

A Bibliometrics of the Analysis Methods of 3D Printed Concrete Structures

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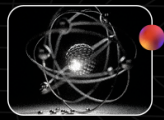
Abstract: 3D concrete printing (3DCP) has revolutionized the construction industry, allowing for the production of complex geometries with greater efficiency and sustainability. This is despite ongoing challenges with structural reliability and long-term performance, which are due to the material's anisotropic properties and layer interfaces. This study performed a bibliometric analysis of the literature on the structural analysis of 3DCP, using VOSviewer to identify research trends and gaps. The methodology included a keyword search in the Scopus database, which resulted in 108 selected articles after a rigorous screening process. The results indicate a significant increase in 3DCP research since 2018, with a projected peak of 40 articles published in 2025. A co-occurrence analysis of keywords revealed a concentration on "concretes," "concrete printings," and "finite element method," highlighting research into material failure and behavior. The 108 works, authored by 374 individuals, were distributed across 8 clusters, with 23 papers showing co-authorship. Maximiliano Cremonesi, Liberato Ferrara, and Giacomo Rizzieri had the strongest collaborations between 2024 and 2025. China and the United States lead in publications, with 37 and 12 articles, respectively, and China also leads in collaborations with 14. The Journal of Building Engineering was the most relevant journal, with 11 publications. Despite these advancements, the study points to significant gaps, such as the need for more sophisticated numerical models to simulate interlayer and multi-scale interactions. The integration of structural reinforcements and a better understanding of the long-term durability of 3DCP are also critical challenges. Furthermore, there is a major opportunity for research in multifunctional materials and the application of artificial intelligence and machine learning to optimize design and predict performance, thereby boosting sustainability in 3DCP.

Keywords: 3D Concrete Printing. Structural analysis. Finite Element Method. Bibliometrics.

1. Introduction

The civil construction industry has witnessed a significant transformation with the advent of 3D concrete printing (3DCP), an additive manufacturing technology that offers the potential to revolutionize how structures are designed and built [1-3]. By enabling the production of complex geometries with greater efficiency and sustainability, 3DCP represents a promising advance compared to conventional construction methods [4-5]. This innovation not only accelerates the construction process but also minimizes material waste and can reduce labor costs, making it an area of growing interest in global research and development [6-8]. However, the widespread implementation of 3D-

printed concrete structures still faces challenges, particularly regarding their structural reliability and long-term performance [9-11]. Unlike traditional cast concrete, 3DCP exhibits distinct characteristics due to the layer-by-layer deposition process, such as the anisotropy of mechanical properties and the presence of interfaces between printed layers [12-13]. Structural analysis, therefore, plays a crucial role, providing the necessary tools to predict performance under different loading conditions and to optimize design and printing parameters. Numerical modeling, and in particular the finite element method (FEM), emerges as an indispensable tool for investigating the behavior of 3D-printed concrete structures [10], [14-17].



Methods like FEM allow for the simulation of the layer extrusion and deposition process, the evaluation of the hardened properties of printed concrete [18], and even rheological and fresh-state properties [14], [19]. Recent studies have explored various approaches to model the anisotropic behavior and the phenomena of damage and plasticity in 3D-printed materials [20-24].

In this context, this research aimed to conduct a bibliometrics of the literature on the structural analysis of 3D-printed concrete, strictly following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [25] to ensure the transparency and reproducibility of the methodology. The VOSviewer software [26] was used to map research trends, identify the main areas of investigation, the most influential authors and journals, and the existing collaboration networks in the scientific community.

2. Methodology

To conduct the research, the PRISMA guidelines were strictly followed [25]. This three-phase approach—search, selection, and data analysis—allowed not only for the identification and critical selection of research literature but also for the evaluation and generation of new perspectives on the analysis of 3D-printed concrete structures.

Initially, the data search phase, conducted in June 2025, used a keyword search in the Scopus

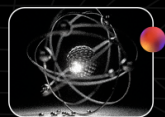
database by evaluating titles, abstracts, and finally, reading the full text.

The search terms were selected to cover the main areas of interest for the review and were combined using Boolean operators (AND, OR) to maximize the scope and relevance of the results. The combination of keywords and Boolean operators adopted was "3D Concrete Printing" AND "Finite element" AND ("structural analysis" OR "experimental testing" OR "experimental program" OR "numerical simulation" OR "numerical modeling"), to identify relevant articles in the Title, Abstract, or Keywords fields. The articles resulting from this search were then analyzed and selected based on the PRISMA criteria for subsequent evaluation. The publication period was not defined, allowing all articles related to the topic to be searched up to the present.

The metadata of the eligible articles included, such as authors, keywords, citations, and co-citations, were collected and processed. The VOSviewer software (version 1.6.15) [25] was the central tool for visualizing and analyzing these bibliometric relationships.

VOSviewer enabled the creation of maps based on keyword co-occurrence, which is fundamental for identifying emerging themes and key research areas.

Additionally, co-authorship analysis was employed to map the collaboration networks among researchers and institutions. This allowed for the identification of prominent research



groups and the extent of collaborations in the field.

Another crucial aspect was the analysis of author co-citation, a sociographic analysis of the countries of origin of the research, and journals. By examining which authors or publications are frequently cited together, VOSviewer helped identify the most influential works and high-impact journals that have shaped the development of the field.

Finally, VOSviewer's ability to visualize the evolution of research clusters over time was explored. This allowed for tracking the emergence of new sub-areas, the decline of others, and changes in research priorities, providing a dynamic understanding of the progress in the study of structural analysis of 3D-printed concrete.

3. Results and Discussion

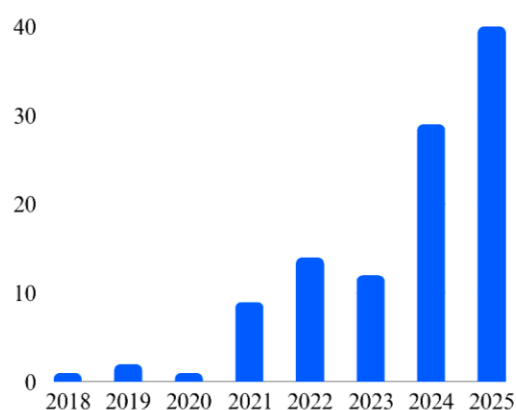
The results of the bibliometric analysis offered a synthesis of the current state of research and are critically presented and discussed in this section, highlighting emerging trends, main topics of investigation, and existing knowledge gaps.

3.1. Descriptive analysis

After applying the PRISMA protocol, 108 articles were included for the bibliometric analysis. This analysis reveals that research on the structural behavior of 3DCP began in 2018, as shown in Figure 1. This first paper presented a numerical and experimental analysis of the mechanical behavior of fresh 3D-printed

concrete [27]. It is important to note that older studies involving 3DCP are found in the literature, but under a broader approach involving 3D printers and printing systems, material research, equipment and technology, design, and impacts on the civil construction sector [28].

Figure 1. Descriptive analysis of publications.



Research involving structural analysis, whether experimental, numerical, or combined, has intensified over the last five years, with a maximum of 40 articles published in 2025.

3.2. Keyword Co-occurrence

The mapping of keyword co-occurrence allowed for the identification of distinct clusters, indicating the main areas of investigation. In total, 1033 keywords were used, and 62 reached a minimum volume of five occurrences. Figure 2 presents the sociogram of this analysis. Table 1 shows the top 15 keywords analyzed.

The 62 items presented in the sociogram in Figure 2 contain 662 links and a total link strength of 4474. For example, "concretes" appears in the center of Figure 2, with the largest number of links (329).

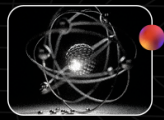
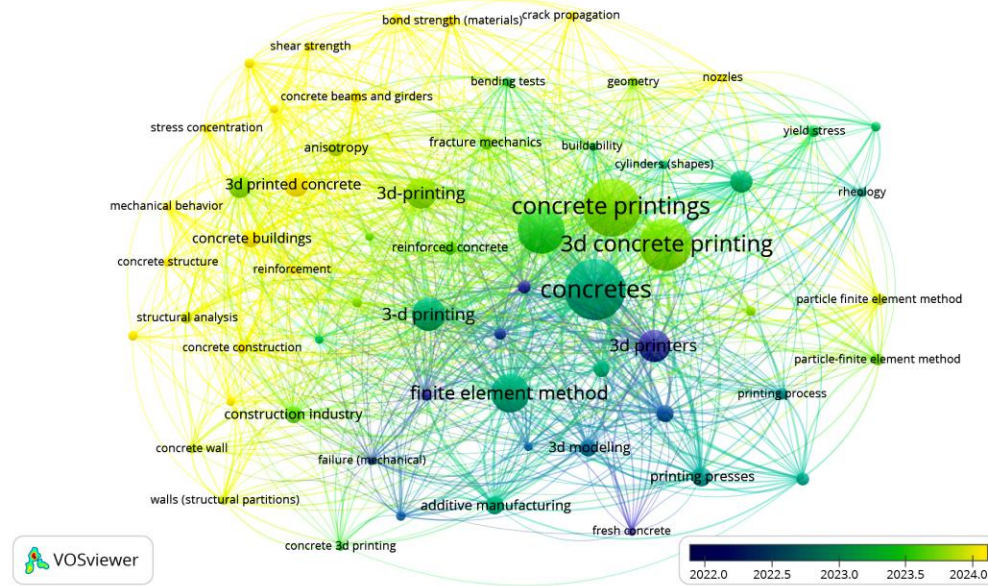


Figure 2. Sociogram of co-occurrence of keywords.



The colors in this figure indicate the research periods, with yellow signifying more recent research (2024) and purple indicating older research (2022).

Table 1. Co-occurrence of keywords.

S n°	Keyword	Occurrences	Total Link Strength
1	concretes	48	329
2	concrete printings	45	283
3	3d concrete printing	40	222
4	3d printing	36	249
5	finite element method	28	219
6	3-d printing	24	175
7	3d printers	23	155
8	3d-printing	22	152
9	3d printing concrete	17	90
10	extrusion	15	121
11	compressive strength	15	95
12	printing presses	13	104
13	additive manufacturing	12	85
14	numerical model	11	93
15	construntion industry	11	82

3.3. Co-authorship Analysis

The co-authorship analysis allowed for the identification of various groups of authors

researching a common theme. The 108 analyzed works were written by 374 authors. Considering a minimum of 3 works written by each author, 23 works were distributed into 8 clusters, as shown in Figure 3. Additionally, 85 links were observed between the authors with a total link strength of 104. The strongest links were from authors Maximiliano Cremonesi, Liberato Ferrara, and Giacomo Rizzieri, with a total link strength of 8 each, and their works were published between 2024 and 2025.

3.4. Sociographic Analysis of Countries

The analyzed works originate from 35 different countries, with China and the United States having the highest number of publications, at 37 and 12, respectively. The countries with the most collaborations were China, with 14, and Australia, with 13. Figure 4 shows the results of the sociographic analysis between countries.

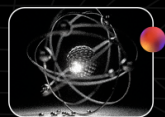


Figure 3. Sociogram of co-authorship.

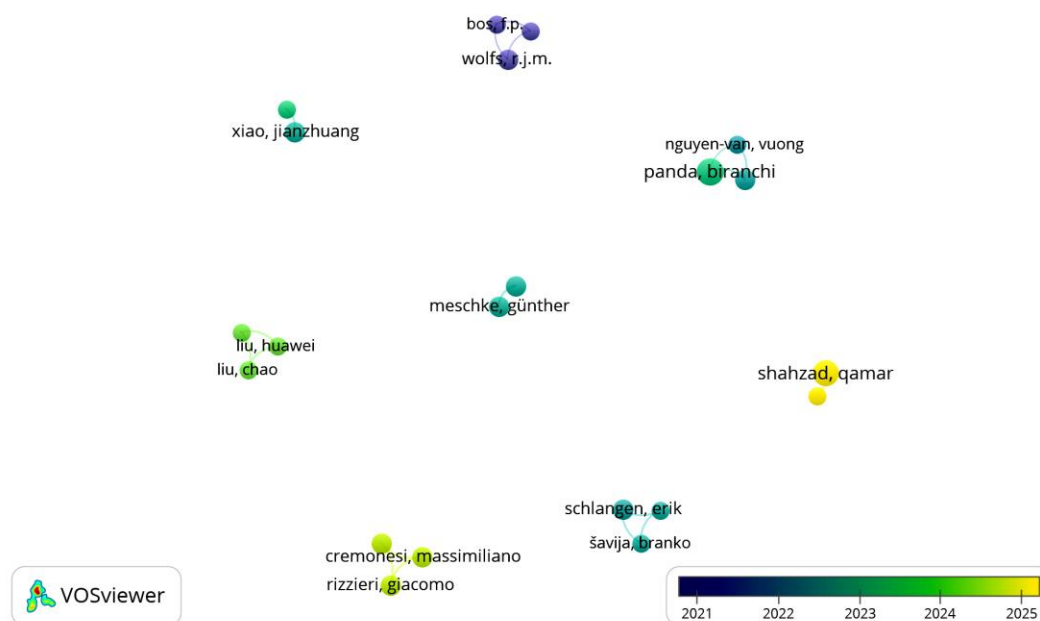
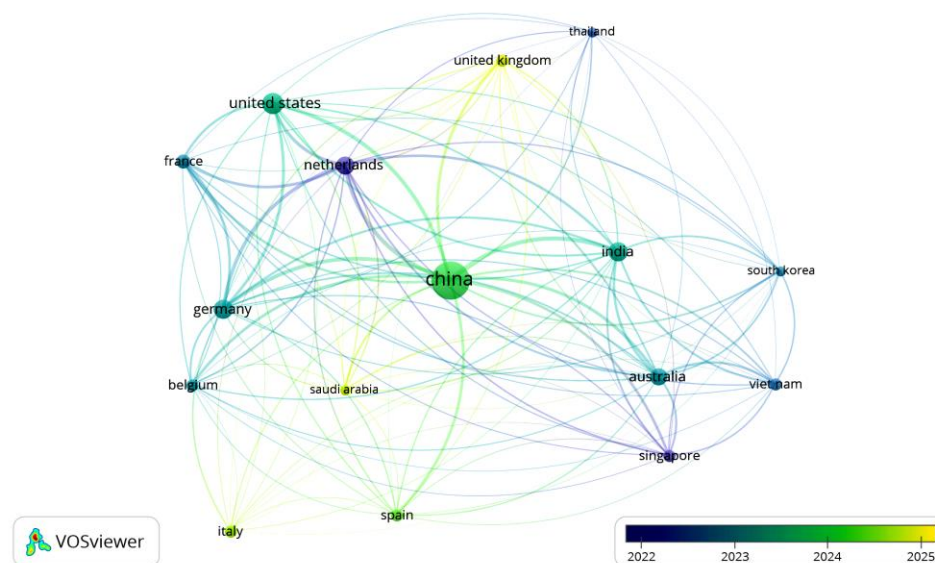


Figure 4. Sociogram of co-authorship.



3.5. Sociographic Analysis of Sources

This analysis made it possible to identify the most relevant journals on 3DCP structural analysis. The articles were published in a total of 41 journals, and by considering a minimum of 2 articles and one citation per journal, this sample was reduced to 19 and is presented in Figure 5.

The most relevant journal was the Journal of Building Engineering, with 11 publications, 315 citations, and a total link strength of 7.

4. Research Gaps and Future Directions

The bibliometric investigation identified growing advances in research as well as the

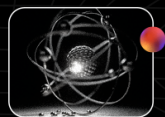
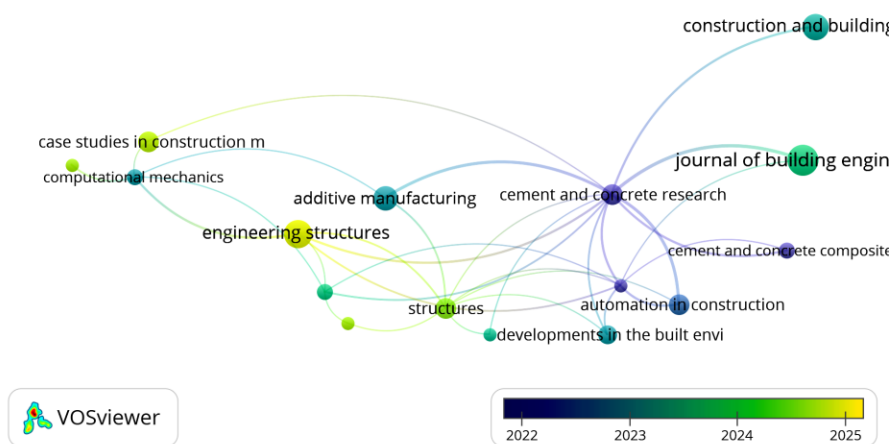


Figure 5. Sociogram of the sources.



main gaps related to 3DCP structural analysis. The keyword analysis found a concentration in research related to the failure analysis of 3DCP in its hardened state and methods based on fluid dynamics for the fresh state.

The development of more sophisticated numerical models that better simulate interlayer interactions and multiple length scales (micro, meso, macro) is a promising future direction.

Models based on Smoothed Particle Hydrodynamics (SPH) [29] and the Particle Finite Element Method (PFEM) [14, 19] are being developed to simulate the flow and deformation behavior of cement paste during 3D printing, considering the material's rheological behavior and properties.

Integrating structural reinforcement into 3D-printed concrete is a significant challenge due to the anisotropy and interfaces created by layer-by-layer deposition. This makes it difficult to incorporate conventional steel bars and properly orient fibers [24, 29-30]. Optimized reinforce-

ment designs aim to improve the structural performance and ductility of 3DPC.

There is a knowledge gap regarding the long-term performance and durability of 3DPC structures, despite the contribution of numerical simulation to understanding failure mechanisms. It is essential to investigate how the properties of 3D-printed materials evolve over time and the impact of environmental factors on structural integrity.

The bibliometric analysis also identified a gap in the integration of artificial intelligence (AI) and machine learning (ML). Such tools offer transformative potential for predicting performance and optimizing printing processes.

5. Final Considerations

This study performed a bibliometric analysis on the structural analysis of 3D-printed concrete (3DCP). Research in the field has grown significantly since 2018, with a peak in 2025, demonstrating the importance of 3DCP in construction.



Keyword analyses focused on "concretes," "concrete printing," and "finite element method," indicating advances in the study of failure and material behavior. Co-authorship, country, and journal analyses confirm international collaboration and the influence of publications like the *Journal of Building Engineering*.

Despite the progress, the study points to several gaps. More sophisticated numerical models are needed for interlayer and multi-scale interactions, with methods like peridynamics and SPH showing promise. There is also a significant opportunity for multifunctional materials and the application of AI and ML to optimize design and predict performance, which would drive sustainability in 3DCP.

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