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3D Concrete Printing (3DCP) Education in the Construction Industry

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Revolutionizing the construction industry, Three-Dimensional Concrete Printing (3DCP) technologies offer a practical remedy for material and labor shortages, mitigating supply chain risks while simultaneously ushering in a wave of new job opportunities demanding advanced skills. The technology is complex though and teaching practices in construction education and professional development need to address the new skills requirements for working with the new technology. The goal of this paper is to provide an overview of the current status of 3DCP education and 3DCP educational needs and opportunities in the construction industry. This paper provides a review of existing efforts in the education of 3DCP. It also explains a case study of the design and construction process of a 3D printed affordable house focusing on the 3DCP education needs and the training approach in the case study project. The research results provide an understanding of current efforts in 3DCP training, potentials of 3DCP education in construction, and the path forward for required education of 3DCP in the construction industry.

Key Words: 3D Concrete Printing, 3DCP, education, training, construction, 3D printing

Introduction

The emergence of three-dimensional concrete printing (3DCP) technologies provides a viable solution to construction material and labor shortages (Mohammad et al., 2020) as well as supply chain risk and introduces new opportunities for jobs with advanced skills. 3DCP is in fact an additive manufacturing technique for building concrete structures by extruding concrete layer by layer without the use of formwork (Mohammad et al., 2020; Sanjayan & Nematollahi, 2019). The 3DCP technology is complex and, as in any new technology, teaching practices in education and professional development need to be developed. 3DCP technology has shown potential to improve productivity, reduce the environmental impact of the construction industry (Mohammad et al., 2020). However, the construction industry requires a skilled workforce to adopt the technology and implement the potentials of 3DCP. As a result, construction education and professional development need to address the new skills requirements for working with the new technology. The goal of this paper is to provide an overview of the 3DCP education in construction and for workforce training. This research seeks to address the following research questions: (1) what is the current status of 3DCP education in construction; and (2) what 3DCP educational needs and opportunities exist for the construction workforce? In the following sections, the paper first explains the importance and evolution of 3D concrete printing technology and then describes potentials for 3D printing education. The research methodology is explained and results are provided accordingly. Then, the discussion and conclusion sections highlight opportunities and research needs in 3DCP education in the construction industry.

3DCP in the Construction Industry

Thomas Edison spent as much time with his other inventions as with creating a machine to build concrete houses in a single pour. Patented in 1917, the complexity of concrete failed his vision (Sanjayan & Nematollahi, 2019). More than a century later, 3D concrete printing is revolutionizing the construction industry. 3DCP is a computer-controlled process to build concrete structures by extruding concrete layer by layer with a printer nozzle (Mohammad et al., 2020). Conventional approaches cast concrete into a mold while 3DCP combines digital technologies and material characteristics to allow concrete construction without the use of formwork (Sanjayan & Nematollahi, 2019). Initially, Khoshnevis developed the contour crafting method to enable 3D concrete printing of building structures by laying down concrete paste with large nozzles considering different consistencies of concrete (Khoshnevis et al., 2006). Various robotic technologies have been used in 3DCP including gantry robots with 3 or 4 Degrees-of-Freedom (DOF) for large projects, and articulated industrial robot arms with 6 or more DOF for smaller objects (Bos et al., 2016).

3DCP technology can decrease construction costs, time, and labor, reduce waste and environmental impact, increase productivity, and improve construction quality, sustainability, and safety (Ahmed, 2023). 3DCP can also enable accurate fabrication of complex geometric forms and hollow structures (Mohammad et al., 2020). Since 3DCP reduces wastes related to formwork, it can improve sustainability in construction (Ahmed, 2023; Sanjayan & Nematollahi, 2019) and significantly reduce environmental impacts of construction compared to conventional methods (Mohammad et al., 2020). Automated construction enabled by 3DCP can potentially improve safety in the construction industry by replacing many of the hazardous and laborious tasks (Sanjayan & Nematollahi, 2019). 3DCP is believed to be a major disruption to the construction industry and as a result, its application in construction creates the opportunity for technology-based jobs (Sanjayan & Nematollahi, 2019).

Potentials of 3D Printing Education

3D printing has shown various benefits in many fields of studies and industries. In higher education, 3D printing has been used in science majors so that students can learn creating 3D models and testing the models for experiments. 3D printing education also includes learning mechanical properties of materials in engineering curricula, for example 3D printed polymer test models, mechanical assessments along with modeling and rapid prototyping have been used in Mechanical Engineering undergraduate courses (Ford & Minshall, 2019). 3D printing has also been used in robotics education, in the design of the robot, development of educational robots, as well as in teaching computer programming (Ford & Minshall, 2019). In fact, integrating 3D printing technology in education can enhance classroom learning by allowing hands-on experience with an emerging technology to increase student engagement and creativity (Elrod, 2016). Additionally, 3D printing technology integrated with Science, Technology, Engineering, and Mathematics (STEM) education can facilitate hands-on learning and help students understand abstract concepts through physical models (Sun & Li, 2018). Combining 3D printing and STEM is a way to transform teaching to be more engaging, experiential, and effective at developing critical thinking and problem-solving skills (Sun & Li, 2018).

3D printing has influenced education in design processes too as a tool for prototyping design artifacts and has been used in interior design, product design, and fashion design majors. The availability of 3D printing impacts students' conceptualization and ideation, suggesting a link between implementation methods and design cognition (Greenhalgh, 2016). In conjunction, Ford and Minshall (2019) found 3D printing is being increasingly adopted in higher education, especially in engineering and design courses, and has shown benefits for student engagement and learning. They summarized uses of 3D printing in six categories: teaching 3D printing skills, educator training, supporting teaching, producing learning aids, assistive technologies, and outreach (Ford & Minshall, 2019). A similar approach can be seen in fashion design, where students can learn the complete process from 3D modeling to printing and design customized fashion accessories (Kwon et al., 2017). 3D printing technology has also enabled various applications in medical education. Creating patient-specific anatomical models for teaching anatomy and surgical planning, enabling practice on 3D printed pathological specimens, fabricating models with different materials to simulate tissue properties, printing customizable components like valves, implants etc., and developing phantoms with layers of different materials to mimic surgical experience for training are among major benefits that 3D printing can offer to medical education (Garcia et al., 2017). While the use of 3D printing in education is still a growing field, the review shows that 3D printing has a positive impact on education across disciplines. But, 3D printing has not been formally integrated in construction education.

Methodology

This study uses a mixed-methods approach to address research questions: (a) to address the first research question, the study uses literature and media review to identify the current status of 3DCP education in the construction industry, (b) to address the second research question, the study employs a case study to identify 3DCP educational needs and opportunities for the construction industry. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was used for conducting the literature review followed by a deeper investigation of the identified literature. Three databases were used to find research papers on the topic of 3DCP for construction inspection. These were Web of Science, Scopus, and Proquest. The search phrase used was: (“3DCP” or “3D concrete printing” or “concrete printing” or “concrete extrusion” or “contour crafting”) and “construction” and (“education” or “training”). The search fields were the abstract, title, and author’s keywords. No filter was applied on the subject or type of source. The results of the literature and media review is provided in the next section. In the case study section, a case of a 3DCP affordable house in Virginia is studied focusing on educational needs and processes. The authors directly led the case study project across its lifecycle: from design to construction and operations.

Current Status of 3DCP Education in Construction

From the literature review it was found that while there are over 1300 papers on 3DCP in the areas of concrete mix, aggregate, 3DCP challenges and potentials, sustainability factors, material properties, mechanical performance, workflow, reinforcement, etc. there are very scarce research papers that focus on 3DCP education in construction. The work by (Cole & Baghi, 2022) is one of the publications that specified education in the context of 3DCP but their focus is only on sustainability and design within 3D printing and prototyping for pre-college education. Therefore, literature review revealed that there is a huge gap in developing theoretical foundations and implementing pedagogical approaches and evaluations of 3DCP education for construction majors and for workforce training. As a result, the study expanded the review process to media including 3DCP technology developers websites, construction organizations, and professional development courses that have focused on 3DCP training. The results of the media review revealed that there have been some scattered efforts in introducing ad-hoc 3DCP training, e.g., continuing education courses by the American Concrete Institute (ACI), Precast Concrete Institute (PCI), and American Institute of Architects University (AIAU), as well as 3DCP operator training courses by 3DCP technology providers like Apis Core and Cybe Construction. This section provides an overview of the identified 3DCP training programs and figure 1 summarizes them based on their training type, mode of instruction, duration, and price range.

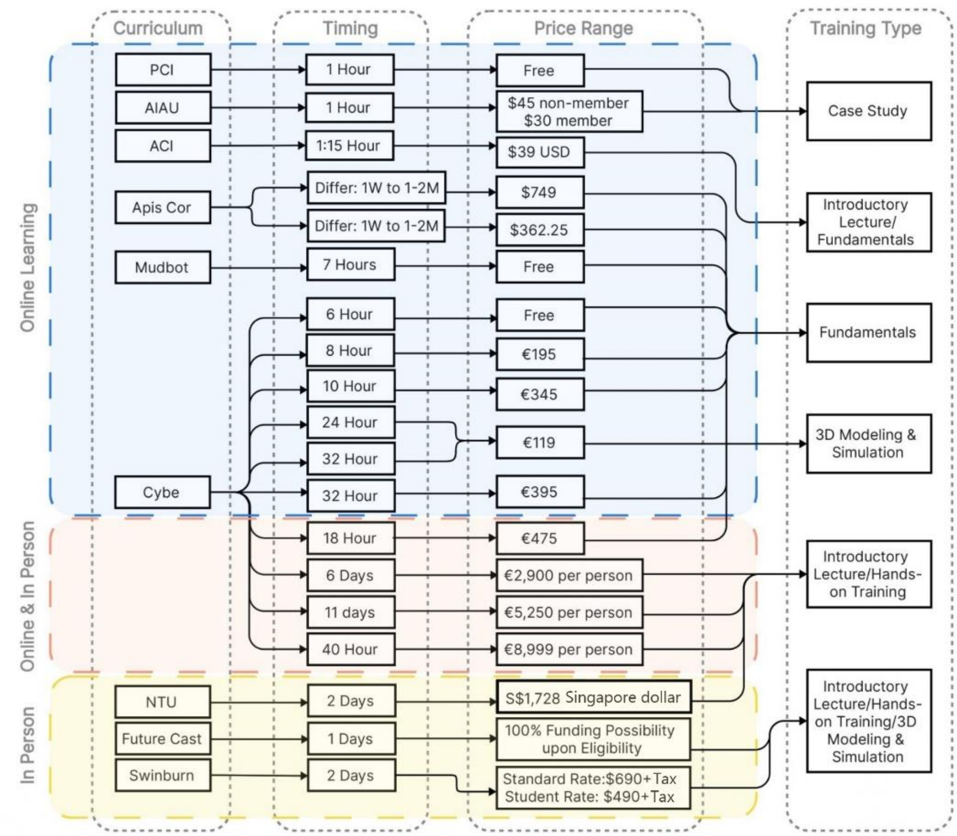

Figure 1. Comparison of the identified 3DCP training programs and their types

ACI offers a 3DCP course that is a 1:15 hour recorded webinar for continuing education that shares the U.S. Army Engineer Research and Development Center experience in automated construction of expeditionary structures (Ellis et al., 2023). Learning outcome in this course focuses on defining 3D printing and advantages of this technology adoption in the construction industry as well as recognition of the additive manufacturing concrete technology demands on concrete performance provisions along with the ACI's role in boosting 3D printing technology (Ellis et al., 2023). PCI offers a 3DCP course that is a one-hour continuing education course and explores a case study of a mixed-use project in Brooklyn, NY that focuses on 3D printing technology application in precast concrete manufacturing procedure (Hanley Wood University, 2022). The course was offered in 2021 with the aim of defining precast concrete and the use of 3D printing technology in manufacturing of prefabricated concrete components (Hanley Wood University, 2022). AIAU also offers a one-hour continuing education course on the applications of 3DCP through case studies such as the Domino Sugar renovation in Brooklyn and the learning objectives include understanding of 3DCP in the production of affordable concrete wall panels and 3D printing concrete forms (AIAU, 2023).

Cybe Construction, a 3DCP technology developer has developed 10 different training programs in the use of their hardware, software and materials ranging from basic introductory lecture to 3D modeling, toolpath performance and 3D printer operation (Cybe, 2023). The duration of the courses ranges from 6 hours to 11 days. Cybe uses a 3-stage cycle experiential learning approach so that learners can develop abstract concepts and apply those concepts in practice. Their course provides training for various systems including the controllers, mix pump system, the robot printer, logistics and strategies with regards to 3D concrete printing. People who can complete Cybe's 3D print operator course will receive a certificate (Cybe, 2023). Another example of 3DCP training is the course offered by Apis Cor. Apis Cor, a technology provider and manufacturer of 3D concrete printers, offers a 3DCP course with two modules (Apis Cor, 2023). The first module is fundamentals of construction 3D printing (with 13 chapters and a final exam) with an overview of construction 3D concrete printing vs. traditional methods, explaining the technologies, material science, equipment, economics, and future perspectives of on-site and prefabricated printing. Their second module is a practical 3D concrete printing course (with 17 chapters and a midterm and final exam) that provides a step-by-step overview of the real estate development process from conceptual design through construction, inspection, and occupancy when utilizing 3D printed construction methods with Apis Cor printer that takes between 1 week to 1-2 months to complete (Apis Cor, 2023). Apis Cor's 3DCP course is a prerequisite for their operator certification course that is required for operating an Apis Cor 3D printer. Apis Cor has plans to offer certification courses for printer operators, contractors, architects, engineers, and G-code developers. G-code is the computer programming language used to drive computer controlled machines like 3D printers. MudBots, another 3DCP technology provider, offers over 7 hours of video tutorials in concrete printing methods and processes with MudBots printers (MudBots, 2023).

Worldwide, the center for professional and continuing education at Nanyang Technical University in Singapore is among very few sources that offers a 2-day continuing education and training certificate in 3DCP (NTU, 2023). The learning outcomes cover introduction and uses of 3D printing in construction, additive manufacturing methods, properties of 3D printed concrete, design of 3D concrete printer, and software practice for generating the printer toolpath simulation as well as hands-on experience on operating a 3D concrete printer (NTU, 2023). Future Cast in Ireland is a non-profit organization with a focus on construction innovation that offers a one-day training in introduction to 3DCP covering history, science, equipment, materials, software, printing process, equipment cleaning, and future applications of 3DCP in construction (Future Cast, 2023). The Swinburne University of Technology in Melbourne, Australia, offers a two-day course on 3DCP at their Digital Construction Laboratory. The course includes lectures and hands-on experiences focused on modeling, materials study, reinforcement, and 3DCP sustainability (Swinburne University of Technology, 2023).

Figure 1 outlines various 3DCP training programs available at the time of this study. Among nine different training providers, curriculum duration ranges from 1 hour to 1-2 months, pricing from free up to €8,999 per person. The training modality includes online, in-person, and hybrid courses and educational focus areas include 3DCP fundamentals, case studies, 3D modeling and simulation, as well as hands-on training with 3D concrete printers. The key differences are the program lengths, costs, modality, and the educational content providing fundamental knowledge and/or practical skills for 3D concrete printing. Majority of courses aim to provide fundamental knowledge on 3D concrete printing, including 3DCP definitions, history, and applications in construction. Many training options provide skills in 3D modeling software e.g., Rhinoceros and Grasshopper and in using a simulation software e.g., slicer for creating printer toolpath. Hands-on training to gain experience with the printer operations and processes is also a common learning objective. Some courses cover specialized topics like reinforcement techniques, customizing concrete mixes, and analyzing costs/benefits. But the core learning goals in hands-on training include basic knowledge of 3DCP and acquiring basic skills to utilize the 3DCP technology through practical training with software applications and printers.

3DCP Educational Needs and Opportunities- Case Study

To identify educational needs and opportunities in the application of 3D concrete printing in construction, this paper focuses on a case study project. Company 3D, an anonymized 3DCP company, and the Virginia Center for Housing Research (VCHR) at Virginia Tech performed a pilot partnership project, hereafter referred to as "the partnership", for 3D printing affordable housing. The authors were directly involed in the project. The partnership built one 3D concrete-printed home prototype, known as "PACT," in the greater Richmond, VA Metropolitan area. This section will discuss the project, 3DCP process in the project, and identified educational needs and opportunities. While PACT was a partnership of VCHR and a printing company, many more stakeholders were required to produce the affordable home. The larger production team consisted of Virginia's housing finance agency, local non-profit builders and homeownership service providers, a general contractor, an architect and engineer of record, a real estate agent, local building and zoning officials, materials suppliers and the printer manufacturer. Together, this larger team designed the home, secured a permit, procured the land and the printer, developed the site, trained and 3D printed the walls, completed the home construction, systems and finishes, qualified an affordable homeowner and helped establish financing for the homeowner between 2020-2022.

Figure 2. Project stages and educational needs in the case study project in Richmond, VA

Main educational needs and opportunities identified during the project are as follows (see figure 2).

- 3DCP Fudamentals: The partnership considered 3DCP examples around the world and decided to follow an American architecture style that printed the exterior walls only and used a conventional wood truss roofing system. The project needed to qualify as workforce housing (120% area median income sales price) with an appropriate scale for neighborhood i.e., 1400-1500 sq.ft. to fit 3 Bedrooms and 2 Baths and to optimize the plumbing and mechanical systems with reduced materials. The project design team needed to learn about 3DCP and to follow 3D printer specifications (e.g., sizing requirements constrain house size to 30'x30'x10') to print 2 wythes of exterior walls with required wall thickness and details.
- 3D Modeling and Toolpath Simulation: The partnership first produced a prototype design and then hired an architect and engineer of record to produce the construction drawings and permit set. The permit set was then translated into a building information model (BIM) using Autodesk Revit. The designers learned the process of 3D surface-based modeling in Rhino as well as 3DCP toolpath simulation in slicer software provided by the printer manufacturer. This enabled the translation of the 3D printed walls from BIM to a geometric surface model that can be translated to the slicer software for creating the G-code for the printer.
- Printer Operations and Prototyping: Faculty advisors in the partnership printed a prototype of walls on a 3D printer using PLA filament to simulate the toolpath before the actual concrete printing so the project team was able to test and learn from this scaled down mock-up prior

to construction. Once the design and simulation were complete, and the permit set was approved, the printer manufacturer shipped the printer and provided a technician on-site for 4 weeks to train the partnership. The partnership expected to have three months of training, testing, and prototyping but due to supply chain difficulties, this time period was reduced to one week. Therefore, the partnership assembled the printer, trained and prototyped 3D printed walls on the back portion of the job site, while footings for the house were being poured by the concrete contractor in the front. The team was trained on the printer, mixer and software and then moved the printer to the front of the site for the actual house print.

- Printer Mobilization and Site Logistics: The printer's footprint required 55 feet by 55 feet, including the printer's large footings, so the area around the house needed to be cleared and flat. The printer mobilization and site setup time were significantly reduced by using a truck-mounted crane for the house print. The crane also significantly improved safety for the site since rigging was more stable and printer pieces could easily be hoisted in place with minimal labor. Also, accessories for the printer included water cooling basin (to bring down the temperature of the water into the mixer), gravity-fed silo (for loading dry mix), in-line mixer, computer station (tables and a tent), and a large (3 foot by 5 foot) diesel generator. Between the accessories and the printer ran 90 feet of concrete pump hose.
- Safety: The team had to learn about specific printer safety and jobsite safety during printing. This project was also dedicated to educating the industry, officials and the public about 3DCP, so the construction site contained a viewing platform. Each day, tours of students ranging from K-12, community college classrooms, university students, local government officials, builders, trades and government leaders were conducted across the site and among the activities. These tours presented new safety requirements in the job site.
- Other specialized topics that the team needed to learn included printer calibration and testing, concrete mixing, extrusion, and testing, structural performance and reinforcing for 3DCP.
- Building Performance Analysis: Faculty advisors in the partnership provided high-performance design simulation including daylighting, energy modeling, and system design for the 3DCP house that helped the team with cost reduction in the project.
- Specialized Roles: While not the case for this experimental project, the goal of the printing operation was 3 employees: (a) the mixing technician is responsible for clean water at a temperature of 62 degrees Fahrenheit, dry mix loading, concrete mixing and testing and pumping; (b) the printing technician is responsible for controlling the computer-based process, importing the G-code into the printer, daily calibration, flow rates, metrics on height and location of the print "ink" and any changes required to the computer-based print along the way; and (c) the supervisor is responsible for the site and managing the overall process, while they often travel with the print head to provide feedback on the print.

Discussions

3D concrete printing potentials in the construction industry (Ahmed, 2023; Sanjayan & Nematollahi, 2019) highlights the need for a skilled workforce equipped with requisite knowledge in implementing the technology. But 3DCP education is not currently included in construction majors and curriculum. The identified technology-specific training that is currently offered by technology providers and through professional development, as well as the identified educational needs for 3DCP in the case study project highlights required new knowledge and skill sets i.e., 3DCP fundamentals, 3D modeling and toolpath simulation, printer operations, logistics, safety, and other specifilized topics. There is a need for both a generalized pedagogical approach for training design and construction teams in the process, and an advanced curriculum that can establish a foundation for more specialized roles in 3DCP projects as identified in this research i.e., mixing technician, printing technician and supervisor.

As discussed in the case study project, the translation of the design intent into numerical controls for a 3D concrete printer changes the basis for how a building is designed and modeled. Adoption of 3DCP also fundamentally changes aspects of the construction process by automating various processes while also requiring human operator supervision and periodic printing intervention. These new processes emphasize the need for proper training of the construction workforce from designers and engineers to builders and machine operators. In the design phase, designers should be able to produce an accurate surface-based model of the building in addition to the building information model. This building model is supposed to contain proper geometrical data that is compatible with the printer specifications to both enable the simulation of the 3D printer toolpath and generate the G-code for the machine operations. Therefore, engineers should be equipped with the knowledge of design for 3D printing, modeling and simulation as well as building performance analysis of the 3D printed building. Developers, general contractors and construction trades should be equipped with requisite knowledge and training for the new site logistics, mobilization, installation, operations and demobilization requirements of the 3D printer and its accessories on the job site following both job site safety and safe operations of the machines. Further, this emergent technology creates educational opportunities and safety concerns that all practitioners need to train for and prepare to address during prints.

Conclusion

This study investigated the current status of 3DCP education and identified educational needs and opportunities for the construction workforce through literature and media review as well as a case study of a 3D printed affordable house. 3DCP represents an automated construction process that creates concrete structures layer by layer using data from 3D models. This innovation is anticipated to tackle numerous issues currently encountered in construction and provides novel design and construction opportunities. However, currently there is a significant lack of efforts in developing pedagogical approaches and fundamental curriculum for the purpose of 3DCP in construction education and for workforce training. The adoption of 3DCP requires a new generation of the construction workforce equipped with fundamental knowledge and skills in 3DCP topics (e.g., 3DCP modeling and simulation, printer operations, etc.) and beyond, based on the worker type, education and skill level. Currently there is no educational foundation that can provide construction students and the construction workforce, at all levels, with deep and broad training into the needs of 3DCP printing and 3D printed buildings. This lack of content could result in slower adoption and less production of 3D printed buildings in general and for affordable housing, in particular. A proper curriculum is needed especially for the purpose of 3D printing affordable housing to prepare the new workforce with fundamental knowledge and technical expertise in 3DCP. Future research should identify fundamental learning outcomes, investigate research needs for 3DCP training, and develop and validate a curriculum for 3DCP education through multiple cohorts with students and workforce.

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