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A Bibliometric Overview of Current States and Research Trends in Concrete-Filled Tube Columns

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Abstract

Concrete-filled tube (CFT) columns have gained prominence in structural engineering for their exceptional load-bearing capacity and efficiency. This study conducts a bibliometric analysis of 1,154 publications from 2014 to August 2024, using data from the Scopus database and VOSviewer, to map research trends and key developments in CFT studies. Citation, co-citation, and co-authorship analyses identify influential publications, journals, authors, countries, and institutions. Findings highlight significant growth in research output and increasing focus on advanced modelling techniques, including machine learning. Emerging themes include integrating alternative materials such as Fiber-Reinforced Polymer (FRP), stainless steel, High-Performance Concrete (HPC), Recycled Aggregate Concrete (RAC), and Seawater Sea Sand Concrete (SWSSC), showcasing the potential of multi-material innovations. This analysis offers insights into current research directions and identifies gaps, suggesting that future work explore novel material combinations and advanced modelling approaches to enhance performance and drive innovation in CFT column studies.

Keywords

Concrete-filled tubes, bibliometric analysis, Scopus database, VOSviewer, research trends

INTRODUCTION

Concrete-filled tube (CFT) systems have become a vital structural solution in modern civil engineering, leveraging the synergy between concrete and an external tube. The tube confines the concrete, enhancing its compressive strength, while the concrete core prevents the tube from buckling [1]. This combination creates a robust system capable of resisting axial, bending, and shear forces, making CFTs ideal for high-rise buildings, bridges, subways and other demanding applications [2]. Understanding the evolution of CFT research is crucial for advancing knowledge and refining design practices.

Despite the growing body of CFT research, a comprehensive and holistic analysis of research trends, patterns, and impacts remains underexplored. Bibliometric analysis provides a systematic approach to assess the scope, quality, and influence of research, offering insights into the field's development. This study aims to fill this gap by conducting a detailed bibliometric analysis of CFT research, focusing on publication trends, citation patterns, and key contributions that have shaped the field.

To achieve these objectives, metadata from 2014 to 2024 sourced from the Scopus database, a leading source of academic research, was analysed using VOSviewer (version 1.6.20). This program visualizes bibliometric networks, allowing for an in-depth exploration of relationships between publications, authors, and journals. The analysis aims to identify the most influential publications, authors, journals, and countries and to highlight emerging trends that could shape the future of CFT research.

RESEARCH SIGNIFICANCE

By mapping the research landscape, this study helps researchers (a) identify gaps in the literature while highlighting emerging trends and key thematic clusters for future investigation, and (b) pinpoint influential, active researchers worldwide to foster collaboration and mentorship. The findings also support policymakers and funding agencies in prioritizing research directions, optimizing resource allocation, and advancing high-impact initiatives.

METHODOLOGY

A. SEARCH STRATEGY

To examine advancements and trends in CFT research, this study used publication data from the Scopus database, retrieved on August 3, 2024. Multiple relevant keywords were selected to access pertinent publications. The search command used was as follows:

TITLE-ABS-KEY (((concrete AND filled AND tube) AND (axial OR compression OR column) AND NOT (beam OR slab OR wall OR pile OR arch OR joint OR connection OR tension OR acoustic OR thermal OR fire OR temperature OR impact OR seismic OR cyclic OR fatigue OR blast OR postblast OR explosion OR torque OR torsion)))

The Boolean operators used were 'OR', 'AND', and 'AND NOT', with keywords ‘concrete’, ‘filled’, ‘tube’, ‘axial’, ‘compression’, and ‘column’. These operators enhanced search functionality and precision in the Scopus database [3]. The keywords focused on CFT-related research, specifically on CFT columns under axial compression. To maintain this scope, the following areas were excluded:

- Applications of CFTs other than columns (e.g., beams, slabs, walls, piles, arches).
- Research on joints and connections for CFTs.
- Load conditions other than compression (e.g., tension, torsion, seismic, cyclic, fatigue). ‘Flexural’ and ‘shear’ were not excluded because columns can experience bending and shear failure under certain conditions (e.g., eccentric load, lateral forces, uneven loading, excessive loads). Excluding ‘flexural’ and ‘shear’ may unintentionally exclude relevant articles.
- Responses of CFTs to unusual conditions (e.g., fire, high temperature, explosion, blast, acoustic and thermal transfer).

The search outcome was later filtered as follows:

- Publishing year: 2014 to 2024, capturing the latest developments in the past decade.
- Subject areas: Limited to engineering and material science, excluding fields such as business, management, accounting, astronomy, psychology, chemistry, social sciences, medicine, economics, finance, and pharmaceutics, ensuring relevant research is central to this study.
- Document type: Restricted to articles, excluding conference papers, book chapters, and reviews, focusing on new research findings and primary data.
- Source type: Limited to journals, excluding conference proceedings and book series, sourcing high-quality scientific information.
- Language: Limited to English, ensuring comprehensibility and simplifying the comparison and synthesis of findings from different studies.

No filters were applied to author name, source title, publication stage, keywords, affiliation, funding sponsor, country, or open access. This decision was based on these principles:

- Acknowledge contributions from all authors, institutions, funding sponsors, and countries.
- Screen keywords for relevance and exclude inappropriate ones using the ‘AND NOT’ list.
- Include all journal titles indexed by Scopus, regardless of open access status.
- Include both final articles and articles in press to ensure up-to-date research and capture emerging trends.

B. DOCUMENT COLLECTION AND ANALYSIS

The initial search yielded 2,361 publications. After filtering and title screening, 1,154 publications remained (48.9%) (see Figure 1). These publications were used in the subsequent bibliometric analysis and review.

Data were extracted from the Scopus database and VOSviewer (version 1.6.20) was used to visualize the bibliometric networks. Full counting was applied in all analyses, including co-authorship, co-occurrence, citation, and co-citation (Table 1).

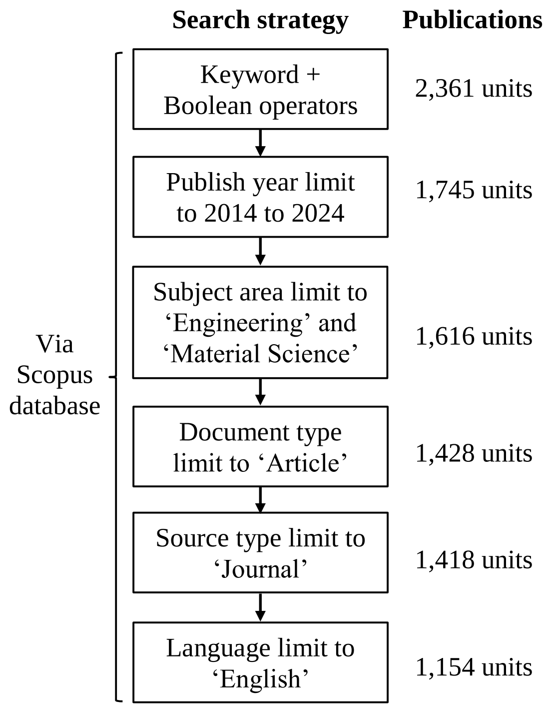

Figure 1 Documents remaining at each stage of the filtering and title screening process

Table 1 Descriptions of features in VOSviewer ver. 1.6.20

Counting method	Full counting	Each co-authorship, co-occurrence bibliographic coupling, or co-citation link has the same weight
	Fractional counting	The weight of a link is fractionalised.
Type of analysis	Co-authorship analysis	The relatedness of items is determined based on the number of co-authored publications
	Co-occurrence analysis	The relatedness of items is determined based on the number of publications in which they occur together.
	Citation analysis	The relatedness of items is determined based on the number of times they cite each other.
	Co-citation analysis	The relatedness of items is determined based on the number of times they are cited together.

RESULTS AND DISCUSSIONS

A. PUBLICATION AND CITATION TRENDS

Figure 2 shows exponential growth in CFT research publications and citations, reflecting rising academic interest. Citations outpaced publications because articles often reference multiple sources, including recent and foundational works. The decrease in 2024 was due to data being collected only up to August, making the dataset incomplete for the year.

Of 1,154 publications, 135 were not cited, leaving 1,019 with 23,163 citations and an h-index of 71. Of the uncited works, 81.5% (110 publications) were from 2023 and 2024 (Figure 3), still new and needing time to gain visibility. These uncited publications made up only 31.1% of the 353 published in 2023 and 2024, indicating a healthy citation trend where recent work was starting to gain traction. Notably, among the 348 publications published before 2020 (over 5 years old), only 7 were not cited (2%), reflecting the strong impact and relevance of CFT research in the Scopus database.

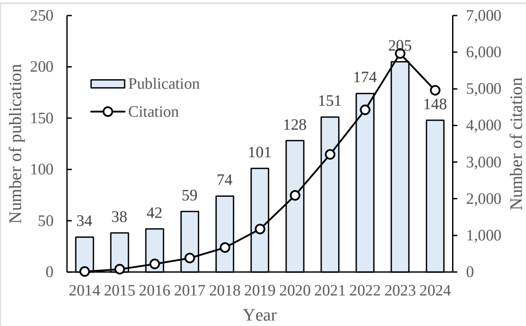

Figure 2 Trends in publications and citations from 2014 to 2024

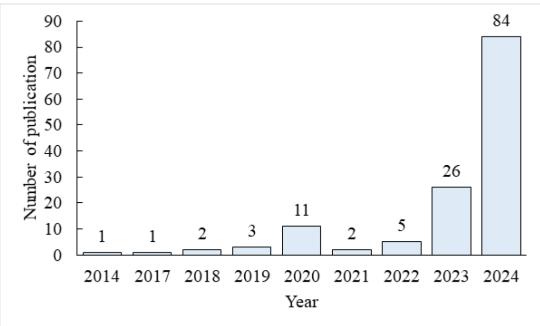

Figure 3 Number of publications without citations by year of publication

B. TOP PUBLICATIONS

The publications ranged from 0 to 245 citations, with 75.6% (873 publications) having 25 or fewer (Figure 4). Only 11 publications from 2014 to 2021 exceeded 150 citations (

Table 2). Key insights based on these high citation counts include:

- Eight of the most-cited publications focused on concrete-filled steel tube (CFST) columns, indicating a strong research interest in understanding CFTs made of steel tubes, especially their strength, stiffness, ductility, and stress-strain responses [4–11].
- There was significant interest in using alternative materials in CFT columns, including recycled aggregates, fibre-reinforced polymers (FRP), Glass Fiber Reinforced Polymer (GFRP), seawater, sea sand, and stainless steel, indicating a trend towards sustainable and innovative materials columns [7, 12, 13].
- Sophisticated modelling approaches, such as path-dependent stress-strain models [6], constitutive models [13], and advanced AI techniques like neuro-swarm and whale optimization models [10], were used to study CFT columns.

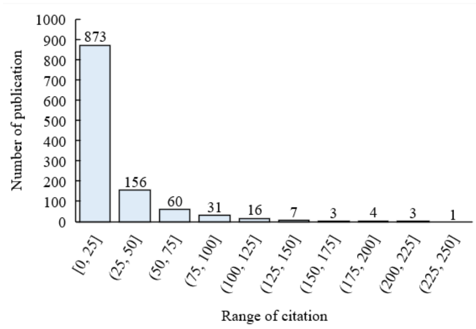

Figure 4 Number of publications versus number of citations

Table 2 The top-cited articles with over 150 citations

Title	Year	Source	Citation	Ref.
Strength, stiffness and ductility of concrete-filled steel columns under axial compression	2017	Engineering Structures	245	[4]
Bond behavior in concrete-filled steel tubes	2016	Journal of Constructional Steel Research	223	[5]
A path dependent stress-strain model for concrete-filled-steel-tube column	2020	Engineering Structures	209	[6]
Testing and analysis of axially loaded normal-strength recycled aggregate concrete filled steel tubular stub columns	2015	Engineering Structures	205	[7]
Experimental study on seawater and sea sand concrete filled GFRP and stainless steel tubular stub columns	2016	Thin-Walled Structures	199	[12]
A theoretical axial stress-strain model for circular concrete-filled-steel-tube columns	2016	Engineering Structures	198	[8]
A path dependent constitutive model for CFFT column	2020	Engineering Structures	178	[13]
Confinement effect of ring-confined concrete-filled-steel-tube columns under uni-axial load	2014	Engineering Structures	177	[9]
Utilization of coal gangue as coarse aggregates in structural concrete	2021	Construction and Building Materials	160	[14]

Table 3 The top-cited articles with over 150 citations (cont.)

Developing GEP tree-based, neuro-swarm, and whale optimization models for evaluation of bearing capacity of concrete-filled steel tube columns	2021	Engineering with Computers	152	[10]
A constitutive model for predicting the lateral strain of confined concrete	2015	Engineering Structures	151	[11]

Table 4 Top co-cited references of co-citation analysis

Title	Citations	Ref.
Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members	121	[19]
Finite Element Modelling of Concrete-Filled Steel Stub Columns under Axial Compression	105	[20]
Axial Capacity of Circular Concrete-Filled Tube Columns	84	[21]
Performance of Concrete-Filled Thin-Walled Steel Tubes Under Pure Torsion	71	[22]
Behavior of Centrally Loaded Concrete-Filled Steel-Tube Short Columns	68	[23]
Axially Loaded Concrete-Filled Steel Tubes	55	[24]
Specification for Structural Steel Buildings (2016)	46	[15]
Specification for Structural Steel Buildings (2010)	34	[16]
Technical Code for Concrete Filled Steel Tubular Structures	34	[17]
Theoretical Stress-Strain Model for Confined Concrete	30	[25]

Table 5 Top-Cited Journals in CFT Research

Journal	Publication	Citation	Citation/ Publication
Engineering Structures	137	4972	36.3
Thin-Walled Structures	96	4241	44.2
Journal of Constructional Steel Research	159	3747	23.6
Construction and Building Materials	52	1383	26.6
Structures	110	1063	9.7
Steel and Composite Structures	51	827	16.2
Composite Structures	26	744	28.6
Journal of Building Engineering	46	743	16.2
Journal of Structural Engineering (United States)	18	712	39.6
Journal of Composites for Construction	6	295	49.2
Total	701	18727	

Identifying these top-cited publications is essential for advancing research on CFT columns. These studies form the foundation for literature reviews and highlight key advancements in the field. Adopting their methodologies and models enhances research robustness and ensures alignment with current best practices.

The co-citation analysis measured how often two publications were cited together. It showed the connections between publications, even if they did not directly cite each other, and identified key works influential to later research.

VOSviewer highlighted 36 references out of 36,214 that were co-cited at least 20 times. The top 10, listed in Table 4, are considered foundational or highly relevant. Among them are three standards: ANSI/AISC 360-16 [15], ANSI/AISC 360-10 [16], and GB 50936-2014 [17]. This demonstrates that co-citation analysis can uncover crucial references beyond journal articles, including standards and guidelines, which traditional citation metrics might miss.

Note that ANSI/AISC 360-10 [16] has been replaced by ANSI/AISC 360-16 [15], with the latest version being ANSI/AISC 360-22 [18]. This highlights a limitation of co-citation analysis: it may overlook the most current standards or guidelines. The lag between the release of a new standard and its recognition in citation metrics arises because citations take time to accumulate, and the analysis depends on citation frequency in the literature. Therefore, it is essential to verify the most recent version of any standard before application or citation.

C. TOP JOURNALS

Most of the top-cited publications in Table 2 (7 out of 11) were in Engineering Structures, which had the highest citation count of 4,972 across 137 articles (Table 5). Notably, the Journal of Composites for Construction had fewer relevant articles but the highest citations per publication (49.2 citations per publication). Table 5 outlines the top-cited journals in CFT research, providing researchers with strong platforms to share their work. Submitting to reputable journals can enhance the accessibility, credibility, readership, and impact of research [3].

D. TOP AUTHORS

The top authors in CFT research were identified using three methods: the number of relevant publications, co-authorship analysis, and co-citation analysis. The number of publications reflected an author's productivity and engagement in the field, co-authorship analysis examined collaborative relationships, and co-citation analysis measured how often an author's work is cited alongside others. Together, these methods provided a comprehensive view of the authors' contributions to CFT research.

Table 6 highlights the top authors in CFT research based on their publication output. These authors had been highly productive, contributing extensively to various aspects of CFT research. Notably, Lu, Y. (Scopus ID: 56174805400), with 33 publications, had been particularly prolific in studying CFST columns. Lu's work covered a broad range of materials, including steel fibre reinforced, self-stressing, self-compacting, high-performance, geopolymer, and recycled concretes [26-30]. Lu employed various methods—experimental, analytical, and numerical—focusing on the compressive behaviour of CFST columns under both axial and eccentric loads [31-34].

Table 6 Authors with the most publications related to CFT research

Initial	Authors	Scopus ID	ORCiD	Publications
Lu, Y.	Lu, Yi Yan	56174805400		33
Ahmed, M.	Ahmed, Mizan	57196194410	0000-0001-5499-3181	25
Hassanein, M.F.	Hassanein, Mostafa Fahmi	36828752900	0000-0002-7931-6299	25
Ho, J.C.M.	Ho, Johnny Ching Ming	55805351400	0000-0002-2755-907X	25
Li, S.	Li, Shan	35220036700		21
Han, L.H.	Han, Lin-Hai	26643480100	0000-0001-8023-3282	20
Liang, Q.Q.	Liang, Qing Quan	7102360180	0000-0003-0333-2265	20
Hou, C.	Hou, Chao	54790893000	0000-0003-4245-9541	19
Wei, Y.	Wei, Yang	35194968400	0000-0003-2915-3898	19
Shao, Y.B.	Shao, YongBo	8679910900	0000-0003-2385-2305	18

The number of publications alone does not necessarily reflect an author's work's quality, impact, or collaborative nature. Researchers often collaborate with others, so a co-authorship analysis was conducted to understand these collaboration patterns. In this study, publications with more than nine authors were excluded based on the following considerations:

- The average number of authors per paper has been increasing by 2.28% annually, reaching 6.25 in 2024 [35], with a projected average of 8 by 2034 [36].
- Papers with 9 authors are in the 75th percentile of 101,580 papers analysed by [37], making this a reasonable cutoff.
- Honorary and guest authorship practices are common [38], and the number of guest and ghost authors has increased with more authors [39]. Many of these authors may not meet the Vancouver criteria for authorship [40] (Figure 5).
- The rise in author count is not solely due to more complex research [41]. This threshold helps exclude potential honorary or ghost authors while recognizing genuine contributions.

In VOSviewer, a threshold of at least five publications was set to ensure that only stable collaborations among authors were represented. Out of 2,608 authors, 151 met this threshold, resulting in the emergence of 18 clusters. The largest group comprised 94 authors, encompassing all the top 10 clusters except clusters 3 and 9 (Figure 6). These clusters were interconnected through specific key authors, highlighting collaborative networks within the CFT research community.

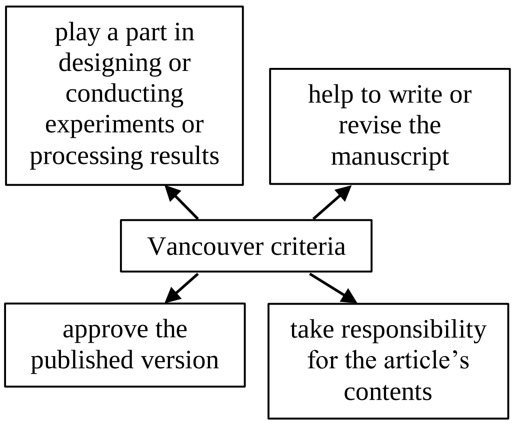

Figure 5 Vancouver criteria for authorship

In contrast, clusters 3, 9, and 14 operated independently, displaying strong internal collaboration and high citation counts. These independent clusters suggest that some research groups have developed distinct, self-sustaining areas of expertise within the field.

Additionally, many other researchers working on CFT are in smaller groups or even individually. This is likely due to challenges such as limited networking opportunities, insufficient funding, or a lack of institutional support. Table 7 lists the authors with the highest citations in each of the top 10 clusters, providing insight into the most influential researchers within these collaborative networks.

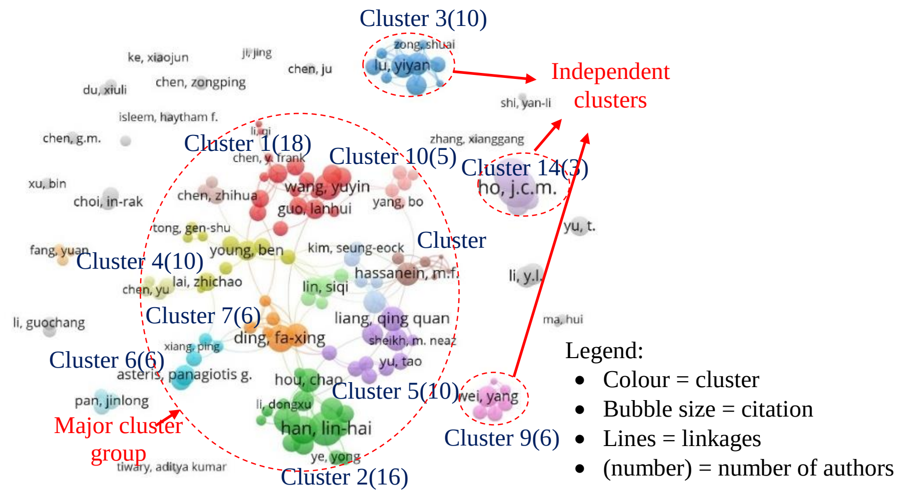

Figure 6 Network and clusters of co-authors of CFT research

Table 7 Top co-authors by clusters

Cluster	Author	Scopus ID	ORCiD	Citations
1	Wang, Yu Yin	7601491532	0000-0002-8641-9165	728
2	Han, Lin-Hai	26643480100	0000-0001-8023-3282	1457
3	Lu, Yi Yan	56174805400	-	578
4	Young, Ben	7402192398	0000-0003-2164-3964	371
5	Liang, Qing Quan	7102360180	0000-0003-0333-2265	622
6	Asteris, Panangiotis G.	7801583268	0000-0002-7142-4981	398
7	Ding, Fa Xing	8503582600	-	790
8	Hassanein, Mostafa Fahmi	36828752900	0000-0002-7931-6299	534
9	Wei, Yang	35194968400	0000-0003-2915-3898	414
10	Ayough, Pouria	57195234100	0000-0001-9187-1319	169

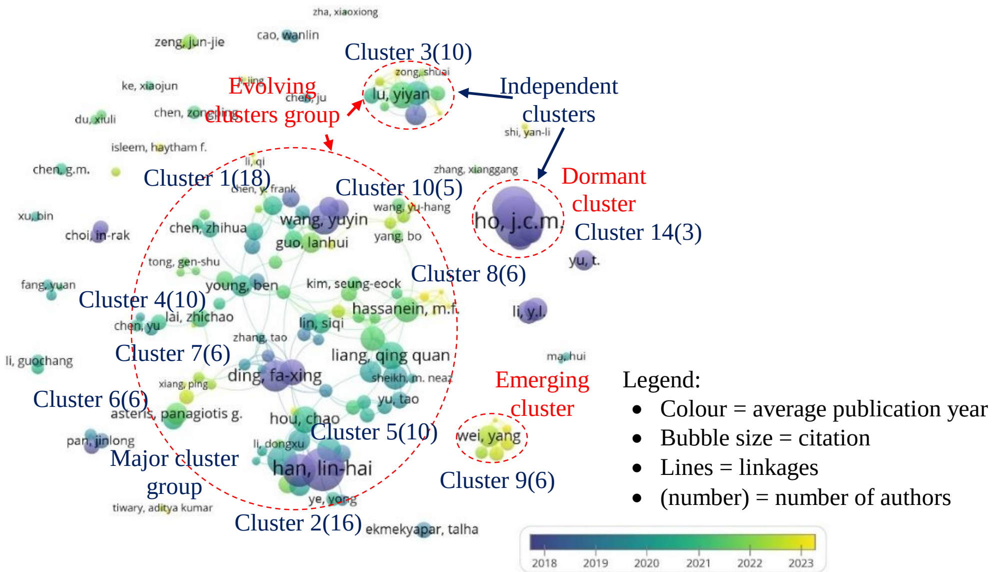

Figure 7 Network of co-authors by publication year

Figure 7 shows the co-authorship network by average publication years. (a) Cluster 14 is dormant, with researchers inactive in recent years but still holding high citations, highlighting its foundational influence on CFT research. However, new insights or methodologies from contemporary researchers across the network could potentially revitalize this cluster, further extending its influence in the field. (b) The major cluster group and cluster 3 include both contemporary and veteran researchers, reflecting ongoing research activity and knowledge transfer through collaboration. This mix of fresh perspectives and deep expertise could drive innovation and growth in the field. (c) Cluster 9 is emerging, with researchers newly venturing into CFT research and producing recent publications. This cluster has significant potential to grow large and influential. Although they may face challenges like limited mentorship and resources, these obstacles could foster creative solutions. Collaboration with contemporary researchers in the major cluster group or cluster 3 could help overcome these hurdles and further enhance their development.

It is noted that the largest cluster does not always correlate with the highest number of publications and citations. For instance, Cluster 1, despite having the most authors, has fewer publications and citations compared to Cluster 2, due to its lower citation per publication (Table 8). This discrepancy highlights the need for a co-citation analysis to better capture an author's influence within the academic community.

The co-citation analysis using VOSviewer showed that out of 21,406 cited authors, 473 had at least 50 citations. Five clusters were identified, with Han L.H., Tao Z., and Uy B. as the top three most co-cited authors (
Table 9). Notably, Han L.H. and Han L.-H. in Figure 8 represent the same person, resulting in the highest total citation count of 3,927. Recognising them is crucial, as it highlights the most influential researchers shaping the field, indicating key research trends and foundational works that guide the scholarly community.

Table 8 Total publication and citation by clusters

Cluster	Nos. of authors	Publication	Citation	Citation / publication
1	18*	138	3923	28.4
2	16	143*	6428*	45.0*
3	10	121	2164	17.9
4	10	74	1741	23.5
5	10	88	2844	32.3
6	6	50	1218	24.4
7	6	60	1801	30.0
8	6	63	783	12.4
9	6	52	1072	20.6
10	5	34	696	20.5

*Highest in each category.

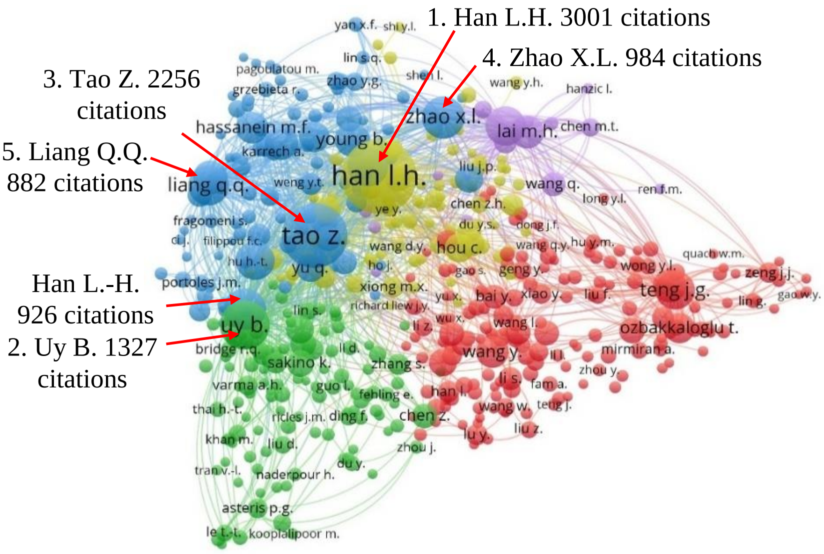

Figure 8 Top co-cited authors

Table 9 Top authors of co-citation analysis

Label	Author	Scopus ID	ORCiD	Co-cited citations
han l.h.	Han, Lin-Hai	26643480100	0000-0001-8023-3282	3927
tao z.	Tao, Zhong	7201884465	0000-0003-2117-2162	2256
uy b.	Uy, Brian	7003535945	0000-0002-4577-2915	1327
zhao x.l.	Zhao, Xiao Ling	55431252800	0000-0001-9659-3995	984
liang q.q.	Liang, Qing Quan	7102360180	0000-0003-0333-2265	882
li w.	Li, Wei	55044176900	0000-0001-7240-490X	871
ho j.c.m.	Ho, Johnny Ching Ming	55805351400	0000-0002-2755-907X	846
lam d.	Lam, Dennis	7201749620	0000-0002-2358-6927	826
teng j.g.	Teng, Jin Guang	7202560250	0000-0001-5161-4502	810
young b.	Young, Ben	7402192398	0000-0003-2164-3964	662

Table 10 Comparison of top authors by number of publications, co-author analysis, and co-citation analysis

Rank	Top publication authors	Top co-authors	Top co-cited authors
1	Lu, Yi Yan	Wang, Yu Yin	Han, Lin-Hai
2	Ahmed, Mizan	Han, Lin-Hai	Tao, Zhong
3	Hassanein, Mostafa Fahmi	Lu, Yi Yan	Uy, Brian
4	Ho, Johnny Ching Ming	Young, Ben	Zhao, Xiao Ling
5	Li, Shan	Liang, Qing Quan	Liang, Qing Quan
6	Han, Lin-Hai	Asteris, Panangiotis G.	Li, Wei
7	Liang, Qing Quan	Ding, Fa Xing	Ho, Johnny Ching Ming
8	Hou, Chao	Hassanein, Mostafa Fahmi	Lam, Dennis
9	Wei, Yang	Wei, Yang	Teng, Jin Guang
10	Shao, YongBo	Ayough, Pouria	Young, Ben

Table 10 compares the top authors based on the number of publications, co-authorship, and co-citation, each reflecting different aspects of research impact. The observations are:

- Authors like Lu, Y., Hassanein, M. F., Ho, J. C. M., Han, L. H., Liang, Q. Q., Wei, Y., and Young, B. appeared on multiple lists, signifying their diverse contributions to the field.
- These authors ranked differently across the lists, demonstrating their varying levels of influence in different dimensions. For instance, Han, L. H. was ranked 6th for publications, 2nd for co-authorship, and 3rd for co-citation. While not the most prolific in terms of publication count, Han was highly influential in collaborative research, with his work being widely recognized by the academic community.
- Han, L. H. and Liang, Q. Q. appeared on all three lists, highlighting their prolific output and significant impact through both collaboration and scholarly influence. In contrast, Lu, Y., Hassanein, M. F., Ho, J. C. M., Wei, Y., and Young, B. appeared on only two lists, showing their influence in specific areas.

E. LEADING COUNTRIES

CFT research includes contributions from 58 countries, with China leading in publications and citations (Table 11). China's output surpasses the combined total of the countries ranked 2nd to 11th by 26.8%. Meanwhile, Hong Kong and Australia, despite fewer publications, have a higher citation impact. Researchers can strategically position themselves by building academic networks and collaborating with high-impact regions to stay updated on developments, access cutting-edge research, and enhance the quality and visibility of their work.

In the co-authorship analysis, 28 out of 58 countries had at least five collaborative works with others. All countries except Jordan and Spain were interconnected in CFT research. China was the central hub, collaborating with 24 countries, excluding Turkey and Algeria, while Australia followed with collaborations with 17 countries (Figure 9). China and Australia produced the most publications in CFT research. Although the correlation may not always be exact, countries with high publication rates typically have more international collaboration. This is often due to (a) extensive research infrastructure and resources, (b) established research capability and reputation, and (c) diverse research interests that attract collaborations from other countries.

Table 11 Top countries or territories contributing to CFT research

Country / Territory	Publications	Citations	Citation / Publication
China	766	15032	19.6
Australia	170	6667	39.2
Hong Kong	78	3295	42.2
India	71	471	6.6
United Kingdom	59	1644	27.9
United States	50	1001	20.0
Egypt	44	665	15.1
Iraq	37	416	11.2
Vietnam	35	1163	33.2
South Korea	30	678	22.6
Japan	30	639	21.3

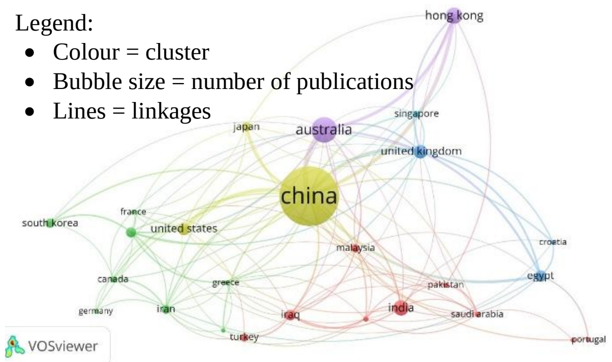

Figure 9 Country Collaboration network on CFT research

F. LEADING INSTITUTIONS

Table 12 and Table 13 highlight why China was the leading contributor to CFT research. Eight of the top 10 funding agencies were from China, with the National Natural Science Foundation of China funding 502 works—1.6 times more than the combined total of agencies ranked 2nd to 10th. This substantial financial support underscored China's strong commitment to advancing CFT research. Additionally, 9 of the top 10 institutions with the highest number of publications were from China, with the remaining institution (ranked 10th) being from Australia.

Table 12 Top funding agencies for CFT research

Funding agencies	Country	Publications
National Natural Science Foundation of China	China	502
Fundamental Research Funds for the Central Universities	China	61
Ministry of Science and Technology of the People's Republic of China	China	57
National Key Research and Development Program of China	China	51
China Postdoctoral Science Foundation	China	40
Australian Research Council	Australia	28
China Scholarship Council	China	20
Natural Science Foundation of Jiangsu Province	China	20
National Research Foundation of Korea	Korea	18
Natural Science Foundation of Guangdong Province	China	18

Table 13 Institutions with the highest number of publications

Affiliation	Country	Publications
Ministry of Education of the People's Republic of China	China	123
Beijing University of Technology	China	53
The Hong Kong Polytechnic University	Hong Kong, China	52
Harbin Institute of Technology	China	51
Chongqing University	China	47
Tsinghua University	China	45
Wuhan University	China	44
Central South University	China	41
Fuzhou University	China	34
University of Wollongong	Australia	32

As one of the largest construction markets globally [42], China is propelled by rapid urbanization and infrastructure development, creating a high demand for advanced construction technologies like CFTs. Widely used in high-rise buildings, bridges, and subways [2], CFTs offer several advantages, including the tube serving as stay-in-place formwork during construction [43], supporting construction loads during concrete casting [44], and reducing material costs and construction time (He et al., 2018). By 2018, China had constructed over 400 arch bridges using CFTs [45]. These reasons could explain China's commitment to the research and development of CFTs.

China, as a leading global manufacturer [46], has vast production capabilities, making raw materials for CFTs, like steel tubes and concrete, both accessible and affordable. This availability likely encourages the widespread use of CFTs in construction, further stimulating research interest.

G. KEYWORDS AND TEXTUAL ANALYSES

The title concisely describes a publication's content, the abstract briefly summarises it, and keywords highlight the main topics or concepts. The current research landscape, common themes, and emerging trends in CFT can be identified by analysing the frequency and co-occurrence of terms in these elements. This deepens understanding and guides future research directions.

Co-occurrence analysis via VOSviewer identified 4,778 keywords, with 107 appearing in 30 publications, reflecting their significance in the research community. This subset highlights core topics within the field, with frequent keywords—'tubular steel structures,' 'concretes,' 'columns,' 'tubes,' and 'axial compression'—showing a focus on the structural behaviour of steel tube columns filled with concrete, especially under axial compression (Table 14). While these keywords reveal a concentrated research interest, the wide range also suggests a diverse landscape with potential gaps and emerging trends for further investigation.

Table 14 Top co-occurrence author keywords identified by VOSviewer

Author keywords	Occurrences
Tubular steel structures	847
Concretes	524
Columns (structural)	361
Tubes (components)	351
Axial compression	290
Compressive strength	289
Finite element method	230
Bearing capacity	213
Concrete-filled	182
Reinforced concrete	177

Error! Reference source not found. visualizes the evolution of CFT research, highlighting foundational work and emerging trends. Foundational keywords such as 'confinement effect,' 'confined concrete,' 'composite structures,' and 'stress-strain curves' establish the groundwork for understanding CFTs, focusing on how concrete and steel interact in tubular structures. Emerging trends like 'machine learning,' 'finite element analysis,' 'carbon fibre-reinforced plastic,' and 'steel corrosion' reflect a shift towards integrating advanced materials and modern computational techniques. This transition shows a growing emphasis on innovative technologies for predictive modelling, detailed simulations, and addressing specific

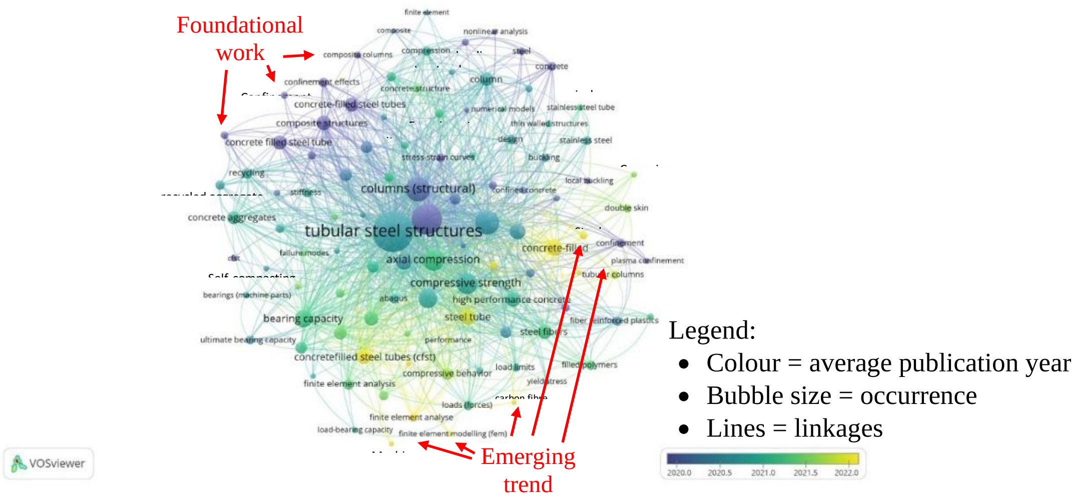

Figure 10 Co-concurrent analysis for author keywords

challenges such as steel corrosion. The progression from fundamental concepts to cutting-edge research underscores an ongoing evolution in CFT studies, aimed at enhancing performance and tackling new challenges.

VOSviewer separately counted similar keywords. For example, variations like 'cfst,' 'concrete filled steel tube,' and 'concrete-filled steel tubes (cfst)' were classified into 10 different categories. To address this, the 107 keywords identified by VOSviewer were consolidated into 70, with the highest co-occurrence keywords listed in Table 15, slightly reshuffling their ranking. Despite this, the main research themes remained unchanged.

Table 15 Top co-occurrence author keywords after consolidation

Author keywords	Occurrences
Concrete filled steel tube columns	1013
Tubular steel structures	847
Concrete	595
Compressive testing/strength/behaviour	579
Column	498
Finite element analysis/method	451
Axial compression/load	421
Ultimate strength/bearing capacity	419
Tubes (components)	351
Composite column/structure	342

Figure 11 highlights the distinct research themes within each cluster:

- Cluster 1 (red): The largest cluster, focusing on the buckling behaviour of concrete-filled steel tubes (CFT) as columns, using experimental, finite element, nonlinear, and numerical analyses.
- Cluster 2 (green): The second-largest cluster, covering CFT behaviour, including confinement, strain, stiffness, deformation, ductility, and failure modes, with studies on recycled aggregate and self-compacting concrete infills.
- Cluster 3 (blue): Recent studies on CFTs, including carbon fibre-reinforced plastics, employing advanced techniques like finite element analysis and machine learning.
- Cluster 4 (yellow): Research on alternative materials for CFTs, such as fibre-reinforced plastics, high-performance concrete, and steel fibres.
- Cluster 5 (purple): The smallest cluster, focusing on corrosion resistance in CFTs, with solutions like stainless steel and double-skin designs.

The co-occurrence analysis examined connections between terms in titles and abstracts using binary counting, which considers only the presence or absence of a term in a publication, not its frequency. Out of 15,769 terms, 237 appeared in at least 30 publications. VOSviewer then selected the 60% most relevant, resulting in 142 terms.

Figure 12 classifies the terms by clusters:

- Cluster 1: The largest cluster focused on CFST (Concrete-Filled Steel Tube) columns, comparing them with design codes like ACI-318 [47], AISC [15], and EC4 [48]. Studies used numerical analysis, experiments, and artificial neural networks to predict CFST performance under various conditions, including eccentric loading and different D/t ratios.
- Cluster 2: This cluster studied load-displacement curves, mechanical properties, and failure modes of steel CFTs, including those under eccentric loads. It also explored parameters like slenderness ratio and the use of recycled aggregate concrete as infill.
- Cluster 3: Focused on the axial compression behaviour of CFTs made of FRP (Fiber Reinforced Polymer), including CFRP, GFRP, steel fibres, and UHPC, with models developed to predict their performance.
- Cluster 4: Studied the compressive behaviour of CFDST (Concrete-Filled Double Skin Steel Tubes) and CFSST (Concrete-Filled Stainless Steel Tubes) using FE models to analyse the interaction between inner and outer tubes under compression.

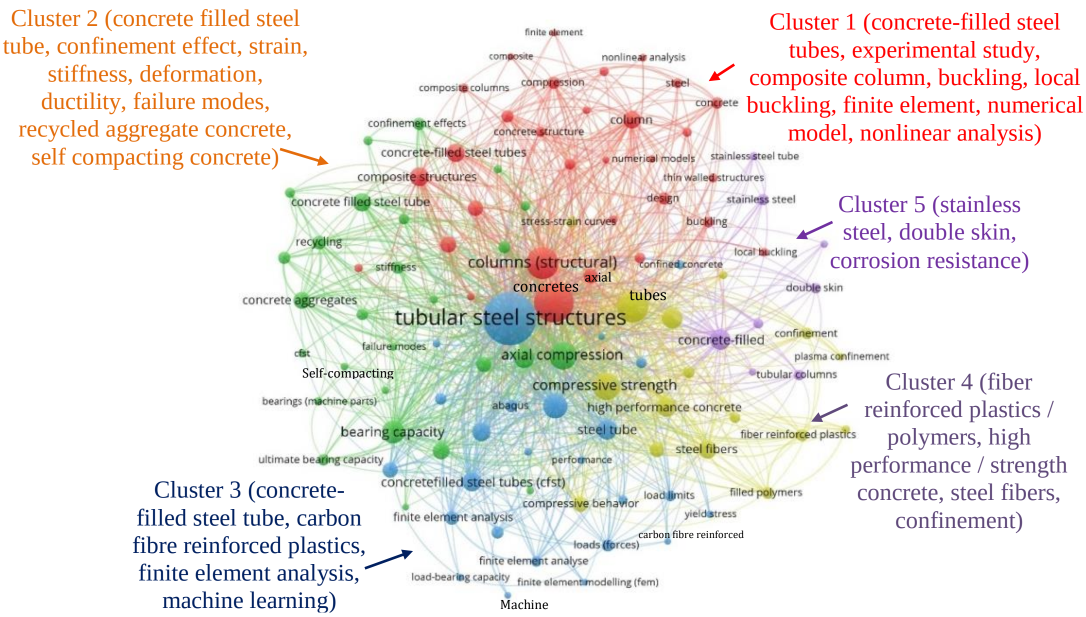

Figure 11 The research themes by clusters (based on authors' keywords)

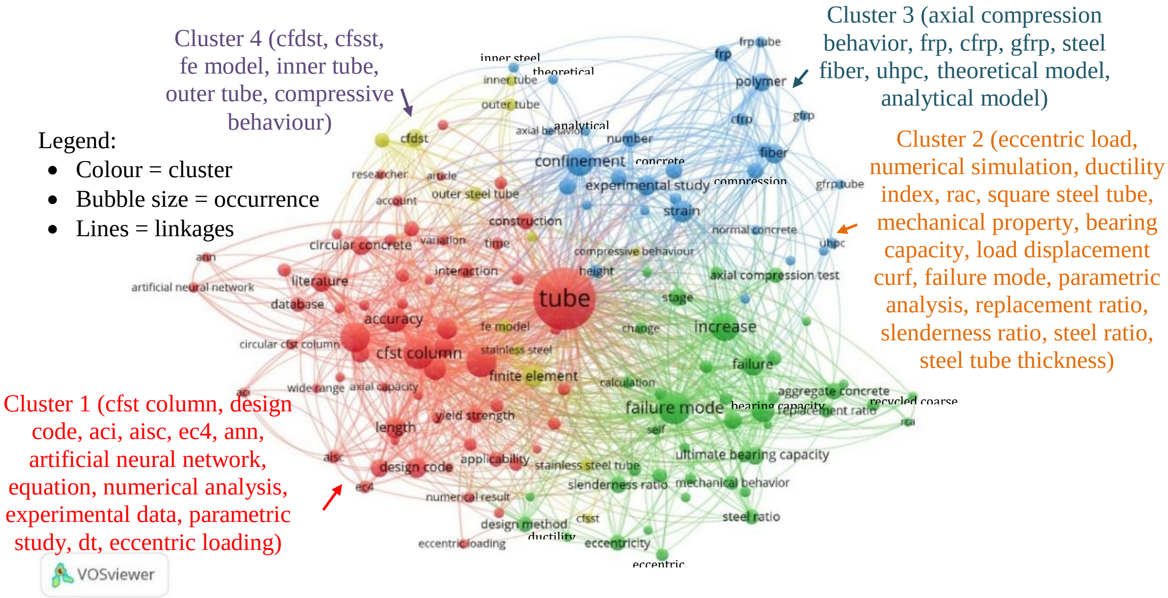

Figure 12 Research themes by cluster (based on titles and abstracts)

From the titles, abstracts, and keywords, the following insights emerge:

- Design Codes: ACI-318 [47], AISC [15], and EC4 [48] are key references for CFT research.
- Alternative Designs: CFDST with double tubes (external and internal) provides a design option beyond conventional CFT.
- Materials: Tubes can be made from stainless steel or FRP (e.g., CFRP, GFRP), with infill materials like UHPC, HPC, high-strength concrete, RAC, and concrete with steel fibres.
- Research Techniques: Studies employ experimental tests, numerical and analytical models, nonlinear analysis, finite element analysis, and artificial neural networks.
- Loading Conditions: CFT behaviour is examined under axial and eccentric loads.
- Mechanical Properties: Research focuses on stress-strain response, confinement effects, bearing capacity, load-displacement curves, stiffness, deformation, ductility, and failure modes.
- Parametric Analysis: Key parameters include replacement ratio, slenderness ratio, steel ratio, and tube thickness.

These insights guide researchers to focus on critical areas, refining their studies to ensure relevance and comprehensive contributions to the advancement of CFT technology.

EVOLUTION AND EMERGING TRENDS

Interest in integrating innovative materials into CFTs is growing, offering alternatives to traditional concrete and steel. Table 16 highlights top-cited publications by material, with FRP and HPC receiving notable attention due to their early adoption in CFT applications. As sustainable development gains momentum, emerging materials like RAC and SWSSC are also attracting increasing interest, contributing to a broader research landscape. Despite the growing focus on alternative materials, concrete and steel remain the primary materials in CFTs.

Among the 81 unique publications listed in Table 16, 15 (18.5%) involved more than one material, as shown in Table 17. This suggests new avenues for innovation by optimizing CFT performance through various material combinations. With many building materials beyond those listed, numerous unexplored or underexplored combinations present significant opportunities, each with unique characteristics and performance benefits. Some researchers, such as [29] and [28] have even used three materials in their CFT studies. The inclusion of multiple materials increases the complexity of CFT research, as each new material introduces additional variables to analyse. Advanced modelling techniques, such as machine learning, offer a promising approach to efficiently analyse large datasets and optimize material pairings.

Table 16 Classifications of publications by CFT materials

Component	Materials	Top citation publications	Total citation
Tube	Fibre-reinforced polymer (CFRP, GFRP, BFRP)	[12, 13, 49–56]	1192
	Stainless steel	[12, 57–65]	917
	Plastic (PVC, UPVC, HDPE)	[66–75]	139
Infill	High-performance concrete (HPC)	[50, 76–84]	1144
	Recycled Aggregate Concrete (RAC)	[7, 53, 55, 57, 85–90]	891
	Seawater and sea sand concrete (SWSSC)	[12, 49, 50, 60, 65, 91–95]	682
	Steel fiber reinforced concrete	[28, 29, 79, 96–102]	348
	Self-compacting concrete (SCC)	[28, 29, 103–110]	330
	Self-stressing concrete	[28, 29, 96, 107, 109, 111–113]	247
	Geopolymer concrete (GPC)	[88, 114–122]	153

Table 17 Material combinations in CFT

Ref.	Fibre-reinforced polymer (FRP)	Stainless steel	High-performance concrete	Recycled Aggregate Concrete (RAC)	Seawater and sea sand	Steel fiber	Self-compacting concrete	Self-stressing concrete	Geopolymer concrete
[29]						X	X	X	
[28]						X	X	X	
[50]	X		X		X				
[12]	X	X			X				
[60]		X			X				
[55]	X			X					
[79]			X			X			
[57]		X		X					
[109]							X	X	
[65]		X			X				
[96]						X		X	
[107]							X	X	
[53]	X			X					
[88]				X					X
[49]	X				X				

The emergence of machine learning (ML) techniques is noteworthy. The authors' keywords indicating their use include: Artificial neural network (ANN), Gene programming/Gene-expression programming, Genetic algorithms, Feedforward neural network, Hybrid machine learning, Invasive weed optimization, Swarm intelligence, Metaheuristic algorithms, Adaptive neural-fuzzy inference system, Artificial bee colony, Support vector regression, Particle swarm optimization, XGBoost, Random forest, Sine cosine algorithm, Surrogate model, GMDH approach, Seeker optimization algorithm, Soft computing, SHAP (SHapley Additive exPlanations), Optimization algorithms, Grey wolf optimizer, Moth-flame optimization, Social spider algorithm, Whale optimization algorithm (WOA), Active learning (AL), Long short-term memory network (LSTM), and Machine-aided intelligent design. This list reflects a diverse range of ML techniques but is not exhaustive and does not preclude the emergence or application of new algorithms in CFT research.

Table 18 highlights publications related to ML, arranged by descending citation count. Despite its significant potential, this research niche has fewer citations than traditional approaches like experimental, analytical, and numerical studies. This could be due to the relative novelty of ML and the ongoing development of its applications in CFT research. The academic community often takes time to fully embrace new techniques, which can result in a delay between the adoption of ML methods, their publication, and subsequent recognition.

Table 18 Publications adopting machine learning technique in CFT research

Title	Citation	Ref.
Practical artificial neural network tool for predicting the axial compression capacity of circular concrete-filled steel tube columns with ultra-high-strength concrete	107	[83]
Evaluating structural response of concrete-filled steel tubular columns through machine learning	87	[123]
Optimization of artificial intelligence system by evolutionary algorithm for prediction of axial capacity of rectangular concrete filled steel tubes under compression	78	[124]
A novel integrated approach of augmented grey wolf optimizer and ANN for estimating axial load carrying-capacity of concrete-filled steel tube columns	70	[125]
Prediction of axial load capacity of rectangular concrete-filled steel tube columns using machine learning techniques	64	[126]
Efficiency of three advanced data-driven models for predicting axial compression capacity of CFDST columns	63	[127]
Evaluation of the ultimate eccentric load of rectangular CFSTs using advanced neural network modeling	61	[128]
Strength prediction of circular CFST columns through advanced machine learning methods	51	[129]
Predicting the axial compressive capacity of circular concrete filled steel tube columns using an artificial neural network	43	[130]
Optimization design of rectangular concrete-filled steel tube short columns with Balancing Composite Motion Optimization and data-driven model	42	[131]

Machine learning (ML) has gained popularity due to advancements in computing power, the availability of big data, and improvements in algorithms such as deep learning, which have expanded its applications. However, the complexity of ML techniques can be daunting for researchers with limited computing experience, potentially deterring them from exploring this field. Additionally, many ML models are considered 'black boxes,' which makes it challenging to interpret the underlying processes and understand the fundamental principles and mechanisms within CFT.

LIMITATIONS

This study provides valuable insights into the current landscape and emerging trends in CFT research but has some limitations. An overreliance on quantitative metrics may overshadow the importance of research quality, originality, and relevance to real-world problems. While bibliometric metrics offer valuable quantitative insights, they may lack qualitative context, potentially overlooking critical aspects such as underlying theories, research methodologies, the robustness of evidence, real-world challenges, and the broader impacts of the research.

The accuracy of the bibliometric analysis depends on the quality and completeness of the data. This study analysed only metadata from the Scopus database, excluding data from other sources such as Web of Science, SpringerLink, Directory of Open Access Journals, ASCE Library, and Engineering Village. While analysing multiple databases could offer a more comprehensive view, challenges arise from potential overlaps among sources. For example, the Web of Science and Directory of Open Access Journals may cover significant content already included in Scopus. Nevertheless, Scopus's extensive dataset, comprising 1,154 publications in this case, provided sufficient data for identifying influential authors and publications for an in-depth literature review.

Additionally, issues such as incomplete or inaccurate citations, variations in author names, and inconsistencies across databases can impact the results. For example, the author's initial 'Li W.' might refer to different individuals, such as 'Li, Wei' or 'Li, Weijie'. Specifically:

- In [132] and [34], 'Li W.' referred to 'Li, Wei' and 'Li, Weijie', respectively.
- In [133], 'Li, Weijie' was listed as 'Li, W. J.'

These variations posed challenges for VOSviewer, which struggled to accurately categorize the different instances of 'Li W.'. As a result, citation counts for 'Li W.' may be inflated, while counts for 'Li, W. J.' might be underestimated. Despite these issues, the study concentrated on identifying influential authors rather than exact citation counts. It offers a valuable starting point for researchers interested in CFT research, assisting them in locating key authors and relevant publications for their literature review.

This study relied heavily on bibliometric analysis, emphasising highly cited authors and publications. This approach may favour more productive authors and popular fields, potentially overlooking significant but less cited work, including emerging or niche research areas. Additionally, temporal bias can affect the analysis, as older publications have had more time to accumulate citations, making them appear more influential than recent publications.

Similarly, veteran researchers who are no longer active in the field might still rank among the top-listed influential authors due to their earlier contributions, even if their current impact is limited. However, this is not necessarily undetectable. For example, researchers like Han L.H., Ho J.C.M., Ding F.X., and Zhao X.L., who are top-listed in Table 10, may be considered veteran researchers based on the average publication years of their work (Figure 13). Their current activity in the field may require further verification to accurately assess their ongoing impact.

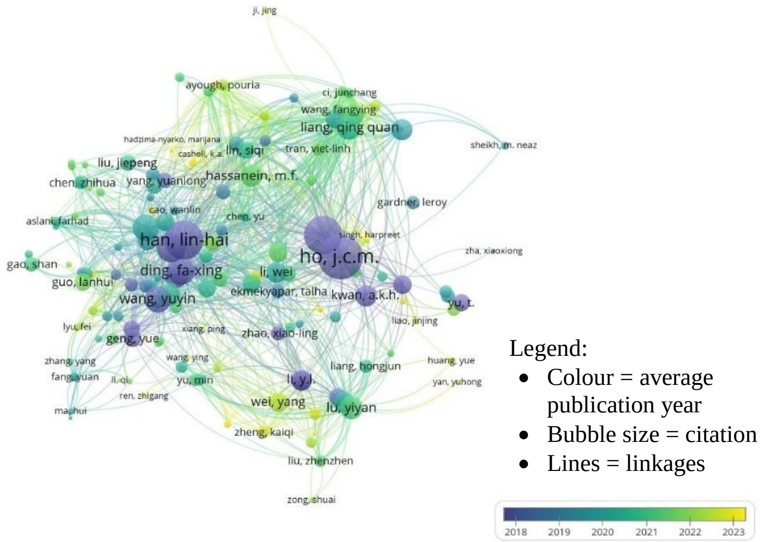

Figure 13 Authors by average publication years

Guest or ghost authorship can complicate credit attribution. To address this issue and prevent distortion in the analysis, publications with more than nine authors were excluded from the co-authorship analysis. However, this approach may not fully eliminate publications with fewer than nine authors that include guest authors. Additionally, it might inadvertently exclude some publications with more than nine authors that do not involve guest authors.

The sampling design also significantly influences the findings of this study. The search strategy restricting the publication years to 2014-2024 may inadvertently exclude fundamental work published earlier. For instance, Han L.H. had 20 relevant publications during this period, ranking number six in Table 5. However, if earlier works were included, Han L.H. would have topped the list with 41 publications. The study focused on the most recent decade to capture current research, new methodologies, and emerging trends while avoiding issues with older, less relevant data.

CONCLUSIONS

This study analyses 1,154 publications on concrete-filled tubes (CFTs) from the Scopus database (2014–August 2024), offering a comprehensive overview of current research trends. The sharp increase in publications reflects a growing interest in CFTs within structural engineering.

China leads globally in CFT research, dominating both publication output and citations. Eight of the top 10 funding agencies and nine of the top 10 prolific institutions are based in China, with many influential authors driving advancements in the field.

The study highlights the rising interest in alternative materials such as FRP (Fiber-Reinforced Polymer), stainless steel, HPC (High-Performance Concrete), RAC (Recycled Aggregate Concrete), and SWSSC (Seawater Sea Sand Concrete), opening new possibilities for multi-material combinations in CFTs. Machine learning techniques are increasingly being applied in CFT research, though their full potential remains untapped.

Overall, this analysis underscores the dynamic nature of CFT research, suggesting that continued exploration of new materials, innovative combinations, and advanced computational methods will be pivotal for future innovations in structural engineering.

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