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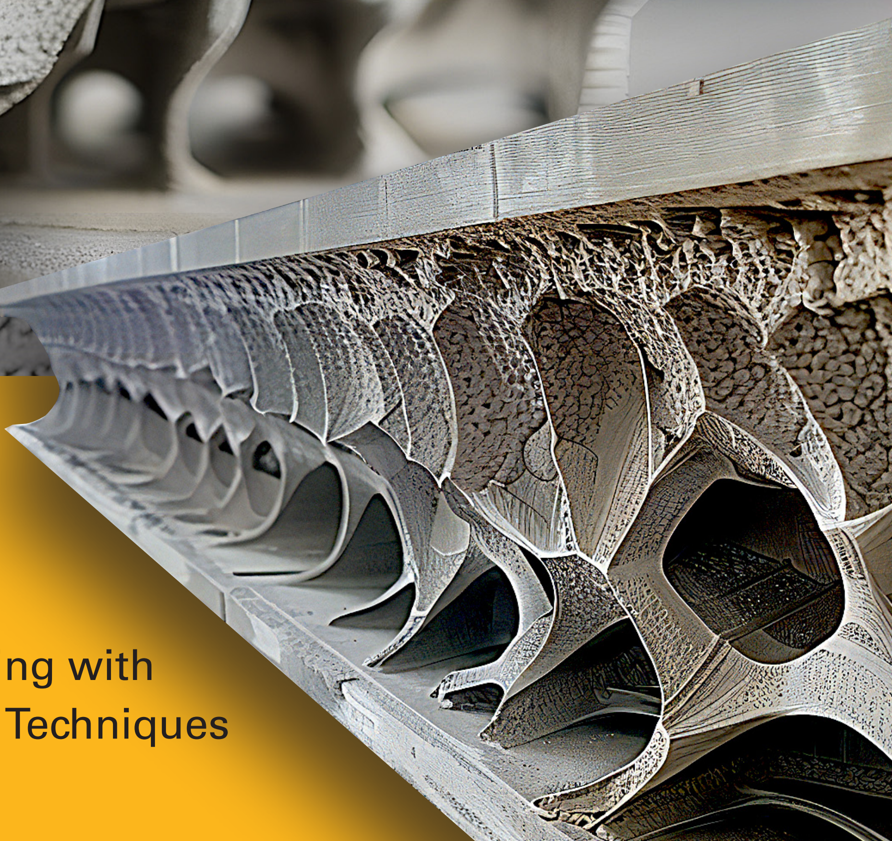

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16. Abstract
The main objective of this study is to investigate the feasibility of using 3D concrete printing (3DCP) for manufacturing prefabricated bridge elements in accelerated bridge construction (ABC) projects. A literature review is first conducted to survey the applications of 3DCP within the construction and building domains. This phase entails exploring diverse additive manufacturing techniques and materials relevant to construction. Incorporation of reinforcement in 3DCP stands as a significant challenge to advancing the 3DCP technology for ABC projects. Therefore, emphasis is placed on examining a range of reinforcement strategies for 3DCP. On this basis, multiple concrete beams are 3D printed with different reinforcement strategies. Three-point bending tests are conducted on the 3D printed specimens and conventionally cast counterparts to characterize their mechanical properties. The beam samples manufactured for the comparative study include cast plain beam, cast rebar-reinforced beam, plain beam with printed formwork, rebar-reinforced plain beam with printed formwork, plain beam with printed studs formwork, rebar-reinforced plain beam with printed studs formwork, fully printed plain beam, fully printed rebar-reinforced beam, and fully printed metal staple-reinforced beam. An important finding is that beams created using the reinforced 3DCP formwork with studs strategy exhibit the highest flexural strength compared to the beams fabricated using other casting and printing methods. Given the substantial costs associated with traditional concrete casting formwork, employing 3D printed formwork with studs can significantly reduce expenses while maintaining optimal performance. Therefore, this strategy is employed for the 3D printing of a small-scale prefabricated bridge element specifically identified as a pier cap. The results of the three-point bending tests indicate that the 3D printed pier cap demonstrates a comparable flexural strength to a conventionally cast prefabricated pier cap, while also exhibiting higher stiffness. The proposed experimental study reveals both promising possibilities and inherent limitations in the current 3DCP technology. Additional research directions and recommendations are presented to enhance the efficiency of 3DCP in ABC projects.

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1. Introduction

1.1. Background

Based on the latest findings from the annual report by the American Road and Transportation Builders Association (ARTBA) [1], the United States stands at a crucial crossroad with its vast network of around 600,000 bridges. More than a quarter of these vital infrastructures require immediate attention, whether through rehabilitation, repair, or complete replacement. This pressing call for action arises from the inherent challenges ingrained in traditional onsite construction methods. These challenges have far-reaching impacts on personnel traffic mobility, safety, and broader economic activities. In the strategic realms of bridge construction planning and design, a compelling imperative comes to the forefront—the adoption of Accelerated Bridge Construction (ABC). This strategic approach places a primary emphasis on modularity as a pivotal element to enhance efficiency and reduce the widespread impact typically associated with bridge construction endeavors. The pivot towards ABC seeks to transcend the limitations of conventional methods and redefine the narrative of bridge construction in the modern era. At its core, ABC advocates for modularity, urging a shift from the traditional sequential construction process to a more parallelized approach. This involves the offsite fabrication of standardized components, which allows for simultaneous construction activities and reducing the overall time required for project completion.

Prefabricated bridge elements and systems (PBES) emerge as a dynamic response to this strategic imperative. PBES can serve as a conduit for innovations in planning methodologies, materials science, and construction techniques seamlessly integrated into the broader landscape of ABC initiatives. PBES are structural components, ranging from beams and decks to piers and abutments, that are built offsite, or adjacent to the alignment. The prefabricated elements are then transported to the construction site. PBES offering a spectrum of advantages including rapid assembly and installation, curtailing construction duration, elevating the overall quality of the fabricated components, fortified security parameters, a diminished environmental footprint emanating from PBES fabrication plants, designing structural elements with optimized topologies, and the facilitation of in-situ repair strategies for existing ABC elements through a prism of customizable design [2].

However, the landscape of PBES unfolds with features poised for enhancement and innovations. In particular, additive manufacturing techniques, commonly recognized as 3D printing, have the potential to transform the construction of PBES. Over the past decade, additive manufacturing has transitioned from a niche application to a bona fide catalyst for disruptive innovation. This paradigm has gained prominence as a transformative force in the engineering field. The multifaceted advantages of this technology are unequivocal—expedited manufacturing processes, unparalleled avenues for product customization, a tangible reduction in operational costs, and an overarching enhancement of product quality. Its potential has been manifested across diverse scales—from the construction of an entire house within a single day to the intricacies of producing precision-engineered medical implants. The application of additive manufacturing stands profoundly logical for bridge construction and maintenance. It offers a coherent and transformative solution to address the challenges embedded in the fabric of traditional bridge construction methodologies. The envisioned synergy between PBES and additive manufacturing can lead to redefining the landscape of bridge construction and building a new generation of bridges that are more resilient and sustainable.

In conclusion, the trajectory of bridge construction is at a crossroad, beckoning the integration of innovative methodologies. The synergy between ABC, PBES, and additive manufacturing not only responds to the challenges of the present but propels the industry into a future where efficiency, sustainability, and resilience converge seamlessly for bridge construction.

1.2 Problem statement

The field of civil engineering and construction has witnessed a transformative journey during the past century. From the rudimentary automation of masonry to the sophisticated automation of concrete construction, and now additive manufacturing, substantial progress has been achieved in both research and practical applications within the construction and building domains. The inception of the concept of 3D concrete printing (3DCP) in 1997 by Dr. Joseph Pegna at Rensselaer Polytechnic Institute (RPI) marked a seminal moment in the construction industry [3]. Recent studies in Europe have underscored the capacity of 3DCP to 3D print a concrete bridge using 60% less concrete, exemplifying the efficiency gains achievable through this transformative technology [4]. However, despite these promising strides, the widespread adoption of 3DCP in extensive bridge projects faces significant impediments, primarily linked to challenges associated with reinforcement and the inherent limitations of current printing technology. The only attempt to 3D print an entire bridge in North America, undertaken by the U.S. Marines in 2019.

This effort highlighted the formidable challenges tied to the need for large-scale 3D printers equipped with cranes and automated arms [5].

Recognizing the current state of additive manufacturing technologies, a more pragmatic approach appears to be the concentration of efforts on 3D printing of PBES rather than attempting to print complete bridges in a single part. This arguably represents a potential paradigm shift in more efficient and sustainable ABC practices. The inherent efficiency of 3D printing for ABC lies in its judicious use of material, depositing it only in locations where structural support is required, thereby minimizing the waste and construction costs. However, despite significant strides in the application of 3D printing technology to various domains within construction and building over the past decade, the application of this technology to concrete bridge construction remains in its nascent stages. A notable endeavor in this arena involves the ongoing 3D printing of a shell using continuous additive layers of ultra-high-performance concrete (UHPC) for a bridge cap beam at Florida International University. However, given the intricacies inherent in ABC projects, particularly the fabrication of PBES with a high degree of customization to meet specific project requirements, there exists a compelling need for more extensive research. This research imperative should focus on the identification of suitable additive manufacturing techniques and materials, unraveling the complexities of 3D printed PBES with reinforcements, and conducting comparative analyses to ascertain their performance against conventional precast components. This research aims at addressing some of these issues with the broader objective of fostering innovation and efficiency within the realm of ABC. It should be noted that the fusion of these technological innovation holds the promise of not only revolutionizing the bridge construction industry but also addressing the critical challenges posed by the demands for sustainable, resilient, and efficient infrastructure solutions.

1.3 Research plan

In this research plan, the primary objective is to explore and validate the integration of 3DCP into the ABC projects. The project spans three integral phases which are formulated to effectively navigate the challenges of implementing 3DCP for the fabrication of PBES in ABC projects. In 3DCP, the incorporation of reinforcement stands out as a major bottleneck that demands concentrated research efforts. Thus, this research strategically focuses on addressing the complexities associated with this crucial aspect of 3D-printed concrete structures. Through a multifaceted approach, this research provides practical insights and guidelines that align with the specific needs and conditions of the Pennsylvania construction landscape.

(1) Literature review

The literature review is designed to survey recent strides in 3DCP techniques, diverse equipment configurations, advancements in cement-based materials, mix designs, and computer modeling approaches. It serves the dual purpose of understanding the current landscape of 3DCP practices and identifying the most suitable methodologies for the fabrication of PBES in ABC projects. A list of recommended 3DCP mixture designs is presented. These formulations encompass a selection of admixtures, including but not limited to silica fume, superplasticizer, and fibers. The integration of these components can enhance crucial properties such as yield stress and viscosity, aligning with the criteria for practical material design of prefabricated elements in the ABC framework. Simultaneously, finding the proper parameters for setting up the concrete 3D printers is a focal point of this phase. Examples of these critical parameters are printing orientation, position, pumping mechanisms, and speed. This dual-track approach ensures that the research lays a foundation for subsequent phases, blending theoretical understanding with hands-on technical proficiency to propel the project forward.

(2) Studying 3DCP with different reinforcement methods

The literature survey in first phase of this study reveals that a substantial body of knowledge exists in the field of materials and concrete mixtures for 3DCP. In contrast, the incorporation of reinforcement in 3DCP poses a challenge which necessitates focused research efforts to overcome inherent complexities. Unlike traditional construction methods that seamlessly integrate steel reinforcement for added strength, 3DCP demands unique considerations. Achieving optimal bonding between printed layers and the reinforcement material, ensuring uniformity in distribution, and addressing potential weak points arising from the layer-by-layer construction process are critical challenges. These complexities underscore the need for an in-depth exploration of innovative techniques and materials tailored specifically for 3D-printed concrete structures.

Recognizing the significance of this challenge, our research heavily concentrates on refining and examining a spectrum of reinforcement strategies for 3DCP. Multiple concrete beams are 3D printed with different reinforcement strategies. The objective is to instigate a comparison between the 3D printed beams and their conventionally cast counterparts. This comparative analysis is pivotal in critically assessing the feasibility of additive manufacturing of PBES for ABC. The study also involves exploring the optimal viscosity conducive to prolonged printing (extrudability) and ensuring structural integrity when stacking layers without compromising the foundational ones (buildability). The outcomes of this phase pave the way for enhanced efficiency in 3DCP of a small-scale PBES in the third phase.

(3) 3DCP of prefabricated elements in ABC system at small scale

Building upon the insights acquired in the preceding phases, the third phase of this research plan signifies a crucial transition into real-world applications. In this stage, a meticulous process is carried out to identify most suitable prefabricated components for 3D printing within the ABC. Elements such as parapets, bridge decks, column caps, and pile caps take center stage as prime candidates for 3D printing. Leveraging the protocols for design, fabrication, and structural testing developed from the earlier phases, this stage aims to provide a holistic assessment of the selected 3D-printed bridge component.

A comparative study is conducted to evaluate the performance of the selected 3D-printed component against a conventionally cast prefabricated counterpart under tightly controlled conditions. Despite the inherent limitation of small-scale testing, the insights generated regarding 3DCP mix design, flow properties, and relevant mechanical properties can serve as a cornerstone applicable to the eventual scale-up of 3D printing for PBES within ABC projects in Pennsylvania.

This detailed research plan unfolds across six structured sections. Section 2 conducts an in-depth exploration of the current state-of-the-art in 3D concrete printing, providing a foundation for the subsequent phases of the research. Section 3 details the mixing design for 3DCP, encompassing critical aspects such as the properties of printing materials, machine selection, and setup. Section 4 navigates through the meticulous preparation of the 3DCP beam model, elaborating on various methods for manufacturing 6×6×21-inch concrete beams and providing a thorough discussion of the accompanying test data. Section 5 shifts focus to the 3DCP of the pier cap, covering dimensions, fabrication processes, and test results. Finally, Section 6 brings the report to a comprehensive close with a thoughtful discussion on conclusions drawn from the research plan and outlines avenues for future work.

2. State-of-the-art of the 3DCP technology

2.1. The evolution of 3DCP technology in construction

In the dynamic landscape of construction technology, the evolution of the 3DCP technology over the last decade stands as a testament to transformative strides that have reshaped traditional paradigms. This innovative approach intertwines material preparation, structural design, and production processes, marking a departure from conventional methods. A distinctive hallmark of 3DCP is its independence from support molds, relying on efficient printing methods and modular production capabilities. These attributes have garnered widespread attention, positioning 3DCP with inherent benefits such as heightened design flexibility, reduced material consumption, and minimized environmental impact. The alignment with green and smart construction concepts further accentuates its progressive nature.

The application of 3D printing in structural engineering continues to evolve. Currently, the 3DCP technology is being studied for finding utility in diminutive temporary constructions, compressive components within low-rise structures, non-load-bearing elements in larger constructions, and landscaping projects. The layer-by-layer printing method, while introducing a revolutionary approach, also brings forth challenges related to the anisotropy of concrete under tension and compression. Addressing these challenges demands meticulous attention to material components, proportions, and the operational nuances of printing equipment.

Conventional reinforcement techniques encounter hurdles when applied to 3DCP constructions, necessitating continuous innovation in this domain. Recent technological efforts have significantly broadened the scope of 3DCP applications, making it applicable to a more extensive spectrum of structures. Notably, flexible structures such as bridges, trusses, and plate shells are now within the purview of 3DCP. This expanded reach is facilitated by advancements in reinforcement techniques, complemented by progress in robotic arms, gantry-type printing equipment, and software capabilities. These advancements collectively contribute to the seamless integration of 3DCP into diverse structural forms, accommodating varying reinforcing requirements, manufacturing procedures, and printing scales. As the 3DCP technology continues to evolve, its trajectory promises further innovations, pushing the boundaries of what is achievable in the realm of construction and engineering.

The current trajectory of the 3DCP research is marked by a pursuit of more efficient use of materials via implementation of optimization techniques, e.g. topological optimization. This entails finding solutions that address the unique challenges posed by the anisotropic nature of 3DCP and the intricacies inherent in the 3D printing processes. These optimization endeavors extend beyond singular parameters and consider multiple factors such as material qualities, nuances of the printing processes, structural profiles, and the intricacies of reinforcing schemes.

In the realm of construction techniques for 3DCP, on-site printing at full scale and prefabricated assembly are the main two paradigms. The former, while showcasing the potential for groundbreaking applications, grapples with challenges stemming from equipment limitations and the unpredictable influence of environmental variables. On the other hand, prefabricated assembly emerges as a more pragmatic alternative, particularly for projects demanding intricate forms and extensive engineering considerations. The controlled conditions inherent in prefabrication, spanning material preparation, environmental factors, and equipment precision, contribute significantly to its feasibility and reliability in large-scale projects.

However, several critical challenges demand concerted attention for the 3DCP technology to realize its full potential. One such imperative lies in the precise measurement of the mechanical characteristics of 3DCP materials, a foundational aspect for ensuring structural integrity and performance. Additionally, the implementation of effective reinforcement techniques remains a pivotal frontier, necessitating innovative approaches to seamlessly integrate reinforcement within the 3D printing process. The design of structurally optimized solutions grounded in sound engineering principles constitutes another crucial arena, demanding a comprehensive understanding of how 3DCP materials behave under varied conditions. Lastly, the development of practical approaches for constructing connections in 3DCP structures emerges as a linchpin for translating theoretical advancements into tangible, real-world applications. In essence, the future trajectory of 3DCP hinges on the navigation of these challenges, presenting a frontier ripe for exploration, innovation, and transformative breakthroughs in the realm of construction technology.

- *A revolutionary shift in construction*

The construction industry has undergone a revolutionary paradigm shift with the emergence of 3DCP. This technology is a convergence of time-honored building materials and cutting-edge digital technologies. The roots of this innovative approach trace back to the late 1990s when the concept of 3D printing structural components and entire structures first captured the imagination of architects and engineers. Early endeavors focused on printing with mortar or cementitious mixes, but it was the technological leaps of the 2010s that ushered in true concrete printing, incorporating recycled and locally sourced aggregates.

A watershed moment in the timeline of 3D printing technology was the construction of the world's first 3D printed bridge in Spain in 2016—an achievement that resonated as a historic milestone. Subsequent developments witnessed the creation of various small-scale structures and structural elements, providing tangible evidence of the viability and potential of 3DCP. The evolution of printing technologies and materials prompted a natural progression toward larger and more ambitious constructions, including buildings and homes.

The inherent advantages of 3D printing have positioned it at the vanguard of the construction sector. Cost savings on labor, a reduction in material waste, and the ability to bring to life intricate geometrical designs that defy conventional building methods have become hallmarks of 3DCP. Ongoing research endeavors are dedicated to enhancing material qualities, ensuring structural integrity, and optimizing cost-effectiveness. Despite these endeavors, 3DCP already stands as a testament to the innovative intersection of construction and digital technology, opening new avenues for sustainable and efficient building practices.

A pivotal aspect of 3DCP's transformative potential lies in its promise to redefine the construction landscape. This technology provides a glimpse into a future where the marriage of technology and tradition seamlessly coalesces to shape the built environment. As 3D concrete printing continues to evolve, it not only challenges preconceived notions of construction methodologies but also paves the way for a construction renaissance—one where the fusion of innovation and tradition propels the industry into uncharted territories of efficiency, sustainability, and architectural possibilities.

2.2. A review of 3DCP technology

This comprehensive review examines various critical aspects that underscore the transformative potential of the 3DCP technology in the construction industry. The analysis focuses on examining the mechanical properties displayed by printed materials, with a special emphasis on understanding how 3DCP structures respond to different loads, environmental conditions, and considerations for long-term durability. The review also explores the range of structural shapes that can be achieved through 3DCP, showcasing its capability to advance architectural design boundaries. Reinforcement techniques emerge as a focal point in the scrutiny of 3DCP technology. The review involves a critical examination of how traditional reinforcement methodologies may need to evolve or adapt to suit the unique challenges posed by the layer-by-layer printing method intrinsic to 3DCP. The optimization schemes employed in 3DCP projects also come under the lens, with a discerning analysis of how material qualities, printing processes, and structural profiles intertwine to achieve optimal results. Moreover, the review addresses the intricate web of connections between printed modules as an important factor in determining the overall stability and robustness of a 3D-printed structure. The challenges and opportunities in module connections are explored, shedding light on the current state of affairs and delineating potential avenues for improvement. The review also underscores the unparalleled potential of 3DCP to address critical global concerns such as housing shortages, environmental sustainability, resource optimization, and heightened productivity. The closing remarks of the review point to the need for sustained exploration and advancement in 3DCP technology. It contends that overcoming current constraints requires not only focused research efforts but also a collaborative approach from stakeholders across the construction spectrum.

(1) Mixing design and material properties:

- *Constitutive Relation and Anisotropic Properties*: The focus on uniaxial compressive and tensile properties in 3DCP aligns with the plastic damage model used in conventional concrete. Notably, 3DCP exhibits distinct anisotropic mechanical characteristics influenced by factors such as the interval time between layer printing, print head height, and moving speed, resulting in directional variations in its ability to withstand compression and tension [6].
- *Strength and Material Composition*: The compressive strength of 3DCP, at times surpassing 100 MPa, can rival or exceed that of cast-in-place concrete. Research underscores the impact of modifying material composition and proportions, with the use

of recycled aggregates showcasing anisotropic characteristics and strength reduction at higher replacement rates.

- *Impact of Pore Structure*: The pore structure significantly influences the elastic modulus and compressive strength of 3DCP, with the three-dimensional printed concrete displaying irregular pores compared to traditional concrete. This irregularity contributes to stress concentration and an increased likelihood of fracture propagation, adding to the directional dependence of 3DCP.
- *Printing Process Factors*: Various factors in the printing process, including the duration between layers, surface wetness, and print head speed, exert considerable influence on the mechanical characteristics of 3DCP. Prolonged printing intervals may lead to moisture loss, negatively affecting layer connection strength and overall material properties.
- *High-Performance Concrete Mixes*: The development of high-performance concrete, including Fiber-Reinforced Concrete (FRC), UHPC, and Engineered Cementitious Composites (ECC), holds promise for enhancing crack resistance, compression, bending strength, and stress transfer efficiency. Challenges, however, persist in optimizing the rheological characteristics of UHPC for improved printability without compromising mechanical qualities.

(2) Chemical Agents and Mix Components:

- *Chemical Agents*: The addition of chemical agents to the mixture plays a vital role in modifying the connection between cement particles, inducing either flocculation or dispersion. This alteration enhances the rheological qualities of the concrete, contributing to improved printability.
- *Successful 3DCP Mixes*: A successful 3DCP mix often comprises a precise combination of components, including cement, micro-silica, fly ash, sand, water, and superplasticizer. The water-to-binder (w/b) ratio, ranging between 0.23 and 0.35, is a critical parameter. Achieving the right blend is essential for optimizing the rheological properties and ensuring the printability of the mixture without compromising mechanical qualities [6,7,14].

(3) Nozzle criteria

- *Extrudability*: Extrudability is a pivotal rheological property in 3D printing concrete. It signifies the material's ability to flow seamlessly from the extrusion chamber to the nozzle through a hose, crucial for successful concrete formulation in 3D printing. This property's evaluation extends beyond power consumption considerations, encompassing qualitative characteristics such as printability, layer adhesion, surface finish, workability, setting time, compressive strength, durability, material compatibility, and fiber reinforcement. Metrics like the Extrudability Constant (PE) gauge spread diameter and rest duration, providing insights into flowability and extrudability, yet a universally agreed-upon criterion for this assessment remains elusive. The multifaceted nature of extrudability underscores the need for a comprehensive methodology in concrete mix formulation, crucial for advancing technology and ensuring its reliable and efficient utilization across diverse building contexts.
- *Buildability*: Buildability, a critical characteristic of 3DCP, refers to the material's ability to retain its shape under load, a fundamental aspect for techniques like 3D concrete printing that eliminate the need for formwork. Buildability depends on material qualities, printing parameters, design considerations, and factors like plastic collapse and elastic buckling. Critical height of buckling, determined using Euler's buckling theory, serves as a key factor in evaluating buildability. Various criteria, such as the coefficient PB, shear strength formula, and "Shape Retention Factor," provide insights into concrete mix resistance and deformation. The success of 3DCP hinges on achieving optimal buildability, emphasizing the intricate balance required in managing material qualities, printing processes, and design factors.
- *Pumpability*: Pumpability, a vital factor in 3DCP, pertains to the ease with which concrete can be transferred from storage to nozzle through pumping while maintaining its intrinsic qualities. The pumpability index serves as a metric, influenced by variables like concrete-to-water flow ratio, pump speed, and rheological qualities. Achieving a balance between water-to-cement ratio, pumpability, and constructability is essential in mix design. The ability to be pumped significantly impacts the effectiveness of the 3D printing process, emphasizing the need for ongoing research and development in concrete technology to optimize concrete mix efficiency while preserving essential characteristics.

- *Printability*: Printability in 3DCP transcends basic filament creation, encompassing pumpability, extrudability, and buildability. Customized rheological properties, including enhanced fluidity, quick setting rates, and elevated green strength, are crucial for successful 3D printing. Printability, influenced by various parameters like nozzle dimensions, printing speed, and rheological characteristics, requires nuanced testing methodologies, considering the intricacies of 3DCP compared to conventional concrete. Achieving an equilibrium between fluidity, setup times, and structural integrity is the challenge at hand, and establishing accurate testing standards for printability is essential for advancing 3DCP technology.
- *Interlayer Bond Strength*: The interlayer bond strength in 3DCP is pivotal for structural integrity, influenced by material composition, mechanical characteristics, and printing factors. Parameters like time gap between layers, nozzle velocity, and extrusion rate affect bond strength. The vulnerability of interfaces between layers to pores and permeability emphasizes the importance of managing the rate of structuration for adequate bonding. Environmental conditions, printing factors, and layer intervals significantly impact interlayer bonding. Innovative techniques to enhance bonding must undergo comprehensive evaluation in practical scenarios to ensure their viability and effective implementation in real-world construction settings.

(4) Printing process and challenges

The 3DCP process commences with the creation of a 3D model of the desired structure, subsequently converted into a universally compatible format like STL. Slicing the model into 2D contours facilitates the generation of tool paths for the printing process. Once the printer is set up at the construction site, concrete is extruded along specified routes, layer by layer, culminating in the formation of a structure with a specific material arrangement and the potential inclusion of void spaces.

The formulation of the concrete mixture is of utmost importance, ensuring that the addition of new layers does not compromise the integrity of existing ones and fosters a robust bond between layers. The material architecture, including distinct surfaces and voids between layers, is profoundly influenced by printer parameters such as extrusion rate, nozzle speed, diameter, and print head location. Tool paths with abrupt changes in direction can lead to defects like material accumulation or fracturing, impacting section dimensions and causing misalignment of layers.

Structures with multiple layers often exhibit weak connections between layers, resulting in directional strength disparities, particularly along connections. For instance, loading applied in the depth direction of printed layers yields higher compressive strength than loading in perpendicular or parallel directions to layer deposition. Flexural strength is contingent on the mixture's stiffness, with an excessively stiff mixture potentially causing void formation.

Leveraging the full potential of 3D concrete printing involves capitalizing on the unique attributes of concrete, incorporating both its fresh and hardened traits like strength and durability. Techniques to enhance adhesive force encompass the use of refined adhesives, geopolymer blends, and adjusting the interval between successive printed layers. Anisotropy, commonly measured in 3DCP, crucially influences binding strength, dictated by printer settings and filament microstructure, altered by mixture contents. For instance, the introduction of nanosilica and polypropylene fibers has demonstrated the ability to create a uniform mixture and minimize compressive strength variations in different directions.

However, the environmental impact is a concern, especially when a larger proportion of Ordinary Portland Cement (OPC) is required, leading to increased environmental strain. Precision in controlling cross-sectional shape is necessary for high fluidity blends, and precise geometry control is vital in preventing issues like filament ripping, buckling, and voids. Surface defect quantification through real-time monitoring techniques is an ongoing area of investigation.

Optimizing the 3DCP process entails a delicate balance between the fresh and hardened qualities of the mixture. The complex relationship between printer settings and material qualities underscores the need for a harmonious equilibrium for technological success. The adoption of real-time monitoring and adaptive control systems holds promise in enhancing the quality and uniformity of printed structures, potentially widening the application of 3D concrete printing in mainstream construction. A nuanced understanding and effective management of concrete flow properties are pivotal for overcoming challenges related to pumping and shaping, paving the way for innovative and environmentally friendly solutions in the construction sector.

(5) Cost

The revolutionary impact of the 3DCP technique on the construction industry manifests through substantial cost-saving benefits across three critical dimensions: time, materials, and labor. To be more specific, the transformative potential of 3DCP lies in its ability to condense building durations to a mere 25% of the time traditionally required [6,7,45]. This efficiency is attributed to its precision in item assessment and positioning, leading to a significant reduction in overall waste. Furthermore, 3DCP, or 3D printed construction, holds the promise of substantially reducing labor costs by streamlining the workforce required for a project, thereby minimizing human errors and enhancing on-site safety – factors that often constitute a significant portion of a project's overall expenses.

An additional financial boon arises from the elimination of the costs associated with formwork, a traditional construction expense ranging from 35-60% of the total cost [10]. However, it is important to note that the adoption of 3DCP introduces its own set of challenges, particularly in terms of the initial expenses linked with the acquisition and maintenance of large-scale printers, which are a relatively recent addition to the market. Beyond these initial considerations, 3DCP demonstrates its versatility in optimizing intricate structures and facilitating small to medium-sized manufacturing processes. The anticipated cost reductions in the wake of technological advancements suggest a paradigm shift in the additive manufacturing sector, indicating a trajectory toward more economically viable 3D printing alternatives. Empirical research substantiates the claim that the integration of 3DCP, or 3D Printed Building, can result in a noteworthy decrease in overall building expenses, ranging from 10 to 37% when compared to traditional methods. This financial benefit is complemented by substantial environmental advantages, notably in the reduction of material use and waste, contributing to a decrease in CO_2 emissions. Additionally, 3DCP has exhibited heightened cost efficiency in the building stage owing to reduced expenses on manpower and formwork [22].

On a global scale, the adoption of 3DCP is gaining momentum, with industry leaders like ICON spearheading initiatives in low-income housing construction. These endeavors underscore the technology's prowess in swiftly and economically constructing homes. For instance, ICON's undertaking in Mexico aimed at constructing 50 earthquake-resistant dwellings saw the successful completion of the initial two buildings within a total printing time of 24 hours, distributed across several days [2,3,10]. The collaborative efforts between the German University of Technology, COBOD, and CEMEX in Oman exemplify the rapid construction potential of 3DCP, enabling the construction of dwellings within a remarkably short five-day timeframe. CEMEX's innovations in mix design, utilizing locally sourced materials, have effectively driven down costs, resulting in considerable expenditure reduction. A noteworthy case study is the 'Office of the Future' project in Dubai, which showcased a 50% decrease in workforce and a 60% reduction in trash, underscoring the environmental advantages of 3DCP technology. Dubai's commitment to integrating 3DCP into 25% of its buildings by 2030 signals the profound impact this technology could have on the construction sector.

The alignment of environmental and economic benefits of 3DCP with global sustainability objectives presents a viable strategy to reduce carbon emissions in the building sector [6,9,46]. However, achieving widespread acceptance necessitates a continued commitment to innovation, cost reduction, and an enhancement in professional knowledge. From a holistic perspective, 3DCP represents a significant advancement in construction technology, poised to reshape the industry. Its demonstrated ability to curtail expenses and building durations while concurrently enhancing safety and sustainability positions it as a frontrunner in the future of construction. As printer costs continue to decline and material effectiveness advances, there is a foreseeable future where 3DCP could establish itself as the norm in construction, providing a sustainable and economically efficient alternative to conventional building techniques. However, to fully leverage the advantages of this technology, addressing challenges related to scalability and staff training becomes imperative as the sector progresses.

(6) Environmental sustainability

The construction and building sector stand as substantial energy consumers, accounting for 33-38% of global energy consumption and contributing a notable 15% to direct carbon dioxide emissions. In 2018, there was a noteworthy 1.7% surge in CO2 emissions within the industry, reaching unprecedented levels. Despite a brief reduction in emissions during the 2020 pandemic, the sector is not currently on track to achieve carbon neutrality by 2050. To align with this objective, all new structures and a considerable portion of existing buildings must be equipped to produce zero carbon emissions by 2030. While the building sector saw a significant increase in energy efficiency investments in 2021, primarily due to economic recovery, these investments must quadruple by 2030 to achieve Net Zero Emissions (NZE) by 2050. To meet the Paris Agreement's target of limiting global temperature increase to below 2 °C, an annual emissions reduction of 2.5% is imperative [4,5,6].

Within Southeast Asian nations, the construction industry constitutes a mere 25% of total energy consumption in the region. However, there are strategic plans in place to enhance energy efficiency and curtail emissions in this sector. The Level(s) framework, devised by the European Commission, advocates for sustainable and circular construction practices to minimize the environmental impact of structures in Europe. 3DCP emerges as a viable alternative for reducing material and water usage, waste generation, and energy consumption. Studies indicate its potential to decrease environmental impacts by up to 50% compared to conventional concrete methods, concurrently reducing material usage by approximately 40% and waste by up to 30% [47]. Additionally, it curtails fuel consumption, mitigates the environmental effects of transportation, and minimizes noise pollution during construction activities.

The integration of innovative and sustainable materials represents an additional avenue for minimizing the ecological footprint. Soil 3D printing, utilizing locally sourced clay and straw, provides effective thermal insulation but does not attain the same level of strength and durability as traditional 3DCP. The incorporation of glass and organic material recycling practices can significantly enhance concrete sustainability. Life Cycle Assessment (LCA) studies affirm 3DCP holds the potential to reduce cumulative energy consumption by 41–64%, resulting in a proportional decrease in CO2 emissions [31,44].

The construction sector, through design optimization, extending building lifespans, and adopting alternative materials with lower carbon intensity, has the potential to mitigate global CO2 emissions. The efficiency and reduced material utilization inherent in 3D printing technology position it as a promising solution for achieving these environmental goals. However, there exists a scarcity of studies examining the environmental consequences of 3DCP or digital concrete buildings. While various studies explore possibilities to reduce CO2 emissions in cement manufacturing and reconsider building design for structural efficiency and material conservation, comparisons between 3DP and older technologies showcase the superior environmental performance of 3DP, particularly in the production of intricate geometries.

In summary, 3DCP is an innovative technology with the potential to significantly alleviate the environmental impact of the construction industry. Aligned with international sustainability goals, it reduces emissions, resource utilization, and waste generation. To unlock its full potential, a continual drive for improvement and widespread acceptance is crucial, accompanied by extensive research on its environmental implications. To meaningfully contribute to the global sustainability and carbon neutrality agenda, responsible scaling of the technology is imperative, considering the complete lifecycle of building materials and the operational energy of structures.

(7) Structural forms and reinforcement method

- Contour Crafting Construction

Contour Crafting (CC), pioneered by Khoshnevis [18], introduces a distinctive approach to 3D printing, where the printer constructs concrete formwork subsequently filled with concrete. This method allows for manual placement of reinforcements, such as rebar, during or after the printing process, depending on the design specifications. Despite the need for precise calculation and design considerations for reinforcement, CC marks a significant stride in construction technology.

By 2016, Khoshnevis and NASA collaborated to build a two-story skyscraper, showcasing the viability and reliability of contour crafting. Subsequently, companies like Yingchuang Construction Technology set a record by constructing the world's tallest 3D printed apartment at Suzhou Industrial Park, emphasizing the use of 3D printed concrete in reinforced shear walls [13,17]. The versatility of 3DCP was exemplified in 2021 with the construction of a double-story home in Germany using three layers of material loaded with insulating chemicals [48].

Non-structural elements, such as columns and corrugated hollow walls, have been designed to enhance structural performance and stability. Noteworthy examples include Xtree in France, which created irregular truss-shaped columns, and ETH Zurich, which experimented with various column shapes for the Origen Festival. These advancements underscore 3DCP's adaptability to meet vertical load-bearing and structural forming requirements.

Despite its successes in replacing traditional formwork, 3DCP structures often rely on conventional reinforced concrete design calculations, not fully maximizing the technology's potential. Exploring the technical benefits of 3D printing in construction remains an ongoing endeavor. While contour crafting significantly improves construction efficiency, its true potential lies in integrating 3D printing into a broader spectrum of architectural design and engineering. This integration includes accurate computer modeling to predict mechanical behaviors of 3D printed materials and their interaction with conventional construction materials.

To unleash the full potential of 3D printing in construction, developments in material science and printing technologies are essential. This involves creating comprehensive models to anticipate how 3D printed materials will behave structurally and how printed buildings will interact with traditional construction materials. A more extensive utilization of 3DCP's capabilities may lead to the creation of entire load-bearing structures with intricate geometries and integrated functions.

- Reinforcement Technology

Integrating reinforcement within 3DCP structures poses significant challenges, including aggregate printing issues, material cracking, and weak interlayer bonds. Innovative solutions, such as the fork-shaped nozzle system by Huashang Tengda and pre-reinforcement technologies, aim to enhance the mechanical properties of 3DCP [4,6,8,15]. These approaches allow mesh reinforcement to be placed and printed simultaneously with concrete, but specialized printing equipment and further validation of the bond strength are required.

Manually inserting horizontal wire mesh during the wall printing process has been experimented with, showing improved interface properties and integration with other structural elements [23]. Although this method is more accessible and encourages broader adoption of 3DCP, its impact on the structural load-bearing capacity is somewhat limited.

ETH researchers have explored the potential of post-tensioned reinforcement within 3DCP columns, offering a diverse range of geometries beyond traditional prefabrication constraints [49]. While these methods enhance construction efficiency and provide reinforcement capabilities, they still face challenges in terms of labor efficiency and applicability to various structural forms.

In conclusion, developing effective reinforcement methods is crucial for the widespread application of 3DCP. While current techniques provide reinforcement, they compromise on time and labor efficiency. The potential of post-tensioned reinforcement needs further exploration for structural suitability. Alternatively, designing high-performance composite structures without traditional reinforcement could be a viable approach, focusing on innovative structural and material design to overcome current challenges in 3DCP reinforcement technologies.

From this perspective, while 3DCP represents a significant advancement in construction methodologies, the industry is still in the early stages of developing effective reinforcement strategies. The future of 3DCP may involve a convergence of material science advancements and novel design approaches, circumventing the need for traditional reinforcement while ensuring structural integrity. Progress in this field promises not only enhanced feasibility and safety of 3DCP structures but also a potential revolution in the construction industry, enabling more complex, efficient, and sustainable building practices.

(8) Existing limitations

- International Technology Specification Development

The unique attributes of 3DCP, including raw ingredients, mixing techniques, deposition procedures, and mechanical characteristics, necessitate the establishment of new specifications tailored to evaluate these distinctive features. Existing test procedures and standards for conventional cast concrete are inadequate for assessing 3DCP. Specifications should encompass rheological performance, mechanical strength, durability, theoretical and numerical modeling, serviceability, and lifespan evaluations for various architectural applications. Chung et al. have contributed significantly by proposing a comprehensive technical specification framework for 3DCP, considering fundamental and additional technological components essential for standardization. This framework, comprising 19 core and 67 additional elements across nine categories, serves as a crucial guide for the industry to ensure the durability and reliability of 3DCP buildings. Implementing these standards ensures uniformity, safety, and durability, paving the way for broader acceptance of this innovative construction technique. This effort not only advances building norms and regulations but also fosters an environment conducive to the growth of 3DCP, promoting the adoption of eco-friendly and efficient building practices.

- Mix Design Optimization

A critical aspect of successfully integrating 3DCP into the construction industry is the optimization of mix design to produce materials compatible with 3D printers. These materials must strike a balance of qualities suitable for the printing process, such as ease of pumping, fluidity for smooth flow and extrusion, minimal shrinkage, and dimensional stability. The diversity and individual features of 3D printers pose challenges in developing materials compatible with all systems. Customizing mix design for conventional concrete materials requires collaboration with material suppliers. Ready-mix powders and superplasticizers designed specifically for 3DCP, as seen in the partnership between COBOD and CEMEX, show promise in controlling setting time, buildability, shrinkage, and interlayer bonding. However, the intrinsic anisotropy of 3DCP introduces a significant challenge. The sequential deposition of filaments and layers results in variability in mechanical behavior due to parameters like the time interval between layer printings, applied extrusion pressure, and changes in rheological behavior during cement setting. This anisotropy can lead to varying strengths and durability under stress in different directions, presenting a challenge for structural engineers. Despite existing challenges, advancements in 3DCP material science and technology are progressing. The creation of standardized, printer-compatible materials is crucial for the broader utilization of 3DCP. A multidisciplinary approach integrating material science, engineering, and construction skills is essential to create and enhance materials and methods used in 3D printing.

- Construction Scale and Full Automation

The size and capabilities of current 3DCP printers on the market impose limitations on the scale and scalability of structures. Various types of printers, including robotic arms, gantry systems, and Delta systems, each with specific size restrictions, are available. While notable projects such as office buildings in Dubai and canal residences in the Netherlands showcase the potential of 3DCP, scaling efforts to larger complexes remains a significant challenge. The construction of multistory structures and the integration of 3DCP into the architectural realm face technological challenges. Continuous research and development are necessary to transition from lab-scale studies to large-scale building projects. Achieving complete digitization with minimal human interaction remains a goal, but certain tasks still require human labor, hindering the full realization of this objective. Despite existing restrictions, ongoing technological advancements may expand printing capabilities, enabling the construction of larger and more intricate structures. Progress relies on developing printers with higher build volumes, faster printing rates, and the ability to interface with other robotic systems. Additionally, advancements in material science are needed to create 3DCP formulations adapted to the requirements of large-scale buildings. The transformative potential of 3D printing in construction, with its ability to reduce labor costs, construction time, and material waste, indicates a promising future. As technology overcomes existing obstacles, 3DCP may become more prevalent in constructing diverse structures, from multistory skyscrapers to single-family houses.

- Reinforcing Structures

In the realm of 3DCP, deploying appropriate reinforcement remains a significant challenge, impeding wider acceptance for load-bearing constructions. Similar to traditional cast concrete, 3DCP exhibits inherent brittleness and weakness in tension, and existing reinforcing technologies do not fully address these limitations. The optimal reinforcing technique for 3DCP must enhance ductility, preserve geometric flexibility, be cost-effective, and environmentally friendly. Current techniques, while showing promise at a small scale, have not been thoroughly explored for larger buildings. These methods include integrating polymeric or metallic fibers within the printing material, pre-placement of steel bars, post-tensioning, simultaneous cable application during printing, 3D printing of steel or Fiber-Reinforced Polymer (FRP) bars or fibers, helical reinforcing rods, barbed-wire reinforcement, and polymeric reinforcing meshes. Combining diverse strategies may be the most effective way to reinforce 3DCP structures. Aligned interlayer fibers could provide basic reinforcement, with additional premixed fibers or cables for regulating shear or torsional loads. For wall-like constructions, preinstalled bars might manage flexural and tensile loads, while post-tensioning might be better suited for curved or complicated geometries. As 3DCP continues to evolve, further research and development are necessary to perfect these approaches and fully realize the promise of reinforced 3DCP in building.

- Cost and Environmental Concerns

The cost of 3DCP homes and buildings has witnessed a decline in the last decade, attributed to advances in printed materials, decreasing printer costs, the utilization of large-scale robotic printers, and the emergence of specialist 3DCP firms. Despite these advancements, comparing the cost of 3DCP houses with traditional concrete homes remains challenging, partly due to the higher initial costs in many nations and the evolving nature of 3DCP technology knowledge and public confidence. Cutting-edge housing options, such as Tesla's small home and BOXABL's foldable ready dwellings, present alternatives to traditional building techniques. These options provide economical and practical dwelling solutions, as do mobile cabins. Additionally, other technologies, like Tesla's solar-roof homes, may offer environmental advantages over 3DCP. While 3DCP holds promise for significant financial and environmental benefits, it is still in its infancy and faces competition from established and newer building approaches. The technology's ability to distinguish itself from other cutting-edge building technologies, coupled with ongoing advancements in cost-effectiveness, public trust, and awareness, will be crucial to its success. As scientists and engineers continue to address technological obstacles, the increased utilization of 3DCP for a variety of structures, from intricate multistory skyscrapers to single-family houses, is anticipated. The dynamic landscape of the construction sector ensures that 3DCP's potential will be shaped by its ability to stand out, adapt, and offer sustainable solutions in a competitive environment.

3. 3D concrete printing mix design for the experimental study

3.1 Materials properties

The intricate world of 3DCP unveils a challenge for the selection of printing materials [9]. This challenge is rooted in the profound differences that exist in mixtures and performance between 3DCP and traditional concrete. Navigating this intricate landscape demands a profound understanding of the material properties essential for the success of 3DCP applications.

- The Significance of Extrudability

Printability, a critical dimension, unfolds as a multifaceted consideration, delineated into extrudability and buildability [10]. Extrudability, the initial facet, stands as a linchpin in the 3DCP paradigm. It characterizes the concrete's ability for continuous extrusion through the nozzle—an indispensable requirement for the success of 3DCP. This seamless extrudability facilitates the deposition of concrete filaments, creating a bond with the preceding layer and preserving the structural integrity while maintaining the intended design shape. Achieving this delicate equilibrium necessitates a meticulous exploration of the rheological properties inherent in the concrete mixture.

- Navigating the Complexities of Buildability

Buildability emerges as the second pivotal dimension supporting the foundation of 3DCP. It encompasses the material's capacity not only for continuous extrusion but also for withstanding the mounting hydrostatic pressure generated by subsequent layer depositions [11-12]. This resilience is indispensable, ensuring the structural stability of the printed layers and guarding against collapses or distortions in the printed object. To address these intricate demands of 3DCP materials, a comprehensive approach to formulating a fine aggregate mixture and defining an accurate mixing ratio becomes imperative.

In summary, understanding the material properties in 3DCP involves a careful balance of factors. The interplay between extrudability and buildability sets the stage for successful applications in 3DCP. Taking all these factors into account, the Sikacrete^{R} -752 3D micro-concrete was selected for the fabrication of the 3D printed elements (Figure 1). Table 1 shows the technical information for this concrete.

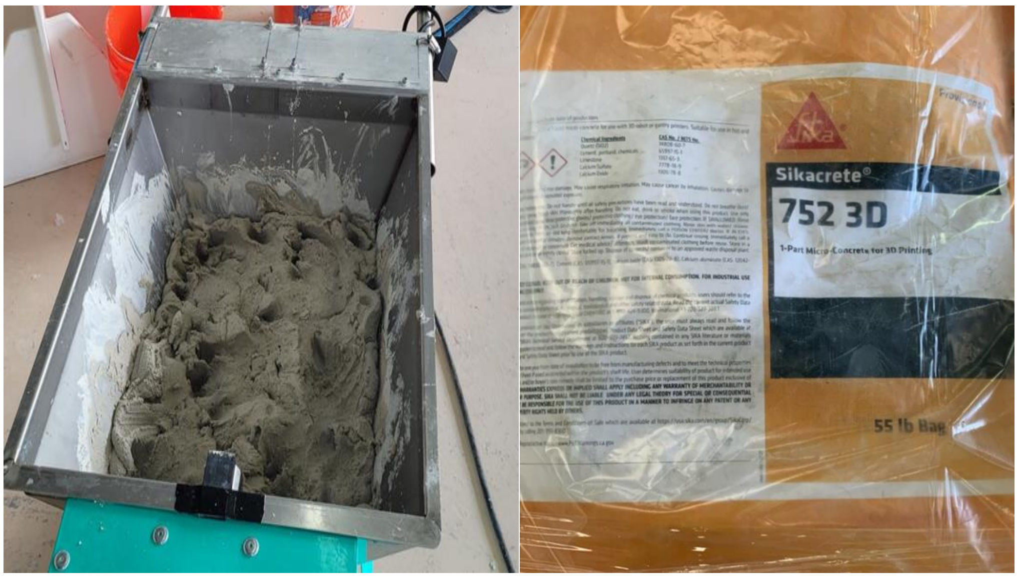


Figure 1. Sikacrete^{R} -752 3D micro-concrete

Table 1. Technical information of Sikacrete^{R} -752 3D micro-concrete

Compressive strength[1]	1st day	~2,900 psi
	7th day	~5800 psi
	28th day	~7,250 psi
Flexural strength[2]	~1,000 psi	
Water penetration under pressure[3]	~0.8 inch	
Service temperature	Under 212 °F	

1) Tested at +77 °F, w/c=17% (1.10-gallon water per 55 lb bag) (ASTM C109)

2) Tested at +77 °F, w/c=17% (1.10-gallon water per 55 lb bag) (ASTM C348)

3) Tested at +77 °F, w/c=17% (1.10-gallon water per 55 lb bag)

3.2 Machine selection and setup

Extensive market research and an evaluation of cost performance have led the team to the discerning choice of the 3D Potter Scara Elite (Figure 2). It boasts an X-Y-Z build volume of 112 inches in diameter and 68 inches in height, with an average printing speed ranging from 1.2 to 3.9 inches per second. The *G-Code* file, sliced by *Simplify3D* with specific printing parameters, is uploaded to the *Scara* web browser interface for precise printing control. During printing, details such as layer time, estimated printing time, and remaining time can be monitored through the web interface. To facilitate continuous material extrusion, the *IMER Mighty Small 50 flow pump* is connected to the printer. This pump can supply concrete with a variable flow rate ranging from 1.7 to 54 cubic feet per hour, pumping up to 6.7 gallons of material per minute through 85 ft of 1 inch hose. The equipment, including the pumper and printer, is shown in Figure 2. The selection of a 0.6 inches nozzle size is based on considerations of mixture fluidity, printer printing speed, and pumping rate.

Figure 2. 3D concrete printing machine and pump used in this project

4. 3D printing of concrete beams with and without reinforcement

4.1 Dimensions and intricacies of the beam

To investigate and assess the long-term printability and buildability of 3D concrete for PBES in comparison to traditional cast elements, small-scale 6×6×21-inch concrete beam structures were designed for fabrication as illustrated in Figure 3. In addition to the traditional cast and fully 3D printed concrete, some innovative production techniques were considered. The plain beam with printed formwork involves creating the formwork through 3D printing, followed by concrete pouring. The plain beam with printed stud's formwork technique utilizes a 3D printer to fabricate a formwork structure with studs, enhancing the shear connection between distinct pieces. Various beam sample manufacturing processes have been designed and scheduled for fabrication, including the casted plain beam, plain beam with printed formwork, plain beam with printed studs' formwork, and fully printed beam. Reinforcing concrete with rebar, mesh, fibers, or staples plays a crucial role in increasing flexibility, enhancing tensile strength, and reducing cracking and failure [14]. The most common and cost-effective approach is passive reinforcement, where the reinforcement is placed during manufacturing in a 'passive' manner, such as 3D printed concrete with conventional steel reinforcement. This method positions the steel reinforcement horizontally between 3D-printed concrete layers, providing a straightforward way to establish a regular reinforcing scheme in structural elements with a standard geometry. Beyond steel rebars, staples are also indicated and utilized for concrete reinforcement. In this part of the experiment, nine samples will be created and evaluated using the four approaches mentioned previously, with or without rebar and staples. Figure 4 illustrates the reinforced detailing of the concrete beam.

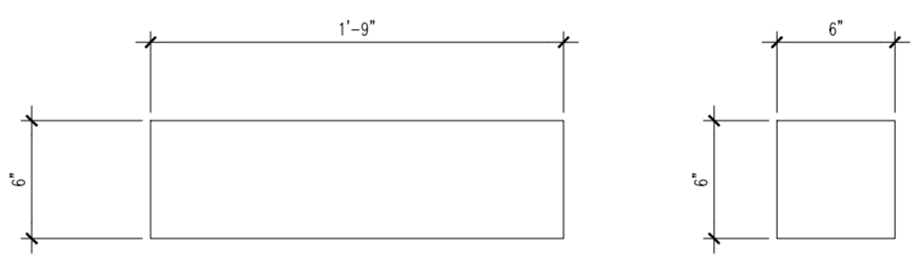


Figure 3. Dimensions of the fabricated beam

Figure 4. Reinforcing details used in the fabricating beam

4.2 3D printing model preparation

Sample models for 3D printing are designed using *SolidWorks* software and then sliced in *Simplify 3D* software for importing into the printer. The designed 3D models for the plain beam with printed formwork, plain beam with printed studs formwork, and fully printed beam are depicted in Figure 5.

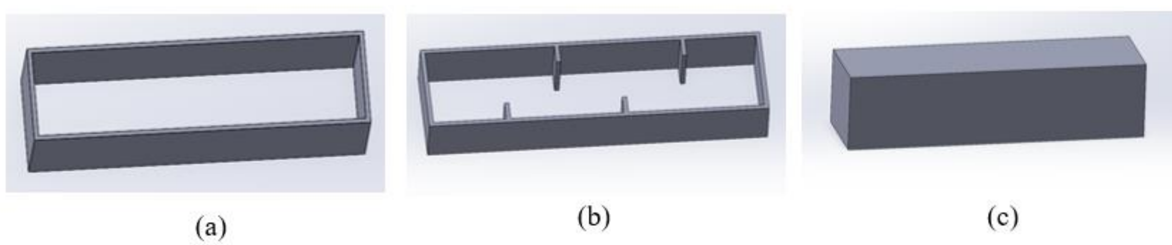


Figure 5. Prepared 3D printing models a) Printed formwork b) Printed studs formwork c) Fully printed

4.3 Beam fabrication

Several samples were manufactured including: 1) Cast plain beam; 2) Cast rebar-reinforced beam; 3) Plain beam with printed formwork; 4) Rebar-reinforced plain beam with printed formwork; 5) Plain beam with printed studs formwork; 6) Rebar-reinforced plain beam with printed studs formwork; 7) Fully printed plain beam; 8) Fully printed rebar-reinforced beam; and 9) Fully printed metal staple-reinforced beam. The reinforcement ratio was the same for the reinforced samples. The printing process for samples 3-9 is exhibited in Figure 6. Formwork printing for samples 3 and 4 took 6 minutes, for samples 5 and 6 involved a duration of 7 minutes and 15 seconds, and for samples 7-9 took 14 minutes, respectively. The casting process was executed for 4 days following the completion of printing, utilizing 3 bags of mixture for each sample. All samples underwent a 28-day curing process under uniform conditions.

4.4 Results and discussion

The testing was carried out at Pitt's Watkins-Haggart Structural Engineering Laboratory (WHSEL) using the Instron compression test machine, which has a maximum capacity of 20 kips. Following a 28-day curing period, a three-point bending test was conducted on the nine specimens to characterize their mechanical properties. Figure 7 provides an overview of the beam test location and layout. Force was applied to the center of the specimen at a speed rate of 0.003 in/min until failure occurred. The samples were continuously loaded until failure.

The failure of concrete beams under various manufacturing methods is illustrated in Figure 8. All samples experienced significant failure. Measurements of the applied force at a specific moment and position at the applied force point were typically taken and recorded. The test results primarily serve to determine the flexural stress (σ_f) and flexural strain (ε_f) of concrete, which are calculated using the following equations:

$$\sigma_f = \frac{3FL}{2bd^2} \tag{1}$$

$$\varepsilon_f = \frac{6Dd}{L^2} \tag{2}$$

where, *F, L, b, d,* and D indicate the applied force at given moment, span length, beam width, beam thickness, and deflection at the applied force point, respectively.

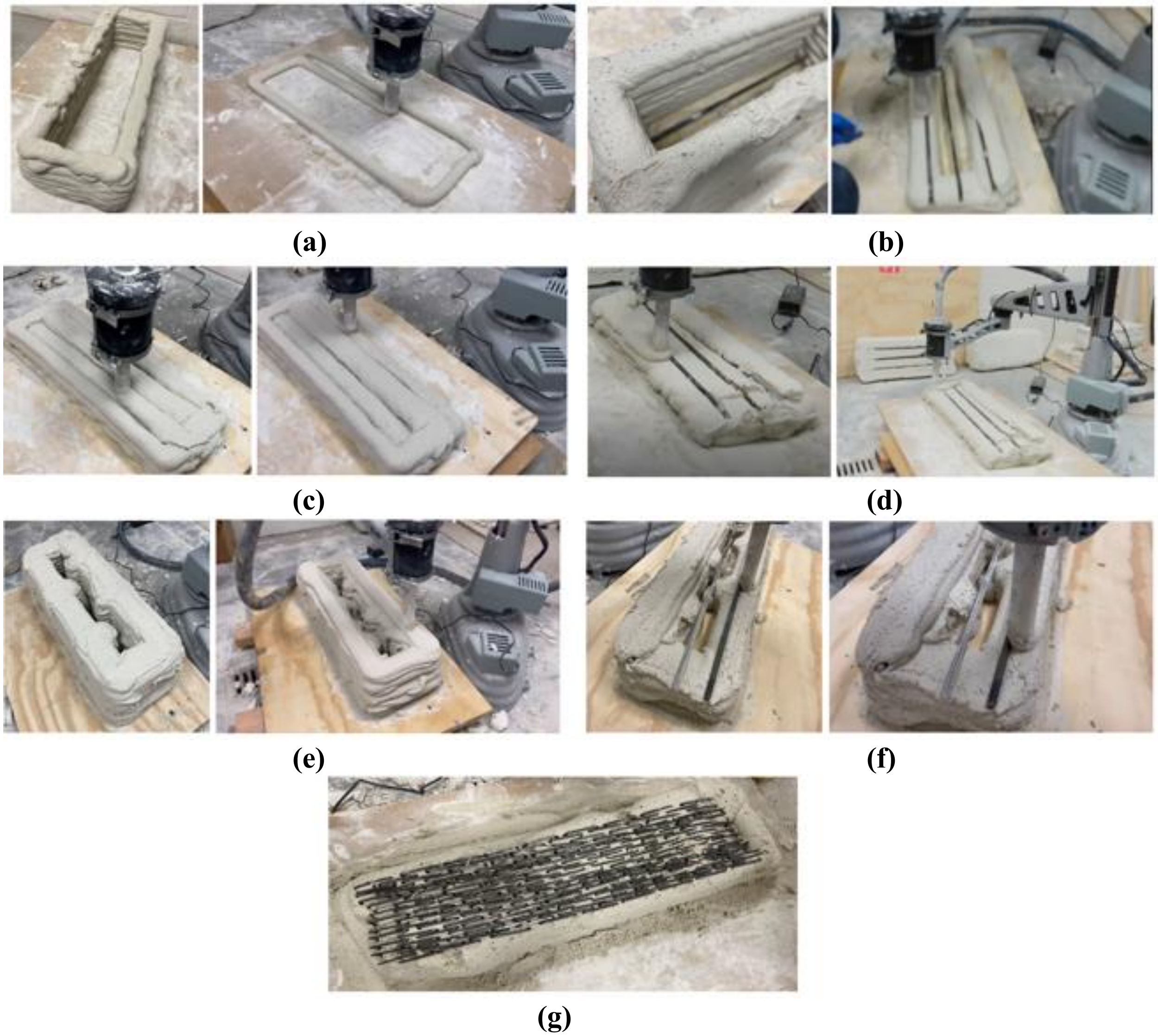
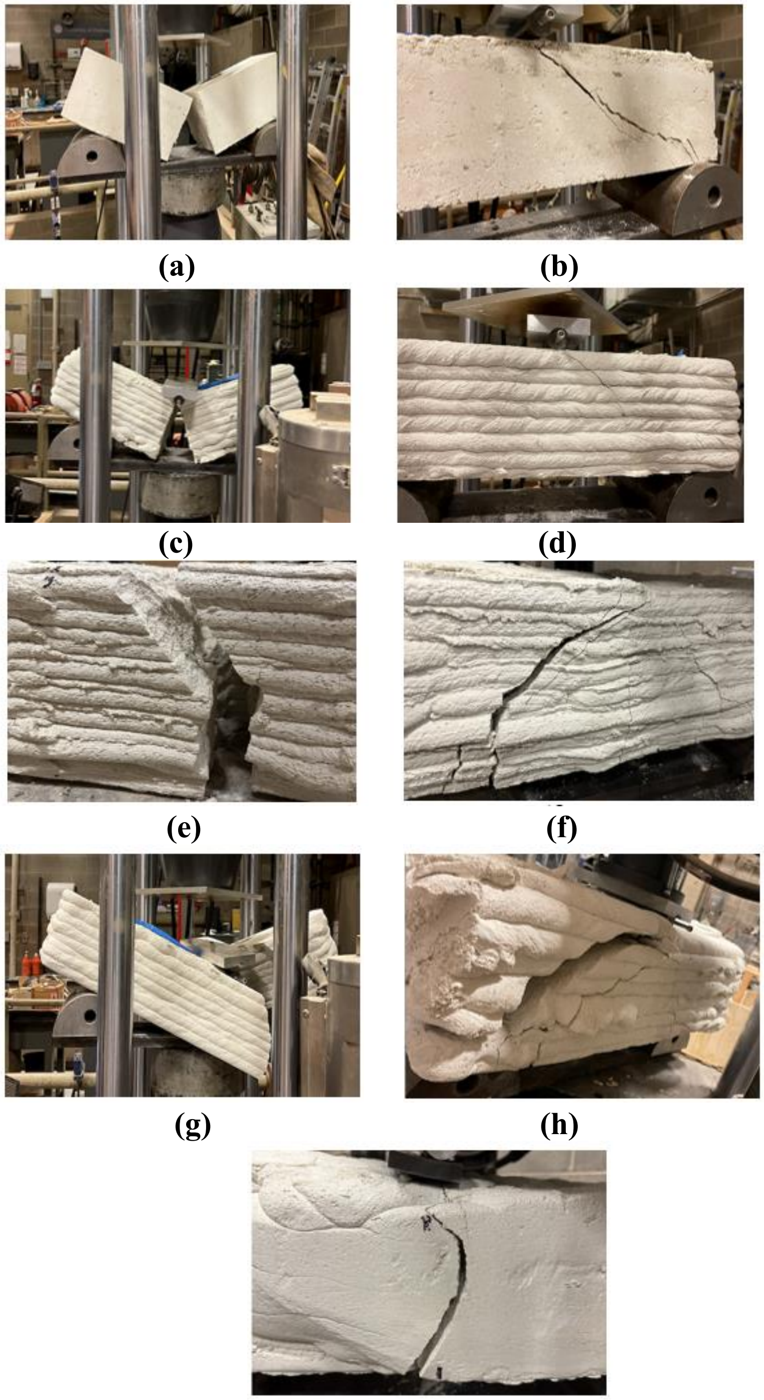


Figure 6. Beam fabrication printing process a) plain beam with printed formwork; b) rebar reinforced plain beam with printed formwork; c) plain beam with printed studs formwork; d) rebar reinforced plain beam with printed studs formwork; e) fully printed plain beam; f) fully printed rebar reinforced beam; and g) fully printed staples reinforced beam

Figure 9 shows the strain-stress relationships of the concrete beams. Samples fabricated using the 3DCP method demonstrated acceptable performance, particularly the fully 3DCP sample. Although the strength of 3DCP formwork specimens, with or without studs, did not match expectations compared to traditionally cast concrete, the flexural strength increased significantly after reinforcement incorporation. The reinforced 3DCP formwork with studs and the fully 3DCP samples showed that the application of 3DCP formwork technology, potentially in conjunction with traditional concrete mixtures, can enhance concrete strength. This is an important observation as formwork costs in traditional concrete casting projects account for 35% to 60% of the total cost of the completed projected[1]. Using 3DCP for constructing the formwork can substantially decrease these expenses while ensuring optimal performance. However, the test result for fully 3DCP with staples was undesirable. The consistency length and overlaps of staples require additional investigation, which could significantly impact reinforcing capabilities. Table 2 summarizes the properties of each concrete beam at ultimate strength. Considering further fabrication and the process of placing reinforcement, reinforced 3DCP formwork with studs has been identified as a novel fabrication approach for additional prefabricated bridge elements.

Figure 7. Three-point bending test setup

[1] Cost-effective forming <http://www.concreteconstruction.net>



(i)

Figure 8. Failure Beams a) Cast plain beam; b) cast rebar reinforced beam; c) plain beam with printed formwork; d) rebar reinforced plain beam with printed formwork; e) plain beam with printed studs formwork; f) rebar reinforced plain beam with printed studs formwork; g) fully printed plain beam; h) fully printed rebar reinforced beam; i) fully printed staples reinforced beam

Table 2. Concrete Beam Properties at Ultimate Strength

Sample	Strain (in/in)	Stress psi
Without Rebar		
Casted Plain	0.010	627.4
3DCP Formwork	0.012	379.0
3DCP Formwork with Studs	0.015	271.9
Fully 3DCP	0.021	761.5
With Rebar		
Casted Plain with Rebar	0.022	1687.1
3DCP Formwork	0.035	1529.7
3DCP Formwork with Studs	0.036	2029.7
Fully 3DCP	0.033	1876.6
Fully 3DCP with *Staple*	0.011	348.9

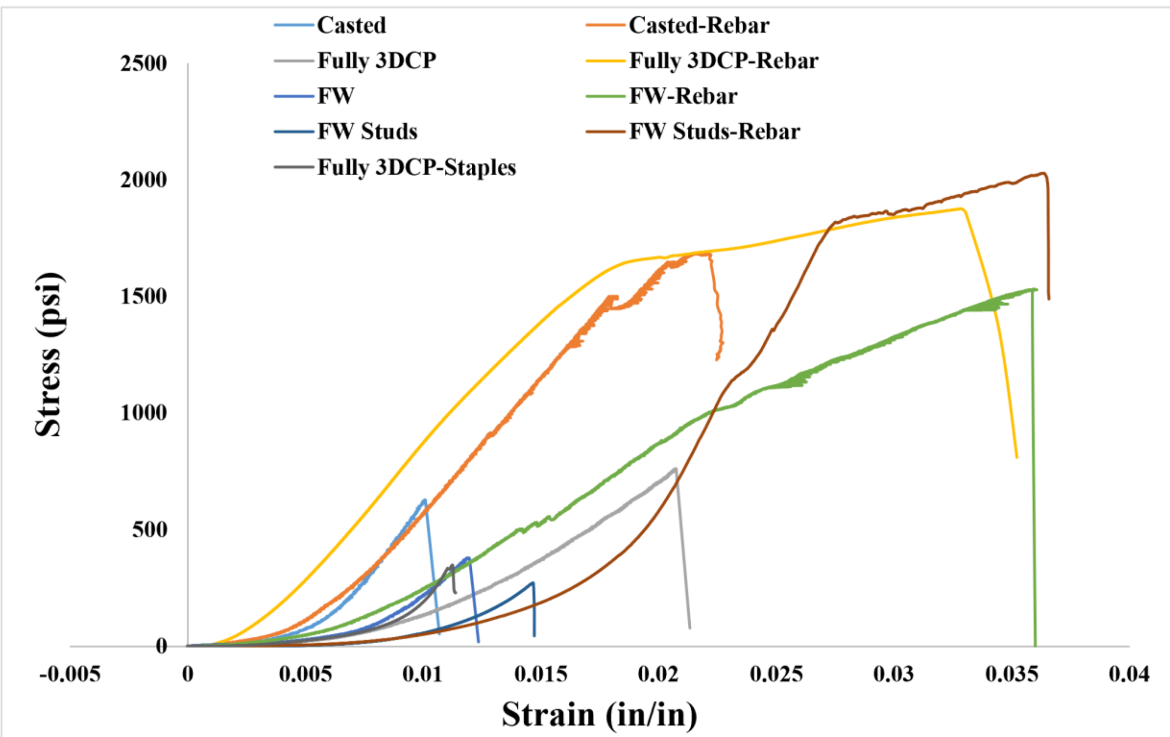


Figure 9. Strain-stress curve of the fabricated concrete beam

5. 3D concrete printing in ABC systems

5.1 Bridge main components review and selection

Bridges represent critical infrastructural systems, comprising several fundamental elements that collaborate to ensure stability, functionality, and durability, thereby ensuring the safety of passengers and motor vehicles navigating the bridge [15]. Figure 10 illustrates various components of a traditional bridge system, considered suitable candidates for fabrication [15]. The superstructure encompasses decks, parapets, and girders, with its primary goal being to support and distribute loads, including but not limited to the bridge's self-weight, traffic and pedestrian loads, as well as environmental factors like wind and earthquakes. The substructure includes abutments, pier caps, and foundations, offering support to the superstructure and transferring loads into the ground. The bearing, typically positioned between the girder and the pier cap, serves to connect superstructure and substructure elements. Each component plays a significant role, being an essential part of the bridge system. After discussions with the project panel members and considering the roles of bridge components, fabrication methods, properties of 3D printing machines, and practical operations, the pier cap was identified as the suitable component for this study. Following the outcomes observed in the 3D printed beam study, the decision was made to adopt reinforced 3DCP formwork with studs for the fabrication of the pier cap.

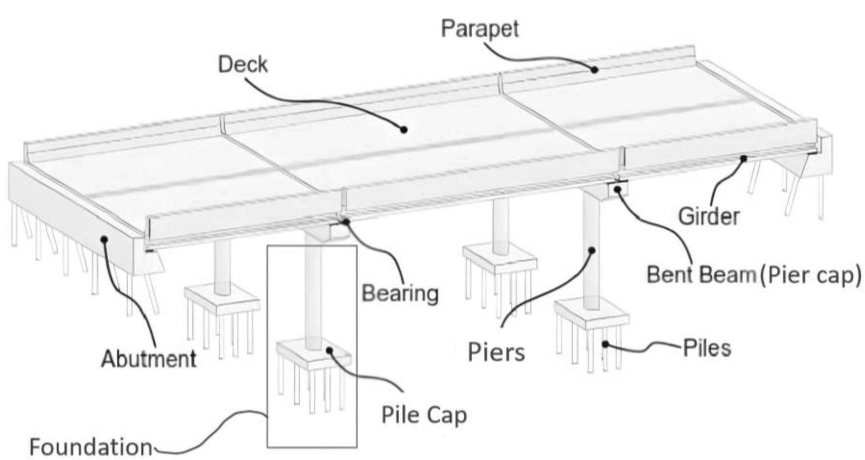


Figure 10. Typical bridge components [15]

5.2 Pier cap description and detailing

The 28-day compressive strength of the concrete is 7250 psi, and the yield stress of the reinforced steel is 60 ksi. The investigation specifies the maximum printing size in the X and Y directions as having a diameter of 112 inches, and the test machine capacity is approximately 225 kips. Considering the 3D printing machine's maximum printing size in the X-Y-Z direction and the capacity of Pitt's WHSEL compression test machine, Figure 11 depicts the geometry of the pier cap. The overall length of the cap beam is 48 inches, with a cantilever span length of 15 inches. Due to the unique liquidity of the printing concrete and the manufacturing method, the cap beam is designed as a rectangle with no slope, perpendicular to the pier. The cross-sectional area of the pier cap is 16×20 inches, and the cross-sectional area of the pier is 16×10 inches.

The reinforcing details for the bridge pier cap design are illustrated in Figure 12. Four No. 7 longitudinal tension ASTM standard reinforcing bars are positioned at the top of the pier cap in one layer. These bars are anchored with 90-degree standard bending hooks with a bend diameter of 6db; the development diameter is based on the ACI 318-14 [16]. The transverse reinforcing comprises 6 No.3 stirrups uniformly distributed with a spacing of around 8 inches. In the pier cap beam region, the reinforced ratio for horizontal and vertical is 0.005 and 0.016. Four No.6 longitudinal reinforced rebars are on each side of the pier, with three No. 3 stirrups spaced around 4 inches on-center. It is noteworthy that this test is designed to be shear failure-dominant, rather than flexural failure.

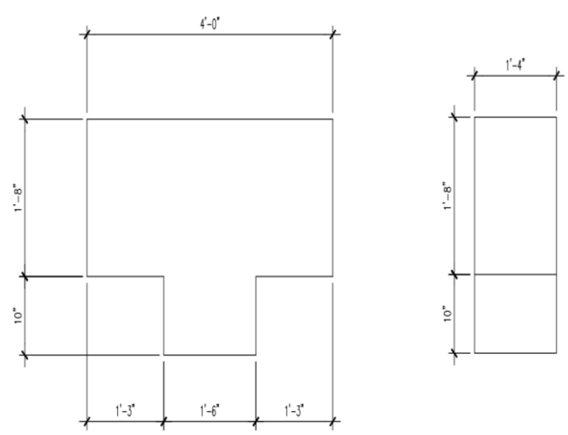


Figure 11. Geometry of pier cap (dimensions in inches)

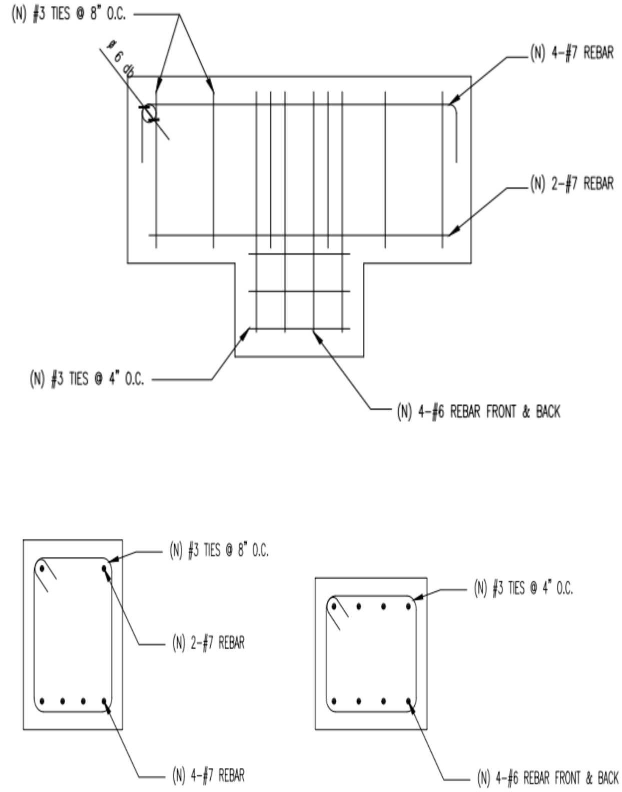


Figure 12. Reinforcing detail for pier cap

5.3 Conventionally cast and 3D printed pier cap fabrication

5.3.1 Reinforced steel cage fabrication

The well-constructed steel cage serves as a critical component of the concrete pier cap structure, providing essential tensile strength. The fundamental dimensions and details of the steel cage strictly adhere to the reinforcing detail drawings described earlier. Steel rebars are cut and bent to the required length and specific shapes in the rebar manufacturing company, and then shipped to the laboratory. Subsequently, 16-gauge black oxide steel and 6 inches overall length double-loop wire ties are employed to manually assemble the rebars, with a handle twist. The tying process involves securing the intersections of the rebars with the wire ties, maintaining the cage shape and structural integrity. To further secure the position of the cage, 3×15×3-inch steel slab bolsters are added at the bottom, ensuring the correct depth of the cage within the concrete at 3 inches. The head and tail of the slab bolsters are cut off to fit the size of the concrete. The final completed reinforcing steel cage is depicted in Figure 13.

Figure 13. Reinforcing steel for pier cap

5.3.2 Fabrication of conventionally cast reinforced pier cap

In civil engineering projects, the conventionally cast prefabricated pier cap fabrication method is a standard practice for bridge components. An integral step in the conventional cast prefabricated reinforced pier cap fabrication involves creating formwork. Due to the insufficient strength of thick plywood sheets to support the weight of concrete, sturdy No.2 wood studs are added for reinforcement. The formwork is crafted using ½ inch thick plywood sheets and 2×4-inch SPF wood studs, meticulously cut to match the geometric dimensions. The manual cutting and assembly of formwork may result in minor gaps in wooden joists, potentially compromising the structural integrity of the formwork. To address this, waterproof duct tape is applied to seal gaps, preventing concrete leakage during the settling period. Once the reinforcing steel cage is positioned within the formwork, the concrete mixture is prepared for casting. A total of 24 bags of

3D micro-concrete are mixed and poured into the formwork. A vibrator is employed to eliminate trapped voids and air bubbles from the wet concrete, ensuring long-term durability. To minimize temperature differentials and maintain concrete humidity during the curing period, a plastic mat is used for coverage. The fabrication process for this specific pier cap takes approximately 7 hours, encompassing formwork creation, concrete casting, and formwork dismantling.

Figure 14. Conventionally cast prefabricated reinforced pier cap

5.3.3 Fabrication of 3D printed reinforced pier cap

3DCP, with its additive manufacturing technologies, presents a novel and distinctive approach compared to traditional pier cap fabrication. The entire process, including printing, assembly, and pouring, was executed in three distinct phases. Figure 15 (a) illustrates the model preparation in SolidWorks for the printing process, and Figure 15 (b) the printer's actual printing model. The stud size, determined at 0.75× 0.75 inch, was chosen by considering the printing nozzle size, practical printing width, and space reserved for the reinforcing cage. After the final layer of cap beam printing, the reinforcement was placed inside the formwork. The pier part was printed separately from the cap beam and assembled after more than 3 days of printing to ensure proper concrete curing. The printing formwork for the cap beam with studs and the pier process required 8 bags of 3D micro-concrete. The pouring process was initiated 5 days after completing the printing, utilizing 14 bags of mixture. The construction duration for this pier cap is estimated to be around 3.5 hours, covering the 3D printing concrete time of 30 minutes.

(a) (b)

Figure 15. (a) Prepared model using SolidWorks and (b) actual printing

Figure 16. 3DCP of pier cap formwork

5.4 Results discussion

After 28 days of controlled concrete curing, the test specimens were transported to the experiment location using a forklift in preparation for the compression test. Two #4 rebars were left outside to facilitate slinging the specimens and fitting them inside the machine. Figure 17 illustrates the pier cap test location and layout details. For simplicity in the experiment procedure, the pier cap was tested in an inverted position. Two 2-inch diameter rollers were positioned under the pier cap at an edge distance of 6 inches. Axial compression load was applied using a computer-controlled universal testing machine at the top center of the pier cap with a test rate of 0.002 in/s. The data was recorded at a frequency of 10 Hz, and the load was applied until failure occurred.

Figure 17. Test setup for the prepared 3DCP pier cap

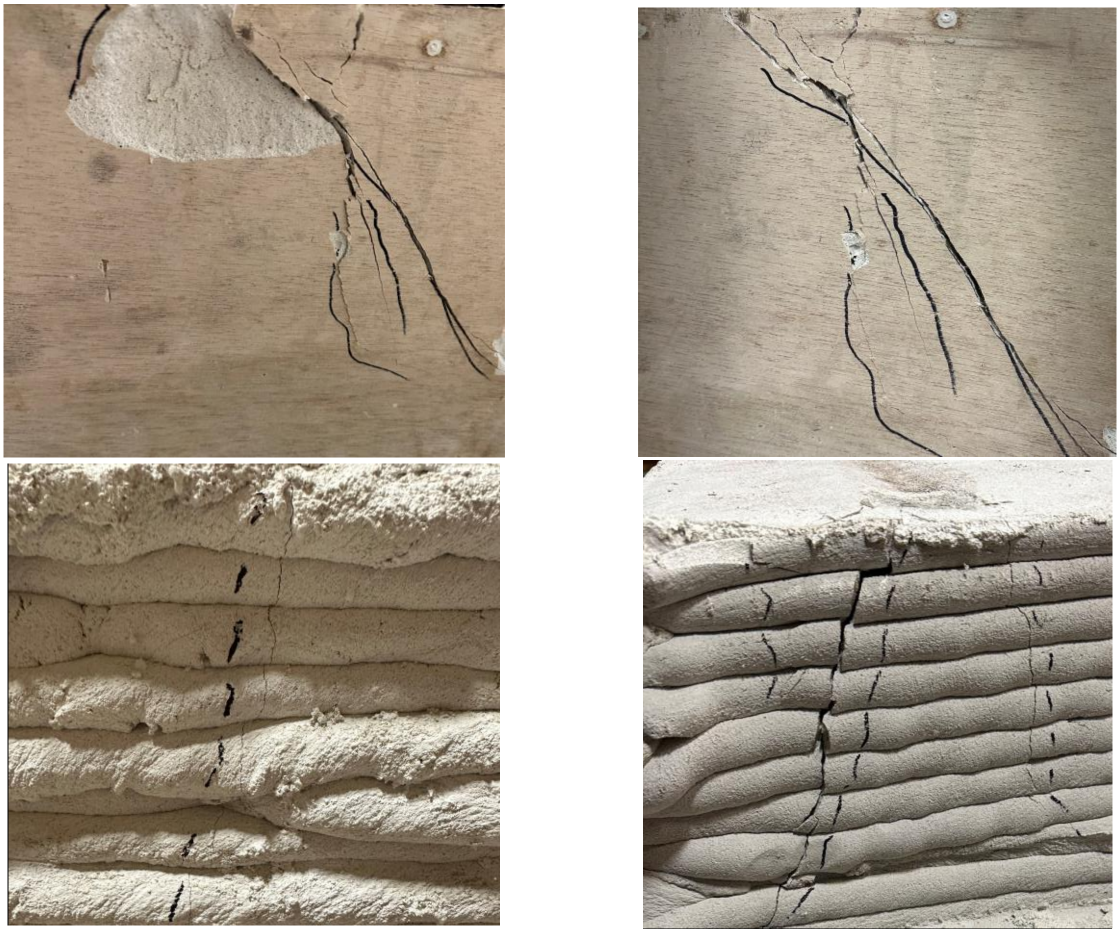


Figure 18. Shear failure of pier cap

Figure 18 shows the failure of the pier cap. These cracks are distinctive and easy to distinguish, identifying as shear failure which is conformity with previous conjecture and calculation. Both specimens had significant yielding before achieving the maximum applied load.

Figure 19 illustrates the compression stress-strain relationships for conventionally cast prefabricated and 3DCP reinforced pier caps. Both conventionally cast prefabricated and 3DCP reinforced pier caps demonstrate a relatively close ultimate flexural stress of around 1.6 ksi. The primary distinctions are evident in stiffness and strain at failure. The 3DCP pier cap exhibits the steepest rise, indicating higher stiffness. The conventionally cast prefabricated reinforced pier cap has a higher strain at failure, approximately 0.0265, compared to the 3DCP pier cap with a strain at failure of 0.0230. As stress reaches around 0.4 ksi, the concrete exhibits linear behavior, suggesting an almost identical modulus of rupture for the two concrete pier cap samples.

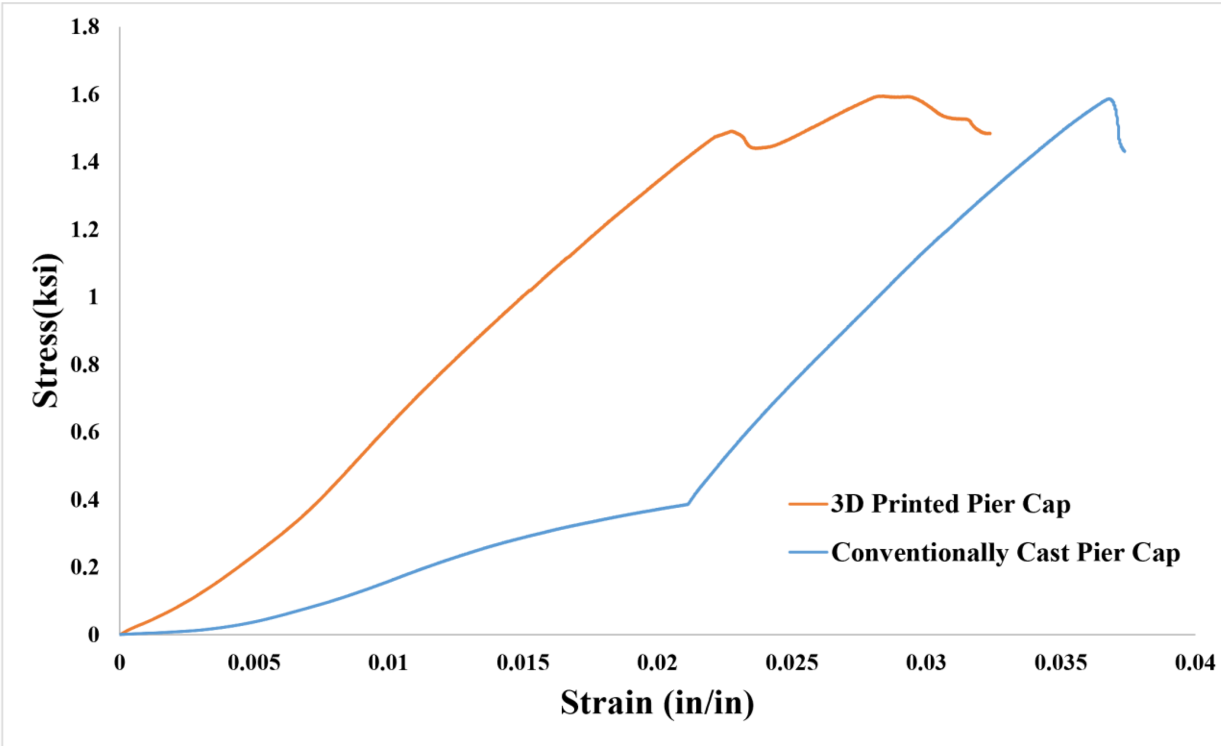


Figure 19. Stress-strain curve obtained during compression test

6. Concluding remarks

6.1 Conclusion

In this project, we investigated the feasibility of using additive manufacturing for developing PBES to advance bridge construction technology. Addressing the incorporation of reinforcement in 3DCP stands as a significant challenge to advancing this technology further. Therefore, our emphasis was on refining and scrutinizing a range of reinforcement strategies for 3DCP. On this basis, multiple concrete beams were 3D printed with different reinforcement strategies and compared with their conventionally cast counterparts. The 3DCP mixture was chosen based on rheological and mechanical properties and the capabilities of the 3D printing machine. 3DCP models were executed and prepared, considering machine printing speed, pump rate, and nozzle size. Pier cap was selected as the PBES for 3D printing. Based on the results, 3DCP beams without refinement demonstrated acceptable strength results compared to the conventionally cast samples. This is while the 3DCP technology for prefabricated elements proved to use fewer materials and have shorter manufacturing times. Reinforced 3D printing formwork with studs showed significantly higher strength than all other samples and was selected for further bridge elements fabrication. Surprisingly, the sample fully printed with staples has the lowest strength despite using the same reinforcement ratio as the other samples. The reinforced conventionally cast prefabricated pier cap provided a similar strength to the cap with reinforced 3DCP formwork with studs. However, the 3D printed pier cap exhibited higher stiffness. During the course of testing, the effects of the combined composite section, of the printed form, and the concrete filled section could be observed. This observation highlights another advantage, where the printed form becomes an integral part of the completed element.

However, despite the significant interest in the 3DCP technology, it appears that its application might not yield as significant advantages within a workshop setting when compared to its utilization in the field. Concrete fabricators demonstrate noteworthy efficiency in form reusability, particularly with standardized beam sizes and shapes. However, the potential impact of the 3DCP technology is likely to be substantial in scenarios where contractors are engaged in on-site fabrication of beam elements, such as in the construction of a cast-in-place segmental bridge. Also, one primary challenge that emerges in this context is the reinforcement aspect revolves around elements normal to the cross-section, particularly in the local z-direction, including any steel components. This challenge extends to various elements, such as post-tensioning ducts, underscoring the need for a nuanced approach to address these intricacies in the integration of the 3DCP technology for on-site fabrication projects.

6.2. Future works

Several recommendations for future work are suggested as follows:

(1) Further exploring the stapling reinforcement method (e.g. understanding how overlaps influence strength). The stapling reinforcement method is appealing as it can be used to fully automate the 3DCP process.

(2) Exploring the scalability of 3DCP technology for larger infrastructure projects, including bridges. Assess the feasibility of upscaling the printing process while maintaining the structural reliability of PBES, considering real-world construction scenarios and challenges.

(3) Investigating the integration of smart technologies, such as sensors and monitoring systems, into 3DCP prefabricated elements. This could enable real-time structural health monitoring, contributing to proactive maintenance strategies and enhancing the longevity of bridge components.

6.3. Further considerations

The proposed experimental study and literature survey reveal both promising possibilities and inherent limitations in the current 3DCP technology. A thoughtful exploration of these limitations is required to advance 3DCP for ABC projects:

(1) Material discrepancies: The divergence in materials between 3DCP and traditional concrete introduces a challenge. The existing testing and evaluating standards, predominantly tailored for traditional concrete, may not seamlessly align with the distinctive properties and behaviors of 3DCP materials. For instance, given the variance in material composition compared to traditional concrete, it is imperative to conduct additional studies aimed at establishing specific specifications for crack sealing and the application of penetrating sealers in structures constructed through 3D printing technology.
(2) Dimensional constraints: While 3DCP holds promise for structural designs, the overall dimensions achievable are tethered to the constraints of the printing system and printer size. This limitation poses a challenge when envisioning large-scale applications, such as bridges or expansive structural components, where conventional construction methods might currently offer more flexibility.
(3) Reinforcement methodology: A critical bottleneck in the trajectory of 3DCP's evolution lies in the implementation of reinforcement. The current state of affairs underscores that a robust and efficient method for integrating reinforcement into 3DCP structures is yet to be fully realized. The absence of a streamlined and automated process for reinforcement installation hinders the seamless transition of 3DCP into a bona fide large-scale construction methodology.
(4) Manual intervention: Manual inputs are still indispensable in various phases, including design intricacies, material preparation, the intricate process of installing reinforcement, and post-processing tasks. This reliance on manual intervention introduces an element of variability and

raises questions about the scalability and efficiency of 3DCP in achieving large-scale, automated construction.

(5) Durability and long-term performance: While the focus often rests on short-term structural performance, there is a paucity of comprehensive studies addressing the long-term durability and performance of 3DCP structures. Understanding factors such as material degradation, resilience to environmental factors, and the evolution of structural properties over time is crucial for establishing the true longevity and sustainability of 3DCP construction.

(6) Economic viability: Despite its potential, the economic feasibility of 3DCP on a large scale remains a critical concern. The cost-effectiveness of materials, the efficiency of the printing process, and the overall life-cycle cost analysis need meticulous examination to position 3DCP as a viable and competitive construction method on a broader scale.

(7) Environmental impact: Conducting a comprehensive assessment of the environmental impact of 3DCP technology in the fabrication of PBES can involve analyzing factors such as material consumption, energy usage, and waste generation to ascertain the sustainability credentials of 3DCP compared to traditional construction methods.

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7. Appendix I: Pier cap estimate design calculations

The following estimate design calculation factors and equations based on ACI 318-14. For the experiment, nominal capacity is deal for $\phi = 1$.

Flexural:

With $\phi, A_g, A_{st}, f_c', f_y$ the nominal flexural strength at section can be calculated:

$$\phi Pn = 0.8\phi[0.85f_c'\left(A_g - A_{st}\right) + f_y A_{st}] \quad (3)$$

$$\phi Pn = 0.8 * 1 * [0.85 * 7.25ksi * (320in^2 - 5.25in^2) + 60ksi * 5.25in^2] \quad (4)$$

$$\phi Pn = 1803\ kips$$

Shear strength:

With d assume equal to the height of the cap beam,

Nominal shear strength provided by concrete (V_c):

$$V_c = 2\sqrt{f_c'}b_w d \quad (5)$$

$$V_c = 2 * \frac{\sqrt{7250\ psi}}{1000} * 16\ in * 20\ in = 54.5\ kips \quad (6)$$

Nominal shear strength provided by reinforcement (V_c):

$$V_s = \frac{A_v F_y d}{s} \tag{7}$$

$$V_s = \frac{2 * 0.11\ in^2 * 60\ ksi * 20\ in}{8\ in} = 33\ kips \tag{8}$$

with the $V_c\ and\ V_s$, the nominal shear strength at section can be known:

$$\phi V_n = \phi(V_c + V_s) \tag{9}$$

$$\phi V_n = (44.11\ kips + 22\ kips) = 87.5\ kips \tag{10}$$

Based on the calculation above, the estimate applied load will be around 175 kips.

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