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STRUCTURAL PERFORMANCE OF BRIDGE SEGMENTS BY 3D CONCRETE PRINTING UNDER STATIC CYCLIC LOADING

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Abstract

This study investigates the structural performance of 3D-printed concrete bridge segments resembling a viaduct box girder bridge at a 1:10 scale. This experimental study included fabricating of 3D-printed concrete bridge segments and conducting load bearing, deformation, and durability tests. The study aims to comprehensively evaluate the structural performance of plain 3D printed concrete bridge segments and to contribute valuable insights into future reinforcement techniques to enhance their strength and ductility response. Findings indicate that a 900 mm non-reinforced 3D-printed segment achieved about 65% of the load-bearing capacity of traditional reinforced concrete segment of the same size, with a maximum load capacity of 90 kN compared to the ACI318-19 design capacity of 135 kN, leading to a brittle failure mode. The maximum deflection recorded was 0.6 mm, demonstrating promising structural performance but limited ductility. The results will not only shed light on the structural behaviour of these innovative structures but also pave the way for the development of resilient and adaptive infrastructure systems. Additionally, the study explores the sustainability aspects of 3D printing technology, considering its potential to optimize material usage and construction processes. In conclusion, the investigation of the structural performance of 3D printed concrete bridge segments presents a promising avenue for advancing the field of construction materials and techniques. The outcomes of this research hold significant implications for the design and implementation of next-generation infrastructure projects, emphasizing sustainability, durability, and adaptability in the face of evolving environmental and structural challenges.

Keywords: 3D printing, Bridge construction, Construction innovation, Load-bearing capacity, Resilient infrastructure, Structural performance.

1. Introduction

3D concrete printing (3DCP) is an automated construction process utilizing cementitious materials to create structures layer by layer. It has the potential to address many challenges in traditional concrete construction, such as labour intensity, safety issues, project delays, quality control problems, and material waste [1]. Research suggests 3DCP could cut construction costs by 50-70% and labour costs by 50-80%, and reduce construction waste by up to 60%, which supports economic and sustainable development goals [2, 3]. The process of 3DCP employs various techniques, with the Inject-Head printing method being the most prevalent [4]. This method, illustrated in Fig. 1, involves three key stages: production (preparing the concrete mix), pumping (transporting the mix to the printing apparatus), and printing (extruding the concrete layer by layer). The success of concrete 3D printing relies heavily on the rheological characteristics of the concrete mix, such as its flowability, viscosity, and setting time [5, 6]. These properties are critical as they directly influence the mix's ability to be pumped and extruded through the printer nozzle, maintain shape upon deposition, and support subsequent layers without deformation [7, 8]. Ensuring the optimal balance of these rheological characteristics is essential for achieving structural integrity, surface finish quality, and the overall viability of printed constructions.

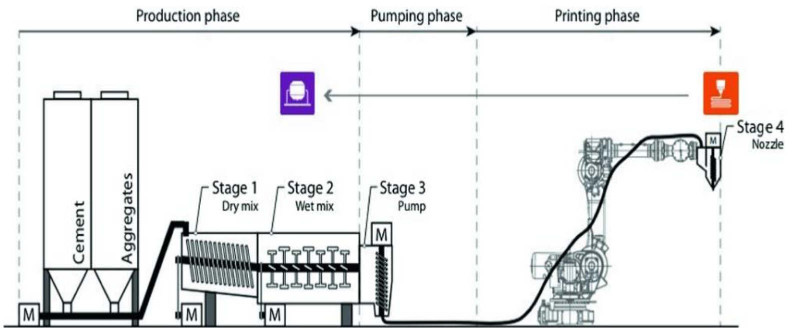

Fig. 1. 3D concrete printing phases [4].

Although 3DCP offers numerous benefits, the widespread adoption of this technology faces significant hurdles, particularly in meeting structural integrity standards [9, 10]. Most 3DCP applications are limited to low-structural requirements like un-bearing walls [11, 12]. Expanding 3DCP's capabilities to high-demand structural elements like beams, columns, and slabs is crucial for its broader adoption. Additionally, challenges like residual deformation in 3D-printed structures must be addressed to enhance structural resilience and recovery from seismic or other unforeseen movements. Therefore, ongoing research, including this proposed study, aims to address these challenges by investigating the structural behaviour of 3DCP bridge segments, paving the way for more frequent adoption of such bridges in the future.

Segmental 3DCP bridges mark a groundbreaking advancement in the construction industry, utilizing additive manufacturing (AM) techniques to construct durable, cost-effective and sustainable load-bearing structures. The primary objective of these bridges is to optimize structural performance by efficiently utilizing materials, minimizing waste, and enduring various forces like gravitational, lateral, and seismic loads, similar to traditional bridges. Designing 3D printed concrete bridges requires a combination of structural engineering expertise and proficiency in digital design, while ensuring compliance with safety standards and design codes, which are not yet available.

Typically, the design process involves creating a digital model that translates into layer-by-layer printing instructions, guiding robotic arms to construct the bridge with precision. Although precision, rheological properties, and the hardened characteristics of 3DCP bridge segments are crucial, they alone cannot guarantee structural integrity without reinforcement [8]. Reinforcement, such as steel bars or fibres, plays a vital role in enhancing ductility and moment resistance, ensuring the durability and strength of these structures. Nevertheless, effective and practical reinforcement techniques are still not yet developed, and extensive ongoing research is devoted to developing these techniques [13]. This lack of effective reinforcement methods is also one of the reasons why 3DCP is not yet widely adopted in load-bearing structural elements. These challenges, along with the absence of design and testing codes and standard, necessitates the need for investigating the performance of 3D printing in large-scale structural applications and underscores the importance for further exploration and innovation in this field.

To date, only a handful of 3D-printed concrete bridges exist globally, serving diverse purposes ranging from pedestrian and cycling paths to prototypes for research and development. Two notable examples of 3D-printed concrete bridges illustrate the potential and current challenges of this technology. In 2019, Tsinghua University in China developed the world's longest pedestrian 3D-printed concrete bridge, measuring 26.3 meters in length [14], as shown in Fig. 2. The single arch bridge, constructed using a polyethylene fibre concrete mix, demonstrated high strength and desirable rheological properties, and was built at a significantly lower cost and time compared to traditional methods. The bridge was repeatedly tested by imposing the load of pedestrians on a smaller physical model with a scale of 1:4. Friis [14] reported pressure resistance and flexural strengths of 65 MPa and 15 MPa, respectively. The cost of the 3D printed bridge was calculated to be two-thirds of that of a conventional bridge of similar size, with only 450 hours of printing using two 3D robotic arms. This is mainly due to the absence of not using any forms or reinforcement which saves both time and costs significantly [14].

Fig. 2. The world’s longest pedestrian 3DCP bridge in China (reprinted from [14]).

In 2017, the Netherlands witnessed the construction of an innovative eight-meter-long 3D printed concrete bicycle bridge in Gemert, realized through a collaboration between Eindhoven University of Technology and BAM Infra Company [15], as shown in Fig. 3. This pioneering project, executed without existing codes for testing 3D printed concrete's structural behaviour, adopted a "Design by Testing" methodology. The bridge spans 6.5 meters, measures 3.5 meters in width, and is designed to bear a load of 5 kN/m^2. Constructed from six printed segments, the bridge utilized post-tensioned prestressing tendons for assembly and enhanced structural integrity. These tendons, placed within the hollow cores of the segments and then stressed and anchored, effectively precompression the concrete, eliminating the need for transverse reinforcement. Additionally, two reinforced concrete bulkheads support the bridge's ends, managing the prestress and splitting tensile forces. Salet et al. [15] asserted that the post-construction tests, involving water-filled containers to simulate a total load of 57 kN, demonstrated the bridge's robust load-bearing capacity with minimal, unmeasurable deflections, indicating a successful application of 3D printing in concrete infrastructure.

Fig. 3. The Netherlands' bicycle 3DPC bridge (reprinted from [15]).

In 2016, Sheikh Mohammed bin Rashid Al Maktoum launched the Dubai 3D Printing Strategy, aiming for 25% of Dubai's buildings to incorporate 3D printing by 2030 [2, 3]. This initiative highlights the need for further research into 3DCP applications in various structural elements to fully leverage its advantages in large-scale projects. However, since there is a significant gap in exploring structural elements constructed using 3D printing, addressing this gap is essential for the broader utilization of 3DCP, especially for critical infrastructure like segmental bridges, which are common in the UAE.

Therefore, the primary objective of this paper is to resemble a viaduct box girder used in segmental bridges using 3D concrete printing and assess its structural performance through a series of three-point static bending tests. This evaluation will facilitate a comparison with traditional concrete structures of equivalent size, fostering a deeper understanding of the structural behaviour of 3DPC structures in terms of loading capacity, fatigue resistance, deflection and cracking patterns.

Additionally, the paper aims to address challenges associated with constructing concrete bridge segments using 3D printing, supporting the formulation of building design codes, and ensuring a comprehensive technology integration in the construction sector.

2. Research Methodology

This section introduces the core principles that serve as the groundwork for the research approach taken in this study. It also sketches out the chosen strategy to meet the research's goals and objectives. A thorough explanation of the various research methods applied concurrently in this investigation is presented, ensuring a well-rounded understanding of the investigative process employed. To elaborate, the structural performance of a 1.2 m 3DPC bridge segment, designed as per ACI 318-19 standards, was examined to evaluate its material and structural characteristics. Through the application of incremental static load cycles, the investigation encompassed a thorough analysis of crack formations, failure modes, deflections, strains, and both compressive and flexural strengths. The objective of this research is to provide insights into the behaviour of 3DPC under stress, with a focus on assessing its applicability in civil engineering, particularly for bridge construction scenarios.

2.1. Materials and design

The concrete mix utilized in 3D printing of the segment exhibits a 28-days compressive strength of 42 MPa. This strength is complemented by the mix's bulk density, which stands at 2150 kg/m^3, reflecting a solid and substantial material composition. Flowability, an essential aspect for 3D concrete printing applications to ensure smooth and uniform layering, ranges between 140 to 170 mm for this mix, offering a good balance between fluidity and stability. It is noteworthy that this mix is purely cementitious, containing no fibers, which emphasizes its reliance on the intrinsic properties of the cement-based components to achieve the desired structural characteristics and performance.

As summarized in Table 1, the bridge segment, designated as Specimen A, was fabricated with a cross-sectional dimension equivalent to a 509 mm by 280 mm rectangular section. It featured a length of 1200 mm and a simply supported span of 900 mm, deliberately designed without reinforcement to explore the pure structural response of 3D printed concrete. This configuration is depicted in Fig. 4. It is worth mentioning that the proposed design of the 3D printed concrete segment resembles a viaduct box girder shown in Fig. 5, at a scale of 1:10 featuring a single cell.

2.2. Printing of the 3DPC bridge segment

The printing task was expertly executed by our partner, the 3DXB Group of Companies. The segment was printed using a circular nozzle with a diameter of 15 mm with an inject-head printer, ensuring precise material deposition. The construction technique adopted allowed for the creation of layers each 10 mm thick and 30 mm wide, optimizing the structure's integrity and appearance. This thorough approach resulted in a final specimen weighing 296 kg, demonstrating the efficacy of 3DXB's printing technology and our collaborative efforts in pushing the boundaries of 3D concrete printing. The printing process of the 3DPC bridge segment as well as the final printed segments are shown in Figs. 5 and 6, respectively.

Table 1. Viaduct dimension details of tested Specimens of bridge segment A.

Geometry	b (mm)	t (mm)	L (mm)	a/d	*f'c* (MPa)
Value	509	280	900	2.25	42

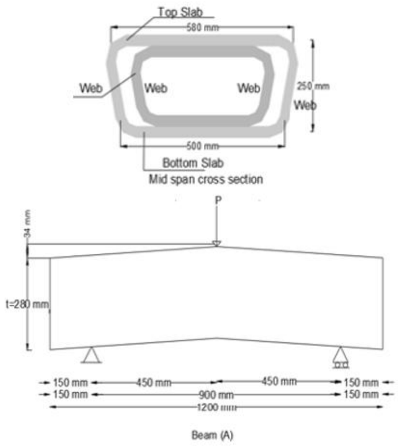

Fig. 4. Cross-sectional drawing of the tested specimen.

Fig. 5. The bridge segment during printing.

Fig. 6. The 3DPC bridge segment.

2.3. Instrumentation and testing setup

In the experimental setup, depicted in Fig. 7 (left), two steel-bearing plates with provided the necessary support conditions, incorporating both roller and hinge to ensure accurate load distribution. This configuration facilitated the application of forces via a substantial steel plate directly to the specimen. The deflection was measured using a highly accurate Linear Variable Differential Transformer (LVDT), positioned to capture the maximum deflection point under load. Additionally, electrical concrete strain gauges were strategically placed to monitor strain in the bridge segment offering detailed insights into the material behaviour. As shown in Fig. 7 (right), Instron 8806 testing machine, a robust system capable of executing both static and dynamic tests with a capacity of 2500 kN, enabling a comprehensive evaluation of the specimen's structural integrity under static loading and unloading cycles of 20 kN at a rate of 0.8 mm/min.

Fig. 7. Experimental setup (left), Instron 8806 testing machine (right).

3. Results and Discussion

In this experimental study, static cycles of loading and unloading were applied in increments of 20 kN at a rate of 0.8 mm/min on the 3DPC bridge segment up to failure. The results obtained from the experimental procedure and the load versus displacement graph, depicted in Fig. 8, indicate that the last repeated force cycle was predetermined between zero to 100 kN. The bridge segment, however, has failed at a load of 90 kN. The segment failed under flexural-brittle failure, with no occurrence of cracks prior to that, as shown in Fig. 9. This is mainly attributed to the brittle nature of concrete and the absence of reinforcement within the segment. The maximum displacement recorded by the LVDT prior to failure was measured to be approximately 0.6 mm. It is important to note that the behaviour of 3D printed concrete is not yet predictable, thus a force-controlled experiment was conducted. Nevertheless, although a force-controlled experiment was conducted, the primary goal of the test was to determine the maximum load capacity that the 3DPC bridge segment can sustain and compare it to the theoretical design value of a conventional concrete segment of the same size. This comparison aims to provide insight into the reliability of standard design codes, such as ACI 318-19, in designing 3DCP members, theoretically calculating their ultimate strength and predicting their behaviour.

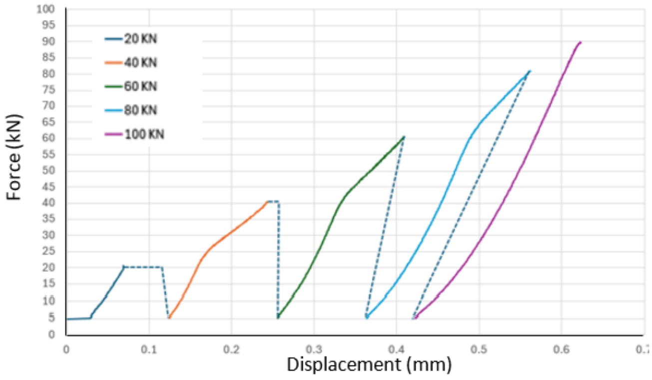

Fig. 8. Force vs displacement graph.

When the performance of this 3DPC bridge segment was compared to that of a conventional reinforced concrete (RC) bridge segment of the same size, designed according to ACI 318-19 standards, it was found that the capacity of the 3DPC segment was approximately 65% of the theoretical capacity of the conventional RC segment. To clarify, the theoretical ultimate design strength of a conventional 1.2 m beam was calculated to be approximately 138 kN, whereas the experimental ultimate strength of the 3DPC segment was found to be 90 kN. This yields a percentage error equal to around 35%. The percentage error calculated in testing the bridge segment using the ACI 318-19 code can be attributed to several factors. Firstly, the design was based on a traditional concrete beam, assuming identical dimensions, but the segment featured curved sides and a hollow centre, which reduces the volume of concrete that is resisting the load in the 3D printed one.

Fig. 9. 3DCP bridge segment after failure.

Experimental errors could also include deviations in the applied load distribution during testing or insufficient load distribution due to the steel plate used. Moreover, the design presumed the presence of reinforcement, which was absent in the tested segment. Additionally, printing inaccuracies and variations in the thickness of the printed layers further contributed to the overall error This passive analysis underscores the disparity in structural resilience between segments fabricated through 3D printing techniques and those constructed using traditional casting methods, particularly due to the absence of reinforcement in the former. This observation underscores the potential necessity for the incorporation of reinforcement mechanisms within the 3D printing process for concrete structures to enhance their structural performance and bring their load-bearing capacities in line with those of conventionally casted reinforced concrete structures. This adjustment could significantly expand the utility of 3D concrete printing in the realms of construction and infrastructure development.

4. Sustainable Waste Management Key Strategies

4.1. Recycling and reuse

Implement a system for recycling and reusing surplus or failed concrete segments. This can involve crushing and repurposing concrete waste for use as aggregate in new printing projects, thereby reducing the demand for virgin materials [16].

4.2. Minimizations of packaging waste

Reduce packaging waste associated with the transportation and storage of printing materials and equipment. Use reusable containers or eco-friendly packaging materials wherever possible [17, 18].

4.3. Design for disassembly

Design bridge segments with disassembly and potential reuse in mind. This involves using modular construction techniques and standardised connections that facilitate easy dismantling and reassembly, reducing the amount of waste generated during future maintenance or renovation activities.

4.4. Waste sorting and management

Implement a waste sorting and management system on-site to segregate different types of waste materials, such as concrete, plastics, metals, and packaging. Ensure that recyclable materials are properly separated and sent to recycling facilities while non-recyclable waste is disposed of responsibly [17].

4.5. Community engagement

Engage with local communities to raise awareness about the importance of sustainable waste management practices in construction projects. Encourage participation in recycling programs and provide education on proper waste disposal methods [18].

The impact on air quality associated with the structural performance of bridge segments printed by 3D concrete under static cyclic loading can vary depending on several factors:

- Emissions from construction equipment: During the construction phase, emissions from heavy machinery such as excavators, cranes, and concrete mixers can contribute to air pollution. These emissions include particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), and carbon monoxide (CO) [18].
- Dust generation: Construction activities, including concrete mixing, cutting, and drilling, can generate dust particles that contribute to poor air quality. This is particularly relevant in urban areas where construction sites are near residential areas [19].
- Transportation: The transportation of construction materials to and from the site can lead to emissions from trucks and other vehicles, further contributing to air pollution [18].
- Indoor air quality: Once the bridge segments are in place, indoor air quality within enclosed spaces such as tunnels or underpasses may be affected by off-gassing from construction materials, particularly if low-quality or improperly cured concrete is used.

To mitigate these impacts and improve air quality, it's essential to implement measures such as:

- Using cleaner construction equipment or electric-powered machinery to reduce emissions.
- Implementing dust control measures such as water spraying and covering materials during transport.
- Opting for sustainable construction materials with lower environmental footprints.
- Implementing construction schedules and logistics to minimise transportation-related emissions.
- Ensuring proper ventilation and air filtration systems in enclosed spaces.
- Adopting green building practices and certifications to promote sustainable construction techniques and materials.

5. Conclusions

The investigation into the structural performance of 3DCP bridge segments has demonstrated promising results for advancing construction techniques and materials. This study illuminated the potential of 3DCP in producing structures that are not only sustainable and intricately designed but also capable of bearing substantial loads. The finding that non-reinforced 3DCP segments achieved approximately 65% of the load-bearing capacity of traditional reinforced concrete segments is seen as a promising result, highlighting the viability of 3DCP in structural applications. It suggests a path forward in enhancing the technology to match or surpass conventional construction methods. The implications of this research are significant, suggesting that with further development in reinforcement strategies, 3DCP could revolutionize the construction industry by combining environmental sustainability with structural integrity. This breakthrough marks a vital step towards the realization of adaptable, durable, and sustainable infrastructure systems, aligning with the goals of modern construction and environmental stewardship.

Nomenclatures

a/d	Ratio of area of segment to effective equivalent rectangular section depth
b	Width of segment
f'c	Compressive Strength of Concrete
L	Span of segment
t	Thickness of segment

Abbreviations

3DCP	3D Concrete Printing
ACI	American Concrete Institute
AM	Additive Manufacturing
LVDT	Linear Variable Differential Transformer
RC	Reinforced Concrete

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