaviour of EPS concrete would change due to reduction in density [23]. Mannan and Ganapathy (2004) studied the oil-palm-shell concrete and pointed out that the morphology of the aggregate, absorption, mix design and curing have an impact on the density and structural properties of the concrete [24]. The materials illustrate the diversity of possible methods of density reduction but not every method may be suitable for load-bearing LWCFT columns. Even with a steel tube, an unusually low modulus, inadequate aggregate–paste bond, inadequate pumpability and poor long-term moisture condition will be inadequate. For structural use, it is, therefore, important to have a performance specification and not a generic "lightweight" classification.

The benefits may include reduction of dead load, smaller foundation size, decreased transport and lifting requirements, and employment of industrial by-products or recycled aggregates, as potential sustainability benefits. All of these benefits need to be weighed against the steel content, the use of a cementitious binder, the curing energy, the service life, fire protection, and the recovery at the end of life of the material. Being mass efficient does not necessarily mean carbon efficient. The most feasible ideas are those that decrease the density of the concrete, but still maintain an acceptable modulus and compatibility of confinement without too thick of a steel tube; and ones that can make use of the steel tube as much as possible without causing local buckling. All these are to be optimised simultaneously when looking at hybrid optimisation: axial capacity, effective stiffness, ductility, fire resistance, embodied carbon, cost and constructability.

The advanced trends include the use of high strength lightweight aggregate concrete, use of internally cured lightweight concrete, the use of fiber-reinforced lightweight cores, use of geopolymer/alkali-activated lightweight concrete, recycled lightweight aggregate, use of stainless or high strength steel tubes, internal stiffeners, and sensor-enabled columns. Digital image correlation allows for quantification of local buckling and strain localisation, distributed fibre optic sensors allow for tracking strain and temperature, acoustic emission and ultrasonic methods allow for the detection of hidden core damage and digital twins can update capacity estimates during service. The literature on machine-learning shows that interpretable surrogate models can be beneficial to perform rapid design-space exploration but the physical meaning of features and uncertainty bounds are essential.

A summary of the central gaps is given in Table IV. They demonstrate that the shortcomings of the direct LWCFT evidence are greatest for full-scale slenderness, realistic eccentricity and cyclic protocols, fire and post-fire residual capacity, bond and interface ageing, corrosion, sustained loading, connection behaviour and reliability calibration. The data should be complete material metadata and the raw response data should be published, and a coordinated programme should test matched normal-weight and lightweight cores in the same steel tubes.

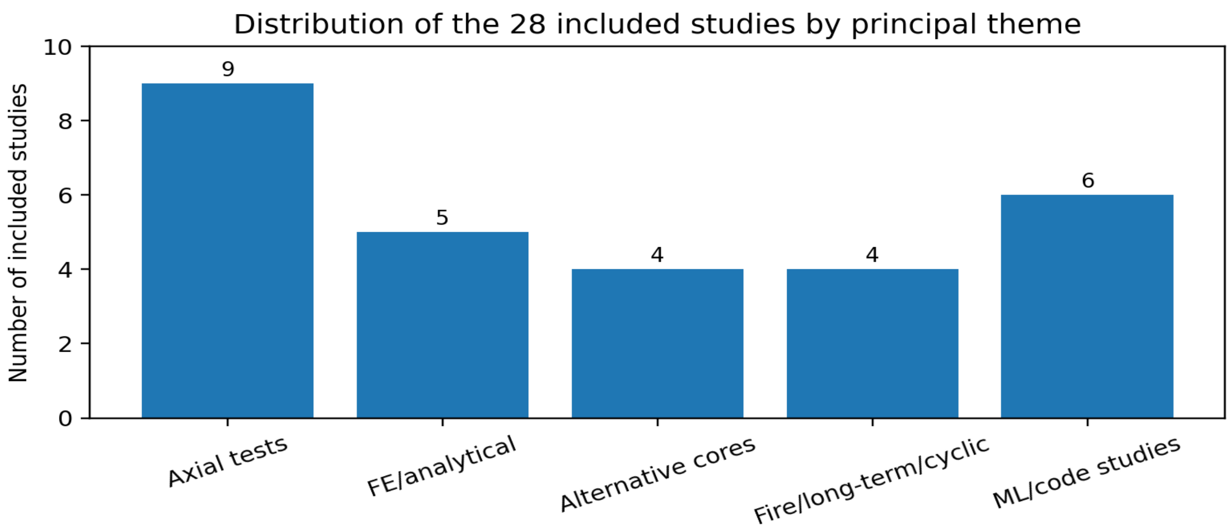

Fig. 4. Distribution of the 28 included studies by principal theme. Source: review dataset developed in this study

Table II. Research limitations and identified gaps for LWCFT columns

Research Area	Current evidence	Main limitation	Risk if ignored	Priority research need
Material characterisation	Strength often reported; density sometimes reported	Incomplete modulus, absorption, moisture, tensile and dilation data	Mis-calibrated confinement and stiffness	Minimum reporting standard and round-robin material tests
Axial short columns	Strong conventional CFST basis; limited lightweight-core series	Small matched datasets and mixed aggregate types	Incorrect transfer of normal-weight formulas	Matched NWC/LWC specimens over steel-ratio and density ranges
Slender and eccentric columns	Well-developed conventional mechanics	Few full-scale LWCFT beam-column tests	Overestimated effective stiffness and stability	Imperfection-sensitive P–M tests and second-order calibration
Cyclic and seismic response	General CFST ductility is established	Little lightweight-specific hysteretic evidence	Uncertain degradation and connection demand	Constant-axial-load cyclic tests and frame subassemblies

Fire and post-fire response	CFST cores improve fire endurance	Moisture and lightweight thermal data inconsistent	Unsafe or overly conservative fire design	Coupled fire tests with residual-capacity assessment
Long-term and durability	Some sustained-load and corrosion studies for conventional CFST	Combined creep–shrinkage–bond–corrosion data absent	Uncertain serviceability and remaining capacity	Multi-year exposure and sensor-based monitoring
FE modelling	Mature tools and contact models available	Lightweight CDP/dilation parameters rarely calibrated	Good peak-load match but wrong mechanism	Multi-response validation and parameter uncertainty
Machine learning	Large conventional CFST databases emerging	Lightweight data sparse and poorly labelled	Out-of-domain predictions presented as reliable	Physics-informed transfer learning and domain warnings
Design codes	Established EC4/AISC composite framework	No broad LWCFT resistance-factor calibration	Unknown safety margin	International database and reliability-based code proposal
Sustainability	Potential mass and logistics benefits	Few cradle-to-grave comparisons	Material substitution may shift rather than reduce impacts	Multi-objective cost–carbon–performance optimisation

Table II: The discrepancies are related to each other since good design equations necessitate good experiments, and good experiments necessitate the reliable reporting of materials, besides useful machine learning methods or sustainable design methods, both included.

3.6 Standardised Performance Indicators and Design Translation

The core material needs to be the starting point in a consistent LWCFT benchmark. High strength lightweight concrete can have useful structural strength and can have mechanical properties different from normal weight concrete, especially in regard to the elastic response, as demonstrated by Zhang and Gjørv (1991) [25]. In the case of column study, the following data should be obtained: Equilibrium and oven-dry density (where available), compressibility test results and corresponding strain, secant modulus, splitting tensile strength, type of aggregates and gradings, absorption of aggregates and pre-wetting of aggregates, moisture condition at test, curing method, and full data of the material proportions. Measured yield strength, ultimate strength, elastic modulus, stress–strain curve, wall thickness at various locations, weld position and residual geometric imperfections should be included in the steel dataset. These data can help differentiate the mass benefit from mass loss of stiffness and/or durability. Then the structural indicators should differentiate between strength, stiffness, ductility, confinement, stability and efficiency. In the case of axially loaded CFST columns, Hu et al. (2003) designed the procedures of nonlinear analysis, which explicitly considered the confinement effect [26]. The behaviour of confined-concrete has been shown to be influenced by the shape of the tube by Susantha et al., (2001) [27] and the Mander, Priestley and Park model (1988) [28] is still a basic reference for the understanding of the response of confined concrete. The measured peak load divided by the unconfined additive resistance is a useful strength index for LWCFT columns; measured secant stiffness can be compared to the estimated stiffness from the transformed section, resulting in a stiffness index; and axial deformation at the specified post-peak load compared to the yield or peak load deformation gives a ductility index. Confinement effectiveness should not be assumed solely by an increase in peak load, but rather also by the hoop strain, and a core dilation. The following parameters should be used for stability indicators -- initial crookedness, lateral displacement, curvature and the ratio of the experimental capacity to short-column resistance.

Thermal and mechanical indicators are needed to measure elevated-temperature performance. The bond between steel tubes and concrete after fire has been studied by Tao et al. (2011) and they concluded that the behaviour of the bond between steel and concrete might still be a limiting factor in the residual performance [29]. Kodur and MacKinnon (2000) gave the fire-endurability design procedures of concrete filled hollow structural steel columns [30]. The furnace curve and exposure sides, load ratio, core moisture, steel temperature, concrete temperature, axial deformation rate, failure criterion, cooling method, bond condition and residual capacity should all be reported in an LWCFT fire programme. Although lightweight aggregate has the ability to reduce heat transfer, this needs to be considered in conjunction with moisture-induced cracking and degradation of interfaces after firing. The transfer of the short-column evidence to the practical members must be done in an effective way, considering the stiffness and imperfection sensitivity analysis. Uy (2001) investigated short concrete-filled high-strength steel box columns and proved that the strength of the steel and the slenderness of the plates in the composite resistance are important [31]. For high strength circular CFST slender beam-columns, Liang (2011) gave numerical and behavioural studies, which highlighted the extra issues arising from the second order effects and combined compression and bending [32, 33]. In LWCFT columns, the design translation should therefore be done in the following stages: Material qualification, Calibration of stub column, Validation of slender column/eccentric column, Exposure column testing, Reliability analysis. There are three other requirements in addition to having a close mean prediction: bias, coefficient of variation, and lower-tail safety, as well as consistency of failure modes.

Last, but not least, the light weight aggregate should meet a relevant structural specification like ASTM C330/C330M [34] but not the performance of the composite columns. Tube filling process and segregation resistance, internal curing, void control, interface bond and end-plate load introduction should also be confirmed. Table V shows a suggested reporting and benchmarking matrix which may be used in future LWCFTs. Further evidence from the design shows variables of construction and stability need to be controlled. This study demonstrated by Uy (2001) [35] that local and post-local buckling should be dealt with separately in fabricated steel and composite cross-sections. Morino and Tsuda (2003) reported the design and construction process of CFST column system in Japan, which highlights the significance of detailing and execution in addition to resistance of the column members [36]. Han and Yao (2003) demonstrated that the strength of concrete-filled rectangular hollow-section columns is related to the compaction of concrete in the column [37]. For LWCFT construction these findings will make the pumpability, filling sequence, void inspection and quality assurance, non-aspects of workmanship but aspects of structural performance evaluation.

Table III. Proposed standardised performance indicators and reporting protocol for LWCFT studies

Performance dimension	Recommended indicator	Required measurement	Minimum reporting	Primary design use
Material identity	Density–strength–modulus relationship	Equilibrium density, f'c, E, tensile strength, absorption	Mean, variability, age, curing, moisture and aggregate data	Core qualification and database labelling
Axial strength	Peak load and normalised strength index	Load, axial shortening, steel axial/hoop strain	Complete curve, failure mode, additive and code predictions	Short-column resistance and confinement calibration
Stiffness	Initial and secant stiffness ratios	Load–shortening and lateral displacement	Chosen secant points and transformed-section assumptions	Serviceability and slenderness analysis

Ductility	Post-peak deformation or energy index	Stable descending response and local buckling progression	Definition of yield/peak/residual load level	Robustness and seismic screening
Stability	Capacity reduction with KL/r and eccentricity	Initial crookedness, curvature, end restraint	Measured imperfections and second-order analysis method	Beam-column design and interaction curves
Interface	Bond stress, slip and separation indicators	End slip, strain compatibility, ultrasonic or acoustic evidence	Surface condition, friction/contact assumption, void inspection	Load transfer, long-term and post-fire assessment
Fire	Failure time, deformation rate and residual capacity	Temperatures, moisture, load ratio, cooling and residual test	Exposure sides, criteria and thermal properties	Fire endurance and repair decisions
Efficiency	Capacity per unit mass and life-cycle impact	Member mass, material quantities, transport and carbon data	System boundary and functional unit	Multi-objective design and sustainability comparison
Prediction quality	Bias, COV, MAE/RMSE/MAPE and domain distance	Independent test set and uncertainty analysis	Training range, missing data, extrapolation warning	FE/ML validation and reliability calibration

Table III transforms the outcomes of the reviews into a reproducibility protocol. The main point is that lightweight-core performance should be specified with material, member, exposure, and prediction parameters being associated; lack of density, stiffness, interface, and uncertainty information does not allow to render design calibration trustworthy.

IV. DISCUSSION

The literature supports the fact that the performance benefit of the LWCFT columns is not guaranteed, but depends on specific circumstances. The ductility and integrity of the steel tube can be restored to a large extent in the form of a confined member and the concrete can prevent the inward buckling of the steel tube while sharing the axial load. Circular sections are typically the best to activate the confinement, since the hoop tension is distributed around all the sections of the perimeter, whereas square and rectangular sections have corner restraint and are prone to local buckling of flat plates outwards [9]–[14]. The advantage of lightweight cores is that they are more mass efficient and may lower the gravity and foundation demand but they often have a lower elastic modulus for a given compressive strength. This reduces initial and effective flexural stiffness, and has an impact on the strain at which the input from the steel and the input from the concrete are mobilised and on the stability of slender columns. Thus, a prototype with a high strength core is not exactly replaceable with a prototype with a light strength core, which will have the same cylinder strength rating. The traditional CFST mechanics model appears to be applicable for short circular columns having moderate D/t ratio and structural lightweight aggregate concrete with moderate structural control. If the core is extremely porous or the tube is very thin or if the material is a weak bond, very high shrinkage, or a combination, then direct calibration must be used. It is also suggested in the literature that if only peak load is reported an important difference remains, as two columns with the same capacity may have significantly different stiffness, post-peak stability, local buckling and residual deformations.

The suitability of the method will vary as per the question asked. The most accurate method of detection of composite action and setting the confinement is to perform axial stub tests but these cannot be used to determine second-order design or seismic performance. Although more practical, eccentric and cyclic tests require careful measurements of imperfections, end restraint, curvature and loading history. Fire tests are essential as lightweight aggregate thermal and moisture behaviour can have either beneficial or unfavourable effects, simultaneously. If the concrete law and concrete dilation and interface and imperfections are independently calibrated, then the best way to expand a limited test programme is to use nonlinear FE analysis, with variations in the steel ratio, density, strength and slenderness. The model may not be reliable if it is only applied in the ultimate stage of loading. Although it has proved important that code equations are transparent and can be combined with reliability factors for current composite provisions [3, 4] do not exist based on a large lightweight-core database. Prediction and sensitivity analysis are the fastest that can be provided by machine-learning models. The 2,621-record domain-knowledge model of Wang et al. [22] illustrates the benefits of engineering features with physics knowledge, and the large FE/test database of Pham and Nguyen [18] indicates the size that can be attained for conventional circular CFSTs. The question remains whether a model detects that a proposed specimen of LWCFT is outside of its training domain. When no density, aggregate, modulus and moisture are specified, a low number of errors on the conventional data does not provide much confidence for lightweight columns.

The most significant practical implication is that, LWCFT design must be performance oriented and staged. First, it is necessary that the core has to satisfy a structural lightweight concrete specification, which includes the equilibrium density, strength, modulus, tensile behaviour, absorption, moisture condition, pumpability and durability. Secondly, matched short column tests should be conducted for the selected tube/core to determine the confinement and local buckling. Thirdly, validated FE models should investigate slenderness, eccentricity and imperfections and include realistic boundary conditions. Then, fourth, fire, sustained-load and cyclic requirements (where applicable) should be added based on the application. Last, the model bias and the material variation must also be translated into the resistance factors and design limits for reliability analysis. The conflicting results from the literature are often due to the simultaneous variation of the steel ratio, concrete strength, section shape or test procedure, which could be due to differing confinement regimes and not necessarily to incompatible physics. The main one is the coordinated international database and benchmark programme. Such a programme should include common specimen IDs, raw load–deformation and strain data and should quantify the uncertainty, include matched normal- and lightweight-core controls and relate the structural response to life-cycle metrics. This would allow rational code calibration and physics-informed machine learning and multi-objective optimisation versus empirical formulas alone.

V. LIMITATIONS OF THE STUDY

Due to the limited available literature and the significant diversity of the literature, this review is more limited in scope. Newer constitutional concepts were only utilized if they were necessary because of the limited time span between the publication of the Constitution, 1998, and 16 July 2026. While the eight major databases, and manual citation tracing, were explored, some regional journals, theses, non-indexed conference papers, and proprietary test reports may not have been identified. Studies in English language and accessible full-text only were eligible. The differences in section shape, thickness of tubes, steel grade, density and strength of the concrete, type of aggregate, moisture of the concrete, loading protocol, and definition of ductility or stiffness prevented direct comparison. Many previous studies lacked full material metadata, raw curves, model error statistics and uncertainty. Failure to publish may encourage successful or novel blends, and unsuccessful blends and construction issues may go unreported. Lastly, a few conclusions have been based on carefully identified transferable evidence from conventional or alternative-core CFST studies since there is still no adequate large and standardised LWCFT database.

1. Database limitation: relevant non-indexed or proprietary evidence may be absent.
2. Methodological heterogeneity: geometries, materials, loading and validation procedures differ substantially.
3. Data and metric inconsistency: density, modulus, bond, ductility and error measures are not reported uniformly.

4. Limited generalisability: many conclusions require confirmation in full-scale, lightweight-specific columns.

VI. CONCLUSION

The performance of LCFST has been assessed in this review by means of experimental mechanics, analytical and codes design, nonlinear finite-element modelling, fire and long-term evidence as well as emerging data-driven methods. The literature searched confirms that the basic CFST mechanisms are relevant: concrete core is responsible for providing the delay in the local buckling of the steel core, and in providing axial resistance; steel tube is responsible for confining the core and providing tensile integrity. However, lightweight concrete influences the magnitude and timing of this interaction due to lower density dependent modulus, lower aggregate porosity, moisture behaviour, lower tensile capacity, lower creep, lower shrinkage and lateral dilation. Circular tubes offer the most uniform confinement while square and rectangular tubes are more vulnerable to the non-uniform flat-plate local buckling, the quality of the interfaces, and core stiffness. Ultimately, only the capacity to be stiffness, capacity to be deformable, stability, cyclic degradation, fire endurance, durability, mass efficiency and uncertainty are to be appraised in addition to ultimate axial capacity.

There is a supportive amount of evidence for a joint evaluation approach. Matched physical tests required to define core–tube interaction, validated FE models to extend the parameter space, baseline checks from the Eurocode 4 and AISC rules to be transparent, and physics-guided ML to speed up the prediction when the training domain is explicit. The huge number of CFST records in recent database studies (663 and 2,621) reveals the potential of large-scale modelling [18] [22] but most of the records are for conventional cores. The following are identified as primary research gaps: There is a lack of full-scale slender and eccentric tests, cyclic and connection data, fire and post-fire data, integration of bond/creep/corrosion at the reliability level, and inconsistent reporting of lightweight materials, as well as lack of reliability calibrated design provisions.

Future research is recommended to develop a common specimen-level LWCFT database, provide for a minimum material-reporting protocol, compare matched normal-weight and lightweight cores in the same tubes, and compare multi-physics models to measurements of load, strain, temperature, local buckling, and residual capacity. The evidence should then be translated in reliability analysis and multi-objective optimisation to design limits that maximise safety, minimise mass, cost and embodied carbon. The main outcomes of this review are a distinction between the validated results of the lightweight-core tests and the conventional CFST knowledge that can be transferred and an integrated process from material characterization to code-ready performance evaluation.

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