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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

High Performance, Ultra-Tall, Low-Cost Concrete Wind Turbine Towers Additively Manufactured On-Site

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The efficiency and energy generating capacity of wind turbines increases as they become larger and are installed on taller towers. For example, an ultra-tall 140-meter tower can increase energy production by more than 21 percent compared to a typical 80-meter-tall tower. Building ultra-tall wind turbine towers would enable California to retrofit old wind farms and develop new wind farms that cost effectively capture greater amounts of wind energy. Conventional towers are made from steel in manufacturing plants in the central United States or imported internationally and transported to the wind plant by truck or rail. Existing tower sections needed to support ultra-tall towers (140-meter) are too wide and too tall to be manufactured and transported over roads.

To address this challenge, RCAM Technologies and the University of California, Irvine, developed, demonstrated, and tested a 3D concrete printing technology for building low-cost, ultra-tall wind turbine towers on site at the wind plant. The team completed a preliminary structural design of ultra-tall wind turbine towers made from 3D printed concrete. The team procured and operationalized a 3D concrete printing system to fabricate a concrete tower subassembly in a laboratory. These efforts demonstrated the feasibility of the 3D concrete printing manufacturing process for segmental tower construction on site. Detailed structural testing of the tower subassembly indicated that the 3D concrete printed tower specimen performed beyond the expected levels, validating the design method and manufacturing process.

The team also performed techno-economic and market analyses and planned future development activities, indicating that the technology is expected to be cost competitive in the next five years. Commercialization of this technology will help California meet the goal of powering all retail electricity sold in the state and state agency electricity needs with renewable resources by 2045, as set forth in Senate Bill 100.

Keywords: wind power, wind energy, renewable energy, tall towers, 3D concrete printing, advanced manufacturing, California

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Executive Summary

Introduction

Wind energy is the largest source of renewable energy in California and is required to lower greenhouse gas emissions and reduce the effects of climate change. Based on the California Energy Commission's *Energy Almanac*, California generated over 14,000 gigawatt-hours from wind technologies in 2021. However, in recent years, new developments of land-based or "onshore" wind plants in California have slowed, and many existing wind farms use older, less efficient wind turbines. Wind turbines with longer blades and taller towers can capture more wind energy and are more cost effective, especially in California. However, building tall towers using existing technologies is not feasible due to the inability to transport steel tower sections large enough to support the tower height. By developing 3D concrete printing technologies for on-site manufacturing of wind turbine towers, this project will enable the construction of new wind turbine towers in California that capture more wind energy and help California meet its renewable energy and climate change targets.

Conventional wind turbine towers are made from tubular steel at plants located in Colorado, Texas, or abroad and transported to California wind plants by ship, truck, or rail. Traffic signals, road width, tunnel/underpass height, and weight regulations limit conventional steel tubular towers to a sub-optimal diameter of 4.3 meters. As a result, the average conventional wind turbine tower height installed in the United States is approximately 90 meters tall.

Larger wind turbines capture a greater amount of energy, and tall towers reach heights where wind is stronger and more constant. Ultra-tall 140-meter towers can (1) increase new and repowered wind capacity deployment potential in California tenfold (6 gigawatts to 60 gigawatts), (2) increase a turbine's energy capture by as much as 21 percent, and (3) reduce carbon dioxide emissions 85 times compared to electricity generated with natural gas. However, ultra-tall towers have not been installed in California in part due to prohibitive costs.

3D concrete printing is a rapidly emerging manufacturing technology with the potential to revolutionize on-site construction, thus alleviating the transport limitations on tower size. On-site 3D concrete printing technologies for wind turbine towers or renewable energy applications have not yet been commercialized because the technology is in an early stage. Other start-ups are focusing primarily on housing applications rather than highly structurally loaded components such as wind turbine towers and foundations. Solving these challenges requires ratepayer support in the form of this project to advance the 3D concrete printing technology for wind turbine towers to sufficiently minimize the technology's risk to encourage follow-on investment and commercialization.

Project Purpose

This project aimed to overcome the challenges and limitations of conventional off-site methods of manufacturing wind turbine towers by developing and demonstrating a 3D concrete printing technology for building low-cost, ultra-tall wind turbine towers on site at a wind plant. The objectives of this project were to develop a reinforced concrete additive manufacturing technology that, when scaled-up and commercialized, will: fabricate the lower half of a hybrid ultra-tall wind turbine tower on site, in one day, at half the cost of conventional steel towers; reduce the levelized cost of wind generated electricity in a low-wind-speed site by 11 percent; and increase the California wind capacity deployment potential for new sites and repowered sites nearly tenfold.

The project team designed and analyzed ultra-tall 3D printed concrete towers, designed and 3D concrete printed a tower prototype subassembly scaled at approximately 1:20 in diameter, performed laboratory structural testing and analyses of the tower prototype, and modeled commercial manufacturing costs and the levelized cost of energy. Taken together, these research and development efforts aimed to advance the state of 3D concrete printing for wind turbine tower manufacturing, demonstrate the feasibility of the manufacturing technology, and validate the tower design methodology by testing its structural performance.

The outcomes of this research are critical for developers, contractors, engineering firms, and policymakers in wind energy to assess the feasibility of on-site 3D concrete printed wind turbine tower technologies and to foster market acceptance. The work is also of interest to California's electricity ratepayers as the project supports the development of 3D concrete printing research in the state, supports local concrete and wind energy supply chains, contributes to the construction and engineering workforce in California, and enables further low-cost scaling of California's renewable energy generation capacity.

Project Approach

The project team comprised RCAM Technologies and the University of California, Irvine. The University of Nebraska, Lincoln, and Barr Engineering also supported the project. Key stakeholders from the renewable energy industry, 3D concrete printing technology developers, and wind plant construction companies were engaged in an advisory capacity to improve the applicability of the project's results to industry and increase the odds of successful technology commercialization. The project's technical advisory committee included industry experts from Boulder Windpower Consulting, Mortenson Construction, and UL AWS Truepower, who provided valuable feedback on the manufacturing plans and market needs.

The team first reviewed the state of the art of 3D concrete printing and commercially available equipment for laboratory printing of tower prototypes and emerging technologies for full-scale manufacturing. The team developed design specifications and loads for a 140-meter-tall tower for the California market and completed the structural design of a 3D concrete printed tower and a baseline precast concrete tower following industry standard design methodologies and using finite element analysis, which is a computerized method to predict how the tower would react to forces. The University of California, Irvine, research team also designed, fabricated, assembled, and structurally tested a 3D concrete printed tower prototype subassembly in the Advanced and Multifunctional Materials and Manufacturing for Structures Lab. Significant effort was put into developing a robotic 3D concrete printing capability at University of California, Irvine, developing printable concrete mixtures; testing their mechanical properties; assessing their rheology, extrudability and constructability; and performing large-scale 3D printing, manufacturing, and structural testing of a tower subassembly. University of California, Irvine, developed and validated a finite element model using the large-scale experimental results to support future tower design and development. The impact of the 3D concrete printed wind turbine tower technology on the levelized cost of energy was modelled using a cost model created by the National Renewable Energy Laboratory. The project team also performed a market analysis, which included identification of potential RCAM tower customers, California installation sites, and competitive tower pricing to inform potential wind capacity deployment. Key needs for manufacturing and commercialization were identified through stakeholder discussions and market research.

During the project period, 3D concrete printing technologies rapidly advanced, providing an opportunity to accelerate the project by using commercially available 3D printing systems. This enabled a stronger focus on tower design and engineering and material testing. The COVID-19 pandemic posed the greatest challenge during the execution of the project, considerably delaying on-site research at University of California, Irvine. The project was granted a no-cost extension to enable successful completion of the 3D concrete printing demonstration and structural testing.

Project Results

The research successfully achieved the project goals and objectives. The 3D concrete printing technology was demonstrated successfully in the design, manufacturing, and assembly of a prototype tower subassembly at University of California, Irvine. The structural testing of the tower assembly validated the tower design methodology and assumptions, with the tower exceeding the required structural performance metrics. No substantial design issues were observed. The prototype manufacturing informed the assumptions of the techno-economic analysis, which indicated that 3D concrete printed ultra-tall towers can facilitate re-powering of existing California wind plants and development of new wind sites with a market competitive levelized cost of energy. The technology is expected to be commercially feasible and cost competitive in the next five years of development.

Major lessons learned by the project team included the details of the design process and specification of concrete wind turbine towers, 3D concrete printing mixture development and fabrication know-how, structural behavior of 3D printed concrete at different scales, and structural testing capabilities for wind turbine towers.

The demonstration and analyses validated the competitive advantages of on-site 3D concrete printing of wind turbine towers for follow-on research and development. Further research is required to advance the level of detail of the tower design, increase the fidelity and scale of the fabricated tower prototype, study the post-tensioning concept, assess the fatigue performance of the tower, and demonstrate outdoor 3D concrete printing.

Technology/Knowledge Transfer

The information from this research is intended for use by stakeholders in the development, engineering, and construction of wind plants to gain an understanding of the potential of on-site 3D concrete printing for tower manufacturing.

The team's technology/knowledge transfer approach placed emphasis on discussions with industry representatives and academia and workshop/conference presentations due to the bi-directional technology transfer opportunities provided by these avenues. The team presented the technology at industry and academic conferences such as the 7th International Conference Wind Turbine Towers, the ASTM Symposium on Standards Development for Cement and Concrete for Use in Additive Construction, and the National Renewable Energy Laboratory Industry Growth Forum. The team published peer-reviewed articles, developed online media, and convened stakeholder workshops to cultivate cross-disciplinary knowledge transfer. Industry feedback indicated that the technology is feasible but further development of tower designs, details of reinforcement methods, and larger-scale structural testing are needed before investment in commercial pilots.

During the project, wider applications of 3D concrete printing technologies for renewable energy applications were envisioned. At present, land-based 3D concrete printed wind turbine towers, onshore foundations, and offshore wind turbine anchors have a market internationally and a growing mid-term market (within five years) in California. Within the next 10 years, RCAM expects increased market demand for 3D concrete printed fixed-bottom and floating foundations, as well as 3D concrete printed energy storage applications, in California and abroad.

The project team will continue with technology transfer or commercialization directly through: the team's follow-on project supported by the California Energy Commission; RCAM's research and development projects for 3D concrete printed offshore wind energy and energy storage funded by other agencies; the education and training of the undergraduate and graduate students at the University of California, Irvine, as a future workforce in this emerging field; continued research development; and publications and outreach activities in advancing 3D concrete printing and structural designs.

The results of this project are expected to stimulate growth in the land-based wind energy market in California by demonstrating the viability of a new technology for on-site manufacturing of ultra-tall towers. The information generated in this project may prove of value to enable the development of new wind farms in sites that were previously infeasible with smaller wind turbines due to lower quality wind resource or limited land area. Remaining barriers to commercialization include certification of tower designs and demonstration of a near-commercial scale prototype tower.

Benefits to California

This research is important to California ratepayers because commercialization of the technology will help California meet renewable energy goals with low-cost wind energy while realizing the economic benefits of the developments in the state. This will help ensure that the levelized cost of energy does not escalate while renewable energy generation capacity increases. The project created near-term research and development jobs during its execution. When commercialized, the technology will create new jobs in wind plant design, construction, operations, and maintenance, and will create lease and tax revenues in California communities. Based on wind power projects installed between 2000 and 2008, the California job creation from deploying 50,000 megawatts would create 25,000 jobs while producing 336 million megawatt-hours of electricity annually, assuming a net capacity factor of 30 percent.

Increasing the size of wind turbines will allow installation of a smaller number of turbines to reach a given wind plant nameplate capacity. These plants will create less ground disturbance and reduce visual impacts compared to conventional technologies.

In addition, 3D concrete printed wind turbine towers can provide cost savings and emission reductions compared to incumbent technologies. A preliminary levelized cost of energy analysis estimated an 11 percent reduction in the levelized cost of energy for 140-meter 3D concrete printed towers compared to 80-meter steel towers in a 100-megawatt wind site with a modern 3-megawatt class turbine. Although a conventional concrete wind turbine tower results in about 40 percent more carbon dioxide equivalents (7 grams per kilowatt-hour) than a 140-meter conventional steel tower, this carbon dioxide is inconsequential compared to the carbon dioxide emitted from electricity sources such as coal and natural gas generated electricity. A 140-meter 3D concrete printed tower is projected to result in 85 times less carbon dioxide compared to natural gas-fired electricity generation and 138 times less than coal-fired electricity generation on a lifecycle basis.

The technology developed in the project can be applied to on-site manufacturing of wind turbine towers at various scales, thus advancing California's educational, research and development, and commercial supply chain capabilities for 3D concrete printing technologies for potential future energy, civil infrastructure, and housing applications. The project also helps position California to lead the development of a rapidly emerging technology with tremendous global potential for applications in civil infrastructure, commercial buildings, and affordable housing. This research also created the foundational knowledge necessary for RCAM to develop and attract funding for other projects to investigate 3D concrete printing of infrastructure for offshore wind, floating solar, marine energy, and energy storage applications.

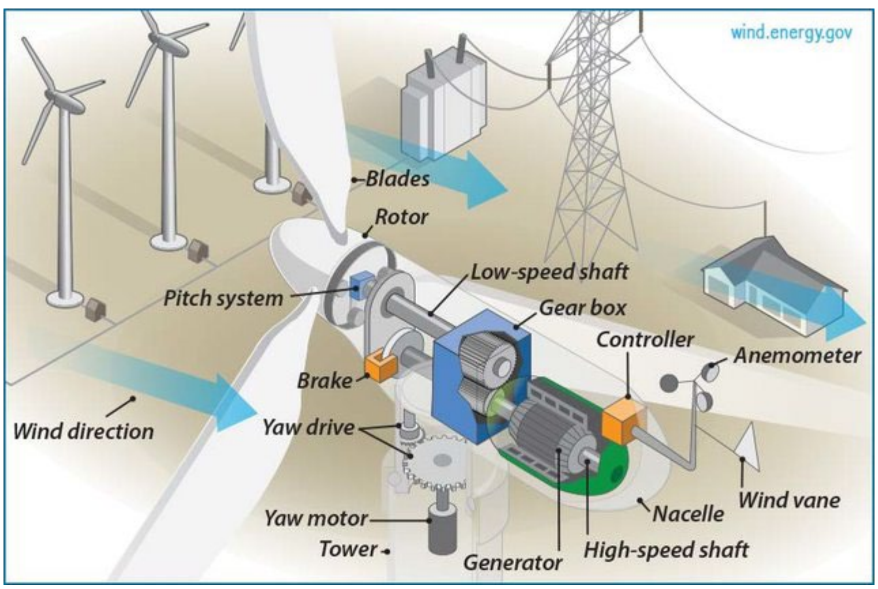
CHAPTER 1: Introduction

Wind Energy

Wind Turbine Operating Principles

Wind power is one of the world's leading renewable energy generation technologies, typically using bladed wind turbines horizontally mounted on towers to capture and convert wind energy into electricity. Figure 1 shows a diagram of a horizontal-axis wind turbine with the major components labeled. Wind turbines convert wind energy into electricity by using propeller-like blades to spin a rotor and generator (EIA, 2021). Wind turbine blades work like an airplane wing to create an air pressure difference across the two sides of the blade. The lift force created is stronger than the drag force, causing the rotor to spin. The rotor connects to a generator directly or through a gearbox to create electricity through electromagnetism.

Figure 1: Diagram of a Wind Turbine



Source: US Department of Energy, Wind Energy Technologies Office

The amount of power that can be harvested from wind is proportional to the blade length of the rotor and to the cube of the wind speed. Theoretically, when wind speed doubles, wind power potential increases by a factor of eight. As wind energy technologies have developed, wind turbine blades have become larger and turbine capacities have increased. The hub height, which is the distance from the ground to the middle of the turbine's rotor, for land-based wind has increased to about 94 meters in 2021. Wind turbines installed on towers with higher hub heights capture greater amounts of wind as the wind typically becomes more constant and has greater speed farther above ground level. For example, an ultra-tall 140-meter tower can increase energy production by more than 21 percent compared to a typical 80-meter tower.

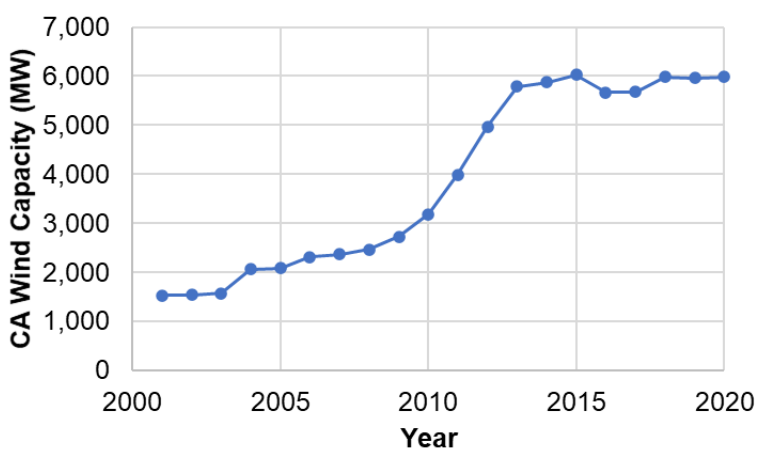
Taller towers are being used in a wider variety of sites, but towers with hub heights of 100 meters and more are most common in the Midwest and the Northeast, which have high wind shear — that is, greater increases in wind speed with height (LBNL, 2021).

Wind Energy Installation Trends

Land-based wind energy has been an important part of the nation's renewable energy generation portfolio and is expected to continue to remain a key part of the energy transition. In 2020, United States wind capacity increased by 16,836 megawatts (MW), accounting for 42 percent of all United States electricity generation capacity additions in 2020 — the largest source of the nation's electric-generating capacity additions (LBNL, 2021). The cumulative United States wind energy generation capacity is 121,985 MW, which is the second most behind China. Wind energy accounted for 8.3 percent of overall energy generation (that is, wind energy penetration) in the United States in 2020. In comparison, Denmark had a 50 percent total electricity generation in 2020 from wind generation, and Ireland, Germany, the UK, and Portugal had 25-40 percent. The total cumulative investment in new wind power project installations in the United States is estimated at roughly $240 billion since the beginning of the 1980s (LBNL, 2021).

California has been a leader in wind energy in the United States, with its first utility-scale wind plants installed in the 1980s. Among states, California has the sixth-largest capacity of installed wind energy generation at 5,922 MW. However, wind energy made up only approximately 6.4 percent of the state's in-state energy generation in 2020, making California the 20th ranked state in wind energy penetration. Figure 2 shows California's wind energy generation capacity in megawatts from 2001 to 2020. Wind generation capacity has remained nearly constant since 2013. Wind energy made up only 10 percent of California Independent System Operator (ISO) capacity additions from 2011 to 2020, with solar energy accounting for the largest portion of capacity additions, followed by natural gas (LBNL, 2021).

Figure 2: California Wind Energy Generation Capacity From 2001 to 2020

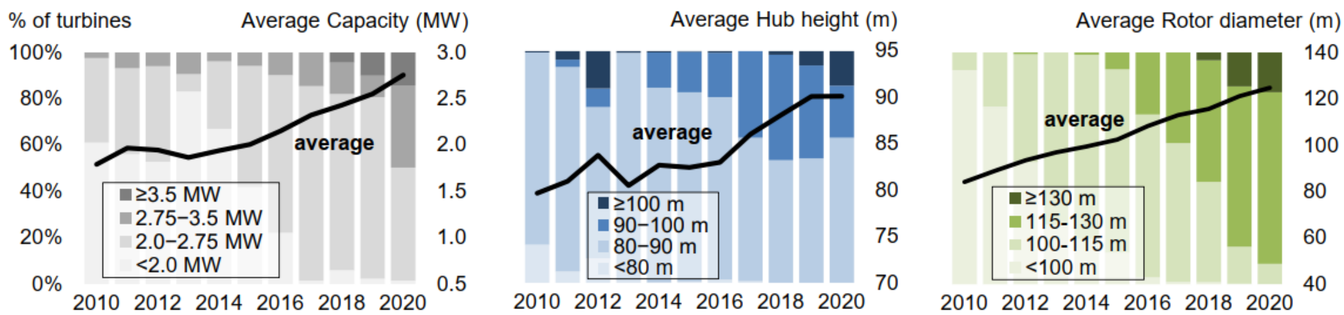


Source: RCAM Technologies, from California *Energy Almanac* data (California Energy Commission, 2021)

Wind technologies continue to increase in size and performance of turbines. Figure 3 shows the trends in average United States wind turbine capacity, hub height, and rotor diameter from 2010 to 2020. The average nameplate capacity of newly installed wind turbines in the United

States in 2020 was 2.75 MW. GE, Siemens Gamesa, and Vestas all now have 6 MW wind turbine models available, and Goldwind recently introduced a 7.2 MW wind turbine primarily for foreign markets (Richard, 2021). Despite the benefits of taller towers, increases in hub height have somewhat slowed. The average hub height in 2020 was 90.1 meters, unchanged from the previous year and up 59 percent since 1998-1999.

Figure 3: Trends in Turbine Rating, Hub Height, and Rotor Diameter 2010–2020



(Left) Increase in average United States turbine capacity (measured in megawatts) from 2010 to 2020, (center) increase in average hub height (in meters) of turbines in the United States, and (right) increase in average United States turbine rotor diameter (in meters).

Source: US Department of Energy (LBNL, 2021)

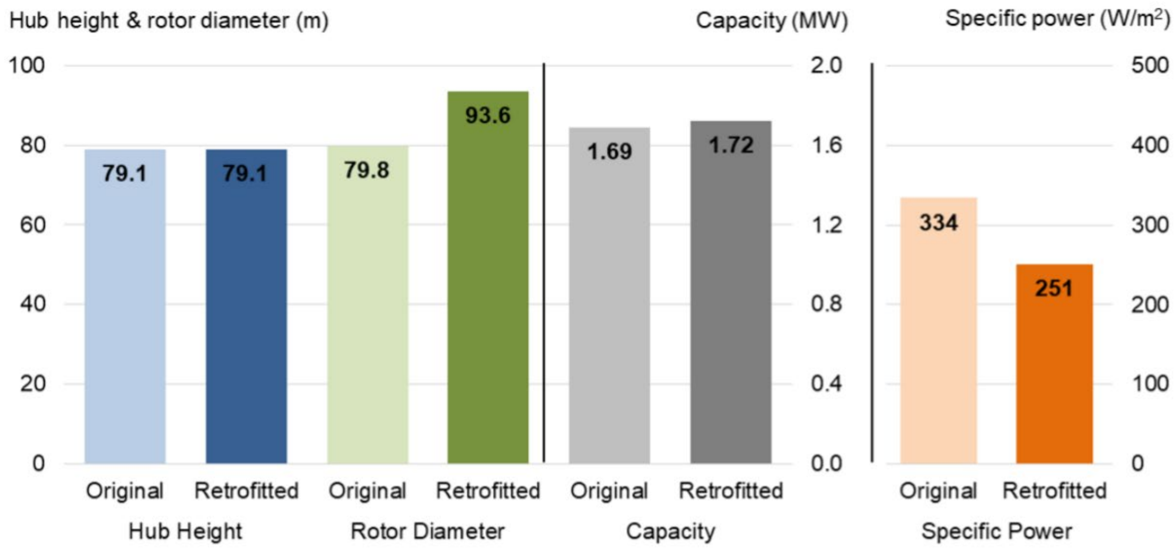
Repowering

Repowering refers to the retrofitting of existing wind plants. Repowering can be partial, in which major components of turbines are replaced, or full, in which the existing turbines are completely removed, or decommissioned, and modern turbines and infrastructure are installed. Repowering is a significant market trend, as many turbines throughout the United States and California are reaching the end of their life expectancy or using obsolete technology that is no longer supported by the manufacturer. Repowering helps reduce noise emissions, improves turbine tower aesthetics, and is often politically favorable. The ability of partially repowered wind projects to access the production tax credit is a primary motivator.

In 2020, 33 existing wind projects (3,087 MW) were partially repowered, mostly in the form of increased rotor diameters and the replacement of major nacelle components (LBNL, 2021).

Figure 4 shows the average hub height, rotor diameter, capacity, and specific power of partially repowered United States wind plants before and after retrofits. The rotor diameter of repowered projects increased by an average of 14 meters, while reducing specific power by 25 percent, which helped increase the capacity factor. Overall, the average capacity of these retrofitted projects increased only modestly.

Figure 4: Change in Physical Specifications of Partially Repowered Turbines (2020)



W/m2 = watts per square meter

Source: US Department of Energy (LBNL, 2021)

Additionally, in 2020, portions of three projects (343 turbines totaling 120 MW) were fully repowered; they were decommissioned and replaced with 50 new turbines totaling 148 MW, including new towers, blades, and nacelles (LBNL, 2021).

Hybrid Wind Power Plants

Another recent trend in wind power is the development of hybrid power plants that couple wind with solar generation and/or energy storage. Commercial interest in hybrid wind power plants is strong in the California ISO, where 37 percent of proposed future wind capacity is hybrid (LBNL, 2021). The only wind hybrid plant currently in operation in California is the Pacific Wind Project and Catalina Solar Project developed by EDF Renewables (LBNL, 2021; Woody, 2012). The combination of wind and solar takes advantage of the differences in peak production: wind tends to blow the strongest at night and in the winter, while the sun is the strongest during the day and in the summer months. Continued development of hybrid wind power plants is a market trend that can make more renewable energy projects feasible, bringing additional value to California’s grid and supporting the state’s renewable energy goals.

Turbine and Tower Manufacturing

Conventional wind turbine towers are manufactured from rolled and welded steel in centralized facilities in the United States and transported to the wind plant by truck or rail. Overhead traffic signals, road width, and weight regulations limit conventional steel tubular towers to sub-optimal diameters of 4.3 meters. Several alternative tower technologies are being developed across the world to cost effectively manufacture and install taller towers.

Figure 5 shows several tower technologies, including guyed towers, modular steel towers, on-site spiral wound steel towers, and precast concrete towers. These approaches extend the height range of transportable towers, using either alternative structural systems with modular or segmental designs or on-site manufacturing to bypass transportation limits.

Figure 5: Wind Turbine Tower Manufacturing Technologies in Development

(Top left) Ramboll guyed towers, (top right) Lagerwey modular steel tower, (bottom left) Nordex precast concrete tower production facility, (bottom right) Keystone Tower Systems spiral welding.

Source: Ramboll, Lagerwey, Nordex, Keystone Tower Systems

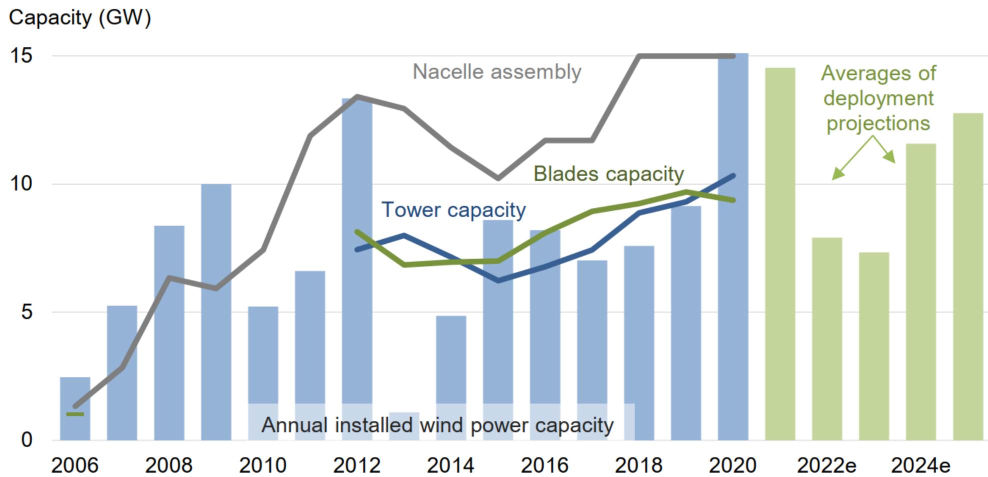
Each of these technologies has benefits and disadvantages. The challenges of modular tower technologies include increased time of assembly due to the need for bolting or grouting a larger number of connections. Tower aesthetics are also an important consideration for project stakeholders. On-site manufacturing technologies are nascent and are difficult to make cost effective for wind plants with a smaller number of large turbines.

Alternatively, developing improvements in turbine control technologies can reduce the overall loads experienced by the towers and allow for a more efficient, lower-weight, and reduced-cost tower design, extending the competitiveness of tubular steel towers to greater hub heights (Lantz et al., 2019).

Domestic content is another important consideration for wind energy manufacturing.

Figure 6 shows the trends of annual installed wind power capacity and manufacturing capacity of wind energy components in the United States from 2006 through 2025. Wind towers in the United States used a relatively large portion of domestic content, 60–75 percent (LBNL, 2021), and tower manufacturing capacity in the country largely was sufficient for United States wind capacity in recent years. However, in 2020, tower manufacturing capacity was significantly outpaced by wind power installations, and approximately $730 million was spent in wind tower imports (LBNL, 2021).

Figure 6: Domestic Wind Manufacturing Capabilities and United States Wind Power Installations



Source: US Department of Energy (LBNL, 2021)

Wind Energy Costs

Detailed assessment of wind plant capital costs is complicated by variations in turbine capacity and loads, installation site geotechnics and seismic requirements, and the limited availability of pricing data on completed projects in California. Several cost figures may be analyzed to inform cost targets for 3D concrete printing towers to be competitive in the California market.

In 2020, the capacity-weighted average installed project capital expenditure (CapEx) for United States wind projects was estimated as $1,460/kilowatt (kW) (LBNL, 2021). However, California ISO prices exceed the national average and are the second highest in the country, at $2,078/kW in 2017 and $1,844/kW in 2018. A wind turbine CapEx is approximately $775–850/kW rated capacity. In 2019, the National Renewable Resources Laboratory (NREL) estimated the tower cost for a 2.6 MW land-based reference wind turbine as $215/kW, with the foundation cost estimated as $59/kW (Stehly et al., 2020). The tower cost was estimated using NREL's 2015 Cost and Scaling Model, which is an internal NREL model that is not publicly available.

CapEx estimates for a state of the art 140-meter steel tower performed by NREL were $616/kW (Lantz et al., 2019). The same study presented breakeven costs in $/kW; these represent the incremental price premium that can be incurred with the improved capacity factors afforded by tall tower technologies and result in an equivalent LCOE (levelized cost of electricity) as the currently available technologies at an 80-meter hub height. The breakeven cost reflects a potential additional cost on top of the estimated total CapEx for 80-meter towers today (estimated as $1,077 /kW by NREL). NREL estimated the average breakeven cost for 140-meter towers in California as approximately $677/kW. Therefore, the CapEx target for tall tower technologies in California is estimated as $1,754/kW.

Project Purpose

The project purpose was to develop, demonstrate, and test a 3D concrete printing technology (3DCP) for building low-cost ultra-tall wind turbine towers on site at the wind plant to capture more wind energy from faster winds aloft. Specifically, the project goals include:

- Development of a conceptual design for a 3DCP wind turbine tower.
- Assessment and selection of 3DCP technologies for tower manufacturing.
- Validation of 3DCP design method via structural testing of a prototype tower subassembly.
- Validation of market competitiveness of 3DCP towers via techno-economic analysis.

The 3DCP manufacturing technology will reduce technological and economic barriers to upgrading, repowering, and expanding wind power generation in California by enabling cost-effective deployment of taller towers built on site. The proposed 3DCP tower manufacturing process eliminates the transportation and logistics constraints by manufacturing structurally efficient large-diameter towers within the wind plant using lightweight reinforcement methods. The towers are made with locally available cementitious materials supplied by standard concrete trucks or an existing concrete batch plant within the wind plant. The manufacturing technology is faster and safer while providing new transformative design possibilities that reduce costs and energy consumption by using less concrete and less labor than conventional construction and by eliminating concrete formwork. This technology will improve turbine aesthetics and reduce environmental disturbances during construction by using larger turbines that reduce the number of turbines for a given wind plant nameplate capacity.

The project is aimed at reducing the technological and economic barriers to upgrading, repowering, and expanding wind power generation in California by enabling cost-effective deployment of taller towers that capture more wind energy from faster winds aloft, in both high-quality and low-quality wind resource regions.

CHAPTER 2: Project Approach

The project scope entailed the development, demonstration, and testing of a 3D concrete printing (3DCP) technology for building low-cost, ultra-tall wind turbine towers on site at wind plants in California. To complete this project, the project team performed several key development tasks:

- Review of 3DCP state of the art and available equipment
- Structural design of 3DCP towers to specified loads
- Fabrication and assembly of a 3DCP concrete tower subassembly
- Structural testing of the 3DCP tower subassembly
- Techno-economic analysis and market assessment
- Planning for future development and commercialization activities

Literature Review

The project team gathered information on additive manufacturing of concrete and concrete tower design to inform the down selection of 3DCP technologies for tower manufacturing. Sources include (1) publicly available documentation such as tower design reports, codes, guidelines, standards, news, and journal articles; (2) discussions and meetings with subject matter experts; (3) conferences; (4) site visits to research institutions and companies developing concrete additive manufacturing (AM) technologies; and (5) a Preliminary Project Stakeholder Workshop with project stakeholders and the Technical Advisory Committee. Table 1 summarizes the information sources related to tower design and 3DCP.

Table 1: Summary of the 204 References Used in the Literature Review

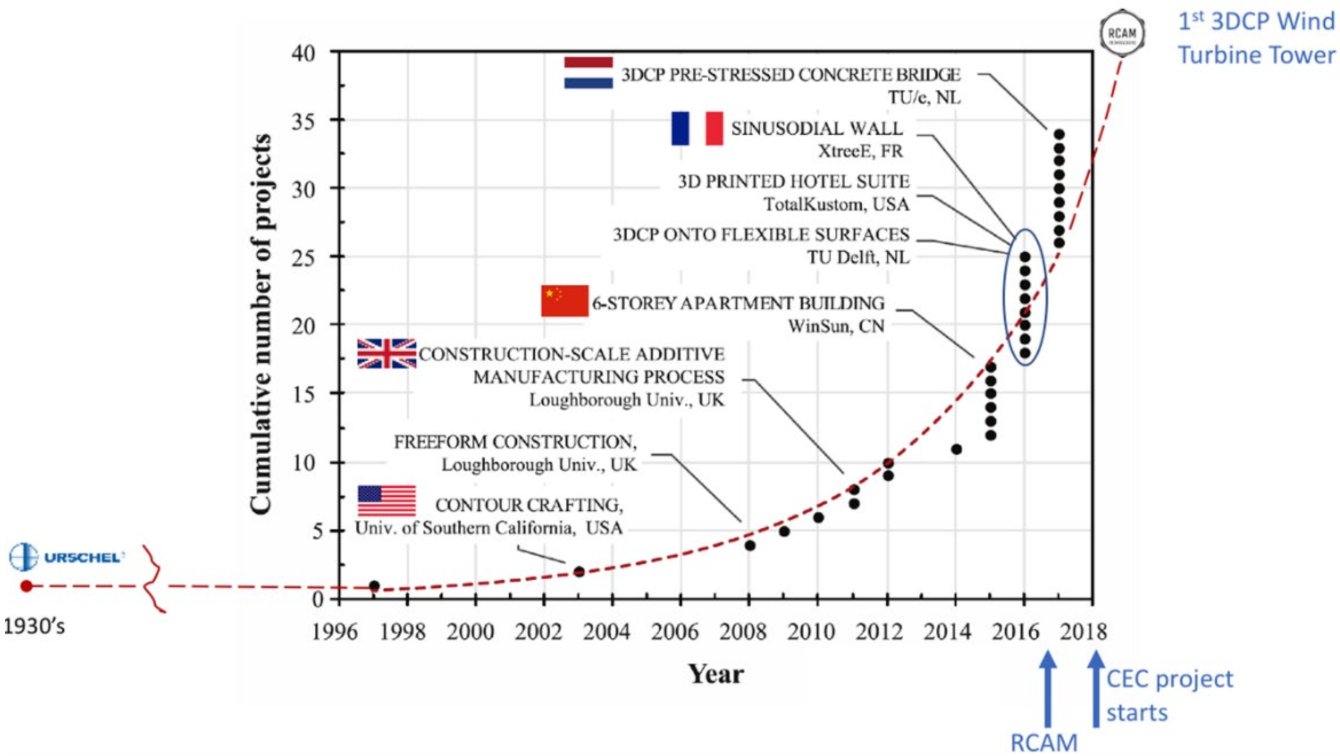
	Articles	Web pages / blogs	Conferences and workshops	Meetings / discussions
3D Concrete Printing Equipment	3	7	3	6
3D Concrete Printing Mixture Design	28	19	2	5
Wind Turbine Tower Design and Logistics	55	41	1	1
Techno-economic Analysis	12	20	1	0
Subtotal	**98**	**87**	**7**	**12**

Source: RCAM Technologies and University of California, Irvine

State of Additively Manufactured Concrete Towers

The team first reviewed the state of the art of 3DCP. Figure 7 shows the exponential growth in 3DCP projects over time. 3DCP was invented in the late 1930s in Indiana by William Urschel and has grown rapidly, starting with Dr. Behrokh Khoshnevis' work at the University of Southern California in the early 2000s. By 2020, more than 40 companies worldwide were known to be engaged in 3DCP, along with numerous universities.

Figure 7: Exponential Development of 3DCP Projects Over Time

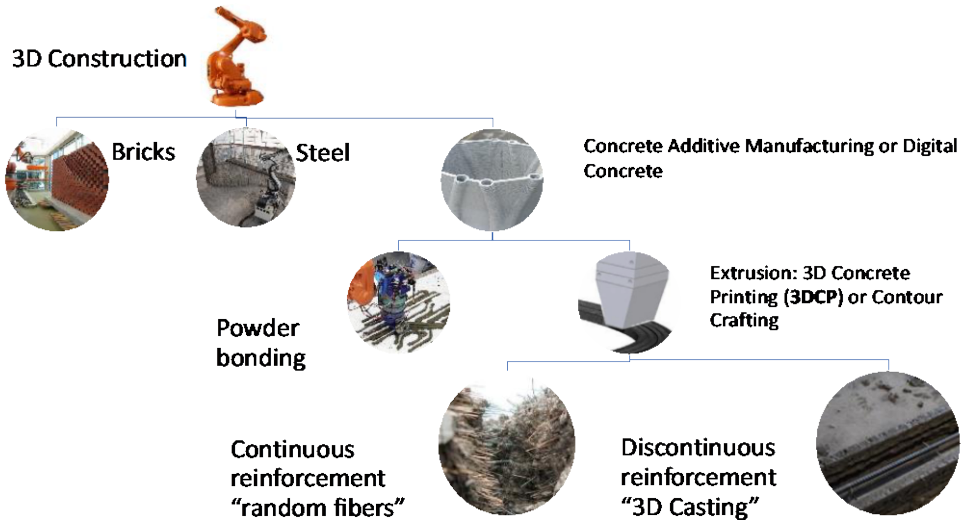


Source: Buswell et al., 2018

3D Concrete Printing State of the Art

Figure 8 shows an overview of various automated 3D construction technologies. 3DCP can be considered a market sub-segment of digital fabrication, which is also called 3D construction. The large construction market ($1.2 trillion in the United States) has attracted substantial interest from developers of automation and information technologies with potential benefits in reducing cost, saving time, and improving quality.

Figure 8: Overview of 3D Construction Technologies



Source: RCAM Technologies

3D casting is an especially attractive method of 3DCP, also referred to as 3DCP with integrated formwork. In 3D casting, the inside and outside wall surfaces are first printed from materials such as concrete before reinforcement and cast materials are inserted in the cavity. The inside and outside wall surfaces (the integrated formwork) become part of the final structure. Plastic pipe can be inserted in the integrated formwork before casting to provide a conduit for additional post-tensioning reinforcement. Post-tensioning is a well-established reinforcement method of using steel cables or rods to compress a structure after curing, which allows for thinner structural sections, longer spans between supports, and stiffer walls to resist lateral and overturning loads. The U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) and other organizations have successfully integrated and demonstrated the design readiness of large-scale, field-deployable 3DCP systems for fabricating bridges and buildings. Figure 9 shows photographs of a building manufactured in 24 hours by CERL using 3D casting. 3D casting has also been demonstrated by XtreeE in France for fabrication of structural panels.

Figure 9: Printing at Construction Engineering Research Laboratory

CERL uses large-scale 3DCP equipment (left) to print a concrete building in 24 hours (right). The inner- and outer-wall surfaces are printed before adding fiber, mesh, or rebar reinforcement (middle) and filling with cast concrete.

Source: RCAM Technologies

Another important development is the commercial availability of large-scale 3DCP systems by companies including COBOD, Rohaco, WASP, and 3D Potter. The companies offer a range of printer sizes from scales of 2 meters to 45 meters. These printers and the associated pumps, print head, and service support provided RCAM Technologies with hardware that could be used or adapted for on-site manufacturing of wind turbine towers at or near the installation site.

RCAM Technologies' visit to COBOD provided evidence that the printer hardware would not limit the printing speed. COBOD demonstrated a horizontal printer speed of 1 meter per second (m/s) during the visit and a printer head width of 8 centimeters (cm). One potential limit on print speed is the ability to pump a sufficiently fluid concrete mix that develops sufficient yield stress to support subsequent additive layers without collapse. RCAM Technologies' visit to the Danish Technological Institute (DTI) provided additional evidence that 3D printing can be performed quickly. DTI has demonstrated vertical 3D printing speeds approaching 1 meter per hour vertically without collapse of the structure. DTI speculates that it might be able to increase this rate by a factor of nearly five using accelerant additives. The method of adding these additives at the printer head is a promising area of research.

The development of high-throughput pumps specific for 3DCP applications is still an area of active research. Compared to conventional concrete pumps, 3DCP requires an especially constant material flow. Another challenge in pumping for 3DCP is particle segregation in the hose from the pump to the printer head, which can lead to blockages caused by mix design and/or insufficient mixing prior to pumping (Buswell et al., 2018).

The information collected by the project team encouraged the team to focus on a hybrid method of 3DCP called 3D casting for on-site manufacturing of wind turbine towers. Further, the accelerated development and availability of commercial 3DCP equipment allowed the team to make use of existing 3DCP for laboratory prototyping.

Tower Design and Analysis

The project team designed a baseline concrete tower and a hybrid 3DCP and steel tower based on the American Concrete Institute (ACI) Innovation Task Group 9 *Report on Design of Concrete Wind Turbine Towers* (ACI Innovation Task Group 9, 2016) and other publicly available tower design reports in a methodology reviewed by wind turbine tower experts.

Tower Specification and Loads

The project team gathered information on ultra-tall wind turbine tower designs and loads from publicly available documentation and discussions with subject matter experts. Five primary criteria were used to guide the selection of specifications, loads, and parameters:

- Choose practical design parameters that reflect the primary value proposition for commercialization of ultra-tall 3DCP towers in California.
- Reduce analysis uncertainty by selecting tower designs and parameters that facilitate an "apples to apples comparison."

- Focus on features for the primary value proposition that existing conventional tower solutions cannot provide.
- Minimize risks in 3DCP manufacturing by selecting 3DCP process parameters that are similar to conventional manufacturing when possible.
- Select wind turbine parameters and models that are readily available and that can be shared with potential business partners, customers, and stakeholders.

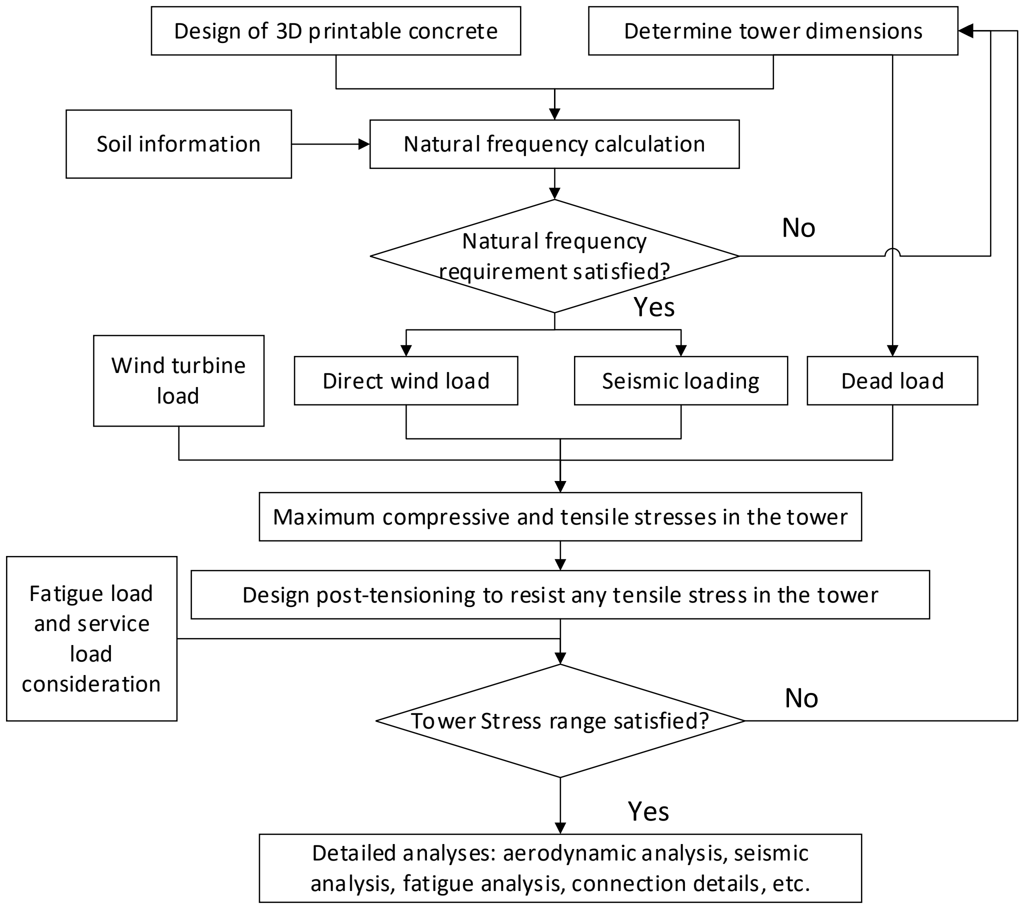
Ultra-tall Tower Design Flowchart

Figure 10 shows a flowchart listing the steps followed in the design and analysis of additively manufactured concrete wind turbine towers. This process is based on standard concrete wind turbine tower design methodology and considers the properties of 3D printable concrete.

The most important standards, codes, and documents identified by the project team are summarized here:

- *Report on Design of Concrete Wind Turbine Towers* (ACI Innovation Task Group 9, 2016) provided the guidelines for the preliminary design.
- *Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10)* gave the details to calculate design loads of the concrete tower, including wind load and seismic loading (American Society of Civil Engineers, 2016).
- *Wind Turbines-Part 1: Design Requirements (IEC 61400-1)* described general information about the design of wind turbines (International Electrotechnical Commission, 2005).
- *Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures (ASCE/AWEA RP2011)* summarized information about design loads, fatigue consideration, foundations, and connections (ASCE & AWEA, 2011).

Figure 10: Flowchart Diagram for the Design of Additively Manufactured Concrete Wind Turbine Tower



Source: University of California, Irvine

The following assumptions were made for the 3DCP tower design.

- The 3D printed formwork is not considered for the loading capacity of the tower. This design assumption underestimates the loading capacity of the 3DCP tower and thus makes the design more conservative.
- The mass of the 3D printed formwork is considered. 3D printed formwork affects the dead load, natural frequency, and seismic performance of the tower.
- 3D printed formwork increases the tower external diameter and is considered for direct wind load computation.

Natural Frequency Calculation and Finite Element Modeling

The tower design must avoid resonance due to the vibration effects of turbine operation and wind. To predict structural performance characteristics, the project team performed analytical studies using a stiff-flexible natural frequency design approach. The University of California, Irvine, (UCI) team used finite element modeling (FEM) in ABAQUS (Dassault Systems, 2018/standard) to calculate the natural frequency of the towers. The model was developed in OpenSees, an open-source finite element analysis (FEA) program developed at the University of California, Berkeley; the model is widely used for simulating the dynamic and seismic response of structural components and systems.

Design Load Combination

There are several types of loads considered in the tower design: dead load, direct wind load on the tower body, wind turbine load on the tower head, and seismic load. The design load combinations are listed here, with maximum factors from the American Society of Civil Engineers (ASCE) 7 Standard *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (American Society of Civil Engineers, 2016) and American Concrete Institute (ACI) *Report on Design of Concrete Wind Turbine Towers* (ACI Innovation Task Group 9, 2016):

- Maximum factored wind load: 1.2 × dead load + 1.6 × direct wind load on tower + 1.35 × wind turbine load
- Service wind load: dead load + unfactored direct wind load on tower + unfactored wind turbine load
- Maximum factored construction wind load: 1.2 × dead load + 1.6 × direct wind load on the tower
- Unfactored construction wind load: dead load + unfactored direct wind load on the tower
- Seismic load: dead load + seismic load

Wind Load Design

Two types of wind load combinations were selected for wind load design: maximum factored wind load and service wind load. For each load combination, both the extreme wind speed model (EWM) and extreme operating gust (EOG) were considered. The moments at each cross-section along the tower height were calculated using industry standard methodologies (American Society of Civil Engineers, 2016). An International Energy Agency (IEA) class III wind turbine tower was used, where the common wind speed at hub height was 37.5 m/s and the extreme three-second gust wind speed at hub height was 52.5 m/s, based on International Electrotechnical Commission 61400-1 (International Electrotechnical Commission, 2005) and ASCE/American Wind Energy Association Recommended Practice 2011 (ASCE & AWEA, 2011).

Construction wind loads consider that the wind turbine has not yet been installed and only tower weight and direct wind are considered. As EWM dominated the tower design, this model was used to consider the maximum factored construction wind load combination and the unfactored construction wind load combination, along with the P-delta effect, which accounts for secondary structural behavior when axial and transverse loads are simultaneously applied.

Seismic Load Design and Analysis

Seismic design was performed under the assumption that the tower is in one of California’s existing wind farms. In lieu of a site-specific design requiring a detailed geotechnical investigation, the soil class for all sites was assumed as class D for stiff soil with shear velocity typically 183–366 m/s. The spectra response acceleration for each wind farm was obtained from seismic design maps (USGS, 2018). The seismic calculations followed ASCE 7-10.

Post-tensioning Design

The design criterion used prestressing steel (that is, post-tensioning) to cancel out any tensile stress due to seismic load or wind load in the tower. The preliminary post-tensioning design was performed based on static seismic loading as described in ASCE 7-10. Because this tower design method is conservative, finite element analysis in OpenSees was used to refine the seismic design and post-tensioning design. The seismic analysis was based on four real seismic ground motions from the San Fernando, Irpinia, Landers, and Chi-chi earthquakes (USGS, 2018).

Tower Design and Manufacturing Method Down Selection

3DCP Tower Design

After reviewing the state of the art of 3D concrete printing, the team down selected the 3DCP configuration and tower manufacturing processes for further development and demonstration.

The selected manufacturing process used commercially available large-scale 3D concrete printers with locally available cementitious materials supplied by ready-mix concrete trucks or by on-site mixing of concrete materials. The project team selected a two-step assembly and manufacturing process to reduce assembly time and crane costs by manufacturing and assembling the towers in sections. Hollow 3DCP stay-in-place forms of the tower sections were stacked before filling additional cast concrete materials in a type of 3DCP often referred to as 3D casting or 3DCP with integrated formwork. The integrated formwork is analogous to stay forms used in the construction industry, which are concrete forms that stay in place after construction is complete.

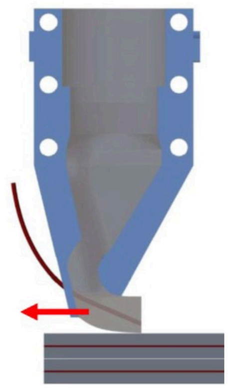
The team estimated that the 3DCP stay forms of the tower sections would be approximately one quarter the height of a conventional tower, enabling the fabrication of sections approximately 10–20 meters tall while remaining within crane capacity limits. The section height of conventional precast tower sections produced by Max Bogl, the leading concrete tower manufacturer in Germany, is limited to about 2.8 meters to accommodate transportation mass and size constraints. The use of RCAM's on-site 3DCP manufactured towers would therefore reduce the number of tower sections, and the number of crane lifts by two to three times compared to a conventional precast tower, accelerating construction by a similar factor. Furthermore, the 3D casting process allowed RCAM to use less expensive cast materials than it would have in attempting to print the entire tower.

Reinforcement Methods

Multiple reinforcement methods were possible in the printed and cast portions of the structure, such as fiber reinforcement, embedded wire, embedded meshes, rebar, and post-tensioned cables. Fiber reinforcement typically uses steel or polyvinyl alcohol fibers randomly mixed into the concrete to increase the concrete's tensile strength and improve fracture behavior. The use of fiber reinforcement in 3DCP concrete is an ongoing research and development area in terms of material pumpability and compliance to building codes and standards.

Ongoing research shows promising advances in reinforcement technologies for automatically embedded reinforcement such as wire or meshes into 3DCP layers during layer deposition. These developing technologies have the potential to reduce the cost and material use for 3DCP towers, as well as increase the production rate by further reducing the manual labor requirements. Figure 11 shows a schematic of a 3DCP nozzle designed to embed wire reinforcement in 3DCP layers. Wire cable has been shown to increase the flexural strength of concrete and induce beneficial strain hardening behavior (Bos et al., 2018; Salet et al., 2018). The method has been demonstrated in laboratory studies but has not yet been widely adopted in industry.

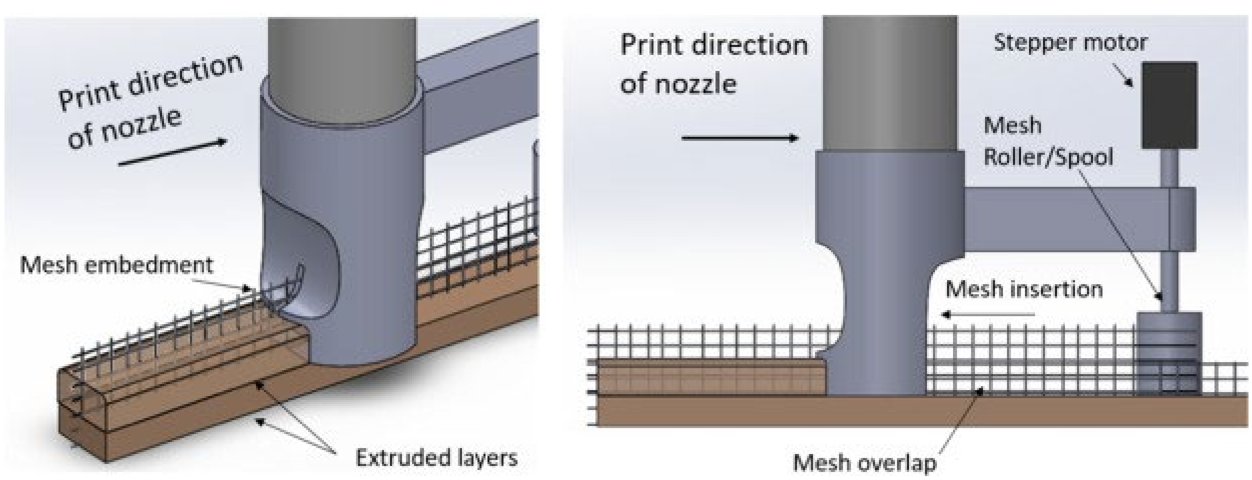
Figure 11: A 3DCP Nozzle Designed to Embed Wire Reinforcement in 3DCP Layers



Source: (Salet et al., 2018)

Similarly, 3DCP researchers have only recently begun to embed meshes into 3DCP structures. Figure 12 shows a schematic of a 3DCP nozzle custom designed to embed overlapping layers of mesh in 3D printed concrete layers.

Figure 12: Example of Mesh Embedment Using a Custom-designed 3DCP Nozzle



Source: Marchment & Sanjayan, 2020

The project's technical advisory committee cautioned the project team about using these advanced methods at this early stage of the design because the conservative nature of concrete design standards and codes would likely delay acceptance of the technologies for wind turbine towers. For these reasons, the project team selected a more conventional steel reinforcement strategy using a combination of wire, rebar, and post-tensioned cables, primarily due to their more proven nature.

The selected method is described as follows. First, wire cable was inserted into the printed layers to provide hoop and radial reinforcement in the walls. Second, rebar rods or cages were inserted in axial channels in the integrated formwork to provide axial strength during assembly of the formwork. Post-tensioning was installed after the cast materials sufficiently hardened, to join the tower segments together. Post-tensioning is a well-established reinforcement method using steel cables or rods that allow thinner structural sections, longer spans between supports, and stiffer walls to resist lateral and overturning loads. Concrete wind turbine towers routinely use post-tensioned reinforcement, with installations in approximately 4,000 cast wind turbine towers, primarily in Europe. The use of these more proven forms of reinforcement was expected to provide sufficient performance and cost advantages compared to conventional construction methods. However, developing 3DCP reinforcement technologies have the potential to reduce the cost and material usage, as well as increase the production rate by further reducing manual labor requirements.

Manufacturing Logistics

The project team examined several manufacturing options within the wind plant, including (1) printing all tower components at the wind turbine installation site, (2) printing tower sections at a central location within the wind plant, and (3) printing tower sections at both a central wind plant location and at the turbine installation site.

The trend toward larger turbines is expected to favor on-site manufacturing approaches (option 1) as opposed to more centralized manufacturing methods (options 2 and 3). Minimizing transportation distances of tower components is important due to their large size and mass, which make suitable cranes and handling equipment very expensive. Tower components should be designed to reduce installation crane costs by reducing the component mass and/or reducing the number of wind turbine tower sections. Option 1, printing all tower components at the wind turbine site, had the highest potential for reducing both handling costs and crane usage by avoiding intra-wind plant transport and by allowing manufacturers to print taller sections directly at the turbine installation site. Advances in 3DCP printer mobility and cost, and the faster 3D casting technique led the project team to favor printing all components at the turbine sites. Furthermore, the recent trend in California (and the United States) for wind plant developers to use larger wind turbines to reduce the number of turbines within a wind plant makes Option 1 more attractive and better suited for next generations of turbines by (1) reducing the number of overall parts manufactured within a wind plant, and (2) facilitating the increased size and mass of tower sections needed for larger turbines.

The specific steps in the team's manufacturing approach included:

- Printing the first tower section (the pedestal), up to approximately 20 meters tall, directly on a conventional or, potentially, a 3DCP foundation.

- Printing the formwork for the subsequent tower sections adjacent to the pedestal up to 10–20 meters tall.
- Hoisting, stacking, and assembling the 3DCP formwork on the pedestal.
- Filling the formwork walls with cast concrete and curing.
- Installing post-tensioning reinforcement to compress the tower assembly.
- Installing the turbine rotor-nacelle assembly.
- After printing, relocating the mobile or portable 3DCP equipment to the next turbine.

3D Concrete Printing Equipment

The selection of the type of 3D concrete printer was an important consideration because the design of the 3DCP tower, the 3DCP manufacturing process, and the manufacturing cost are interrelated. Manufacturers such as COBOD and ICON have already built commercial printers capable of printing dimensions up to 12 meters in diameter and 9 meters tall for the construction industry. Taller heights are possible. Modern 3DCP equipment manufacturers claim they can set up the printers in less than a day. New 3DCP technologies target setup times of less than four hours and breakdown times of approximately two hours. RCAM has invented a mobile gantry printer concept that incorporates a roof for sun and rain shelter and can be driven to the next site to minimize the number of setups and breakdowns. Figure 13 shows renderings of RCAM's mobile gantry printer concept and RCAM's 3D concrete printed tower being manufactured on site. In colder climates such as Northern California or in mountainous terrain, a temporary structure can be constructed for year-round printing.

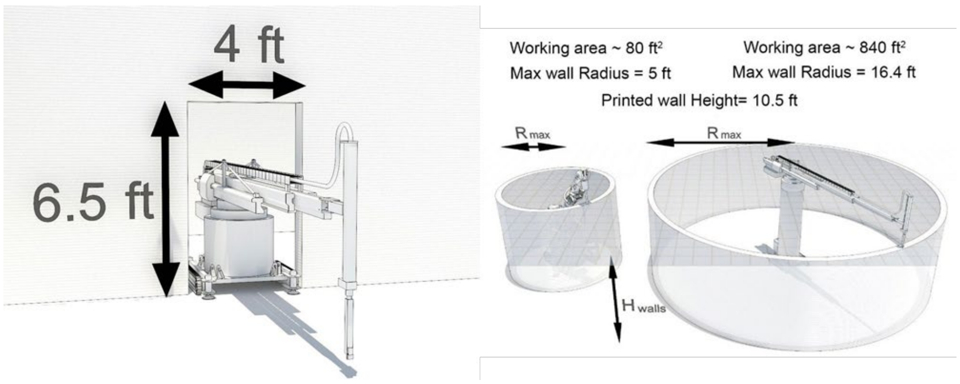
Figure 13: RCAM's 3D Concrete Printed Tower and Gantry Printer Concepts

On-site tower manufacturing concept (left) and gantry printers (right)

Source: RCAM Technologies

More compact radial arm printers are a second printer configuration that offers a more compact 3DCP solution that can be transported between sites without lengthy setup or breakdown steps. Apis Cor offers a radial arm printer that, if placed at the center of the tower section, would be large enough to build the largest sections of RCAM's tower, which is nominally 10 meters in diameter. In addition, radial arm printers can potentially print taller tower sections, potentially higher than 20 meters, in one continuous piece by raising the printer continuously during printing or in stages. Figure 14 shows a compact and mobile radial arm printer designed by Apis Cor.

Figure 14: Example of a Compact and Mobile Radial Arm Printer



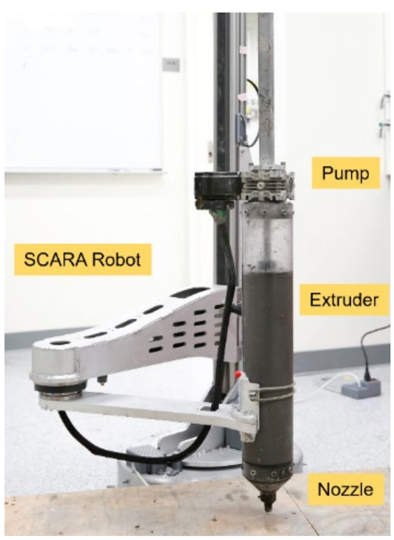
Source: Apis Cor

Tower Prototype Manufacturing

UCI Printing Systems

Two 3D concrete printing systems were used at UCI. Figure 15 shows the two robotic printing systems at UCI: the 3D Potterbot SCARA robot and an industrial six-axis robotic arm system. The movement of the robots was controlled by G-code programming, a commonly used computer numerical control programming language. In addition, to enable larger-scale concrete printing, UCI integrated a continuous flow concrete pumping system with the robots.

Figure 15: Robotic Printing Systems at University of California, Irvine

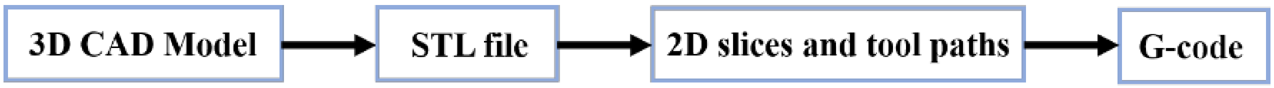


SCARA robot (left) and ABB industrial robot (right)

Source: University of California, Irvine

The concrete 3D printing process consisted of three stages: (1) data preparation, (2) materials preparation, and (3) component printing. Figure 16 shows the workflow of data preparation from 3D model to G-code. Computer-aided design (CAD) software was used to design the 3D model of the tower (or beam) segment, which was exported to the stereolithography (STL) format. The 3D data were described as 2D surface geometries with unstructured triangulated flat facets. These 2D contour lines were used to generate the G-code to control the position and movement of the nozzle head versus time.

Figure 16: Workflow of G-code Data Preparation



Source: University of California, Irvine

The next stage was the materials preparation. The concrete mixing was conducted using concrete mixers with various capacities. Figure 17 shows the Hobart mixer and the higher-capacity Imer mixer used for 3D concrete printing. First, the dry ingredients were mixed, and then water and the chemical admixture were added and mixed to reach the target rheology and coherence of concrete. Then, the fresh concrete mixture was charged into the hopper of the continuous flow pumping system. After material preparation, the concrete 3D printing process started, following the pre-programmed printing path and geometry.

Figure 17: Concrete Mixers With Different Capacities for 3DCP

Source: University of California, Irvine

Mixture Development and Rheology

Rheology is the study of the flow of matter, primarily in a fluid state. For material tailoring, UCI measured the rheology properties of the 3D printing concrete by a dynamic oscillation stress sweep method. Figure 18 shows the TA Instruments HR-2 Discovery Hybrid Rheometer used for these experiments. Two key rheological parameters, yield stress and viscosity, were obtained from the measurements. The yield stress was related to the buildability of the 3D printed concrete and its resistance to deformation during the printing process. The viscosity was related to the extrudability of the 3D printed concrete and the continuity of the printing filaments.

Figure 18: TA Instruments HR-2 Discovery Hybrid Rheometer

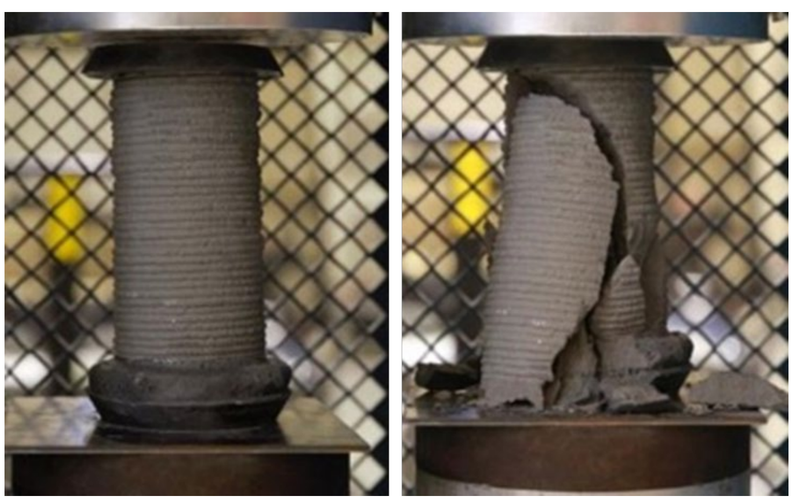
Source: University of California, Irvine

Mechanical Property Testing

Compressive strength is the key mechanical characteristic of concrete. UCI conducted age-dependent compressive testing on 3D printed concrete cylinder specimens with a diameter of 76.2 millimeters (mm) and a height of 152.4 mm using the standard method according to ASTM C39. Six repeat specimens were tested for each type of 3D printing concrete.

Figure 19 shows two photographs of the 3D printed concrete cylinders before and after compressive testing. The testing results demonstrated that the 3D printed concrete has compressive strength equivalent to that of conventional concrete.

Figure 19: Compression Test on 3D Printed Concrete



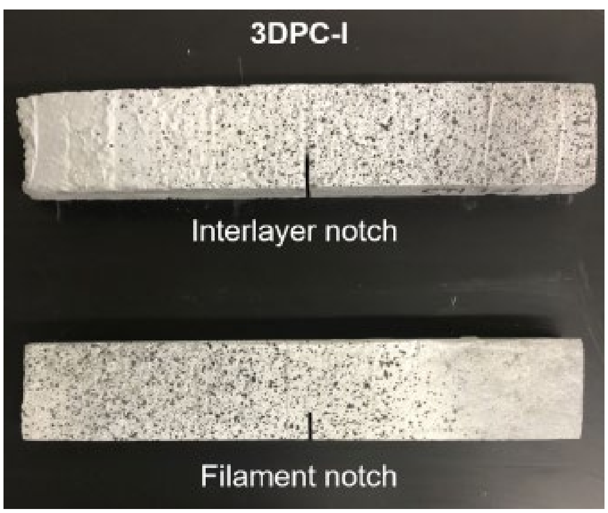
3D printed concrete cylinder before (left) and after (right) compression testing

Source: University of California, Irvine

3D Concrete Printed Beam Testing

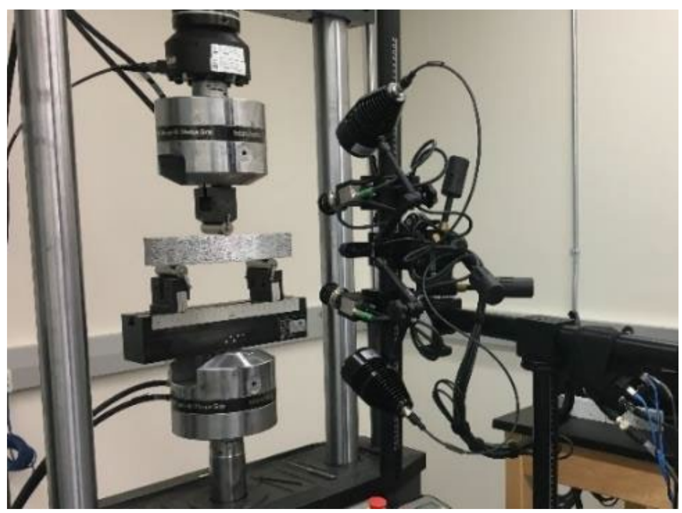
To rationally analyze and reliably design tall wind turbine towers made of 3D printed concrete, it is critical to understand the effect of the new manufacturing process on the mechanical behavior of 3D printed concrete components and structures. Unlike cast concrete, the layer-by-layer deposition process introduces printing filaments and the interlayers between the filaments. The presence of interlayers can affect the fracture behavior of the structural components, subsequently affecting the durability, serviceability, and even safety of the concrete structures manufactured through the 3D printing process. To understand such effects, the UCI team experimentally studied the fracture behavior of 3D printed concrete beams. UCI measured the plane-strain fracture toughness (K_{IC}) of 3D printed concrete filaments as well as the interlayers. The UCI team performed fracture tests under three-point bending on notched beam specimens manufactured by 3D concrete printing along the beam height direction. Figure 20 shows the two different notch locations investigated: inside the filament, and at the interlayer between two adjacent filaments. The UCI team used a hydraulic testing frame to apply load under a closed-loop displacement control through a digital image correlation system; this accurately captured the post-cracking behavior of the specimens, including crack extension and opening under loading. Figure 21 shows the three-point bending test setup.

Figure 20: Notched 3DCP Beam Specimens for Fracture Testing



Source: University of California, Irvine

Figure 21: Photograph of a 3DCP Beam Fracture Test Setup



Source: University of California, Irvine

Tower Prototype Large-scale Testing and Finite Element Analysis

Based on the full-scale 3DCP tower design and the 3DCP materials testing results, the UCI team designed the 3D printed concrete tower subassembly to resist service and extreme loads. It should be noted that the term subassembly is used to denote that the 4-meter-tall test specimen is a "unit" that can be assembled along the height direction into a taller tower. The 3D-printed concrete tower subassembly, including the foundation and loading blocks, is 4 meters tall and 0.51 meters in diameter. The prototype tower subassembly was approximately 1:20 scale compared to the diameter of the full-scale tower base and 1:6 scale compared to the upper segments of the full-scale tower. In height, the tower subassembly was approximately 1:35 scale compared to the hub height of a 140-meter tower. The different scale factors of the tower dimensions reflected the complexity in designing and testing a prototype tower subassembly.

The UCI team manufactured the tower subassembly in the Advanced and Multifunctional Materials and Manufacturing for Structures (AM^3) Lab, including the Materials Lab and the Structural Engineering Testing Hall at UCI. Instrumentation was then installed, including sensors and actuators to measure global and local displacements, strain, and damage during the loading process. The load was applied using a hydraulic actuator anchored to the UCI lab strong wall. The system, including linear variable differential transformers, a load cell, and a servo valve, allowed the displacement control of the actuator to apply force. The detailed design, manufacturing, instrumentation, testing, and results of the 3D printed concrete tower subassembly will be reported in a journal paper.

As full-scale structural testing of an ultra-tall 3DCP tower was not feasible, it was important to develop an experimentally validated numerical model that could subsequently be used for structural analysis of 3DCP wind turbine towers. The UCI team used finite element modeling (FEM) in ABAQUS (Dassault Systems, 2018/standard) to perform numerical analysis of the tower subassembly with geometry and boundary conditions representative of the UCI structural testing setup. Material constitutive models with calibrated model parameters were input into the FEM to simulate the tower structural behavior under loading. The model was validated by comparing the simulation results to the actual experimental data. The validated model could be applied to more accurately and reliably simulate the structural behavior of full-scale 3DCP towers with different geometries and subjected to various loading conditions. The technical details of the finite element model and numerical analyses will be reported in a journal paper.

Technoeconomic Analysis

The levelized cost of energy (LCOE) of wind power plants considers capital expenditures (CapEx), operational expenditures (OpEx), financial parameters, and net annual energy production (AEP_{net}). The LCOE was assessed using the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL). The LCOE was calculated as:

$$LCOE = \frac{(FCR * CapEx) + OpEx}{AEP_{net}}$$

where:

FCR = fixed charge rate (percent)

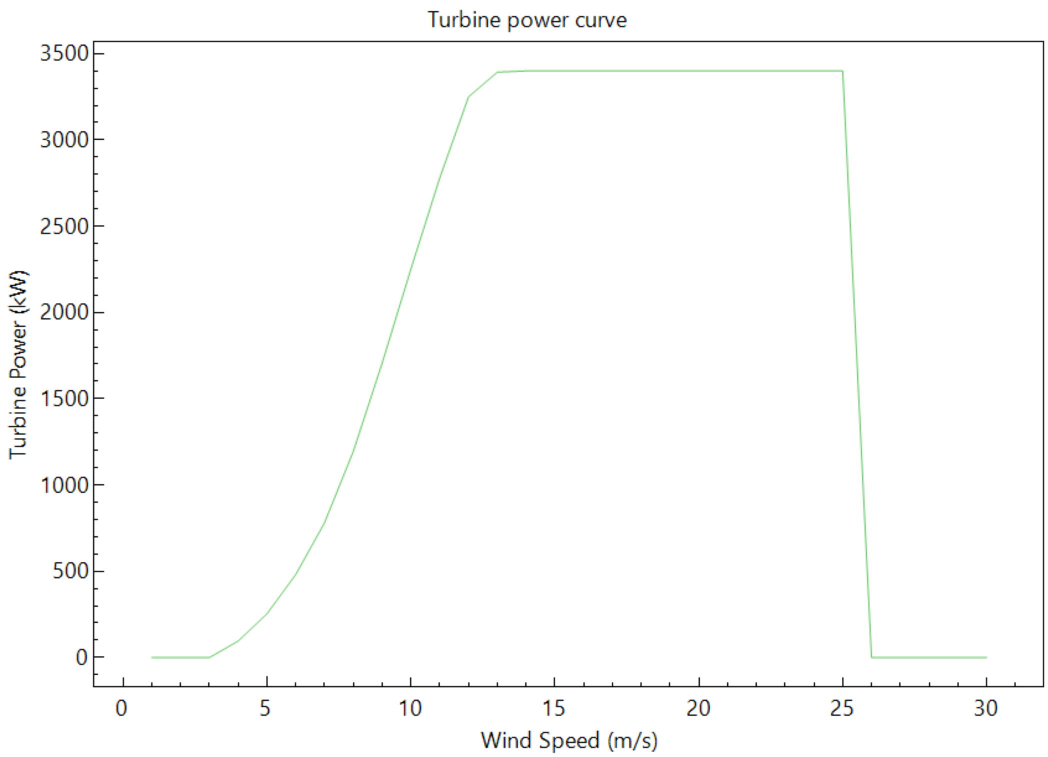
CapEx = capital expenditures ($USD/plant)

OpEx = average annual operational expenditures ($USD/plant/year)

AEP_{net} = net average annual energy production (MWh/plant/year)

AEP_{net} was calculated in SAM using a set of simplified wind plant assumptions. The wind resource was based on a wind resource file downloaded through SAM from the online NREL WIND Toolkit (Draxl et al., 2015) at latitude: 33.92, longitude: -116.62 for a 140 meter (m) hub-height in the year 2013 (the most recent year available in SAM). The turbine model used was a Senvion 3.4 MW with a 114 m rotor diameter and a shear coefficient of 0.14. Figure 22 shows the power curve for the turbine. The wake model was set to Simple Wake Model with a turbulence coefficient 0.1, resulting in a constant loss of 11.02 percent. The wind farm losses were kept at the SAM default values: total wake losses = 1.1 percent, total availability losses = 5.5 percent, total electrical losses = 2.01 percent, total turbine performance loss = 3.95 percent, total environmental loss = 2.40 percent, curtailment and operational strategies loss total = 2.8 percent. No uncertainty was considered in this preliminary model.

Figure 22: Power Curve for the 3.4 MW Turbine Assumed



Source: NREL System Advisor Model

CHAPTER 3: Project Results

Laboratory 3D Concrete Printing

Selection of 3D Concrete Printing Systems

The project team considered procuring and adapting 4-axis and 6-axis industrial robotic arms to fabricate the 3DCP specimens needed for the project. The industrial robotic arms considered were manufactured by Kuka, ABB, and Yaskawa. A purpose-built 3-axis robotic arm manufactured by 3D Potter (the 3D Potterbot Scara V4) that was designed originally for printing ceramic pottery was also considered. The primary advantages of the industrial robotic arms include (1) incorporation of additional rotation degrees of freedom at the nozzle output to accommodate rectangular print nozzles and wider print beads, (2) the possibility of adding a track along the robot's X-axis for printing long slender elements such as beams, and (3) the availability of longer-reach and higher-capacity arms for printing at larger scales. However, industrial robotic arms are more complicated to purchase, set up, and operate and are more expensive than purpose-built 3D printers such as the 3D Potterbot.

The team opted to purchase the relatively new 3D Potterbot SCARA printer initially while continuing to explore other more complicated and expensive printer options that use industrial robots. The primary reason for this approach was to enable earlier and more extensive 3D printing experiments than possible with the industrial robotic arms. The project team has continued to explore the benefits and costs of adapting industrial robot arms and gantry systems for 3DCP applications that have potential for larger scale printing.

The material delivery system was an important 3DCP component. The base 3D Potterbot model uses a polycarbonate extruder tube and extruder screw to deliver the additive materials to the nozzle. The concrete mixture was pre-mixed with a floor mixer and loaded into the transparent tube. The extruder screw was programmed to push the mixture out to process the 3D concrete printing. However, the tube can supply material volume of only 400 milliliters, which is suitable for small-scale material testing (up to about 1.8 meters in diameter) but is not enough for continuously printing specimens at the larger structural scales (from 1.8 meters in diameter to about 8.4 meters) needed to address the effects of scaling. In addition, the polycarbonate extruder tube was subject to cracking when used with highly viscous or abrasive concrete materials because it was designed originally for clay and ceramic materials.

The team explored several continuous pumping systems for the concrete printer needed to print at larger scales. All pumps considered were rotor-stator pumps. The rotor-stator pump technology moves material by circularly rotating the pump rotor inside a stator. For jobs that require thicker materials, a rotor-stator pump can provide the durability and rugged performance needed to complete the job quickly and efficiently.

Continuous pump systems from numerous vendors (manufacturers) were considered, including Graco, 3D Potter (which is manufactured by Graco and modified by 3D Potter to connect with its 3D Potterbot Scara V4 printer), M-Tec, and Ventures Equipment. The Ventures Equipment pump, the 38 Special, was removed from further consideration because the power source was a gasoline fueled generator. The team selected the Graco/3D Potter P30x-HT continuous flow pumping system due to its compatibility and proven performance with UCI's 3DPotter printer, high maximum flow rate, and lower cost compared to the other pump systems (Table 2).

The P30x-HT pump had the highest flow rate, up to 38 liters per minute, which allowed a faster printing process, and a hopper capacity of 60 liters. The maximum capacity of UCI's floor mixer was 28 liters, meaning the concrete mixture could be continually poured into the hopper of the P30x-HT pump; the hopper capacity did not limit the material supply during concrete printing. The maximum particle size of ingredients was 2 mm for the UCI 3D printed concrete material mix design, which could be accommodated by all three pumps.

Table 2: Specifications of Three Different Continuous Flow Pumping Systems

Vendor	Graco ToughTek P20	Graco ToughTek P30x-HT (Selected Vendor)	M-Tek Duo-mix
Maximum flow rate	27.6 lpm	37.9 lpm	22 lpm
Maximum particle size	6 mm	5 mm	4 mm
Hopper capacity	72 Liter	60 Liter	80 Liter
Pump pressure	2 MPa	2 MPa	3 MPa
Power requirement	240V, 30A, 1-phase (240V, 16A, 1-phase)	240 V, 30 A, 1-phase	400 V, 25 A, 3-phase
System weight	136 kg	200 kg	256 kg
Hose dimension	0.4 m x 15 m	0.45 m x 6 m	Diameter: 25, 35, 50 mm Length: 10, 13.3, 20 m
Type of pump	Stator Pump	Stator Pump	Stator Pump
Image			

Lpm = liters per minute; MPa = megapascal pressure unit; V = volt; A = ampere

Source: University of California, Irvine

Figure 23 shows the Graco/3D Potter continuous flow printing system components at UCI. The system contained a main pump unit of the pumping system with 6-meter hose, nozzle assembly part, aluminum printing head, and customized printing nozzles made of polyoxymethylene with diameters of 20 mm, 25.4 mm, 38.1 mm, and 50.8 mm.

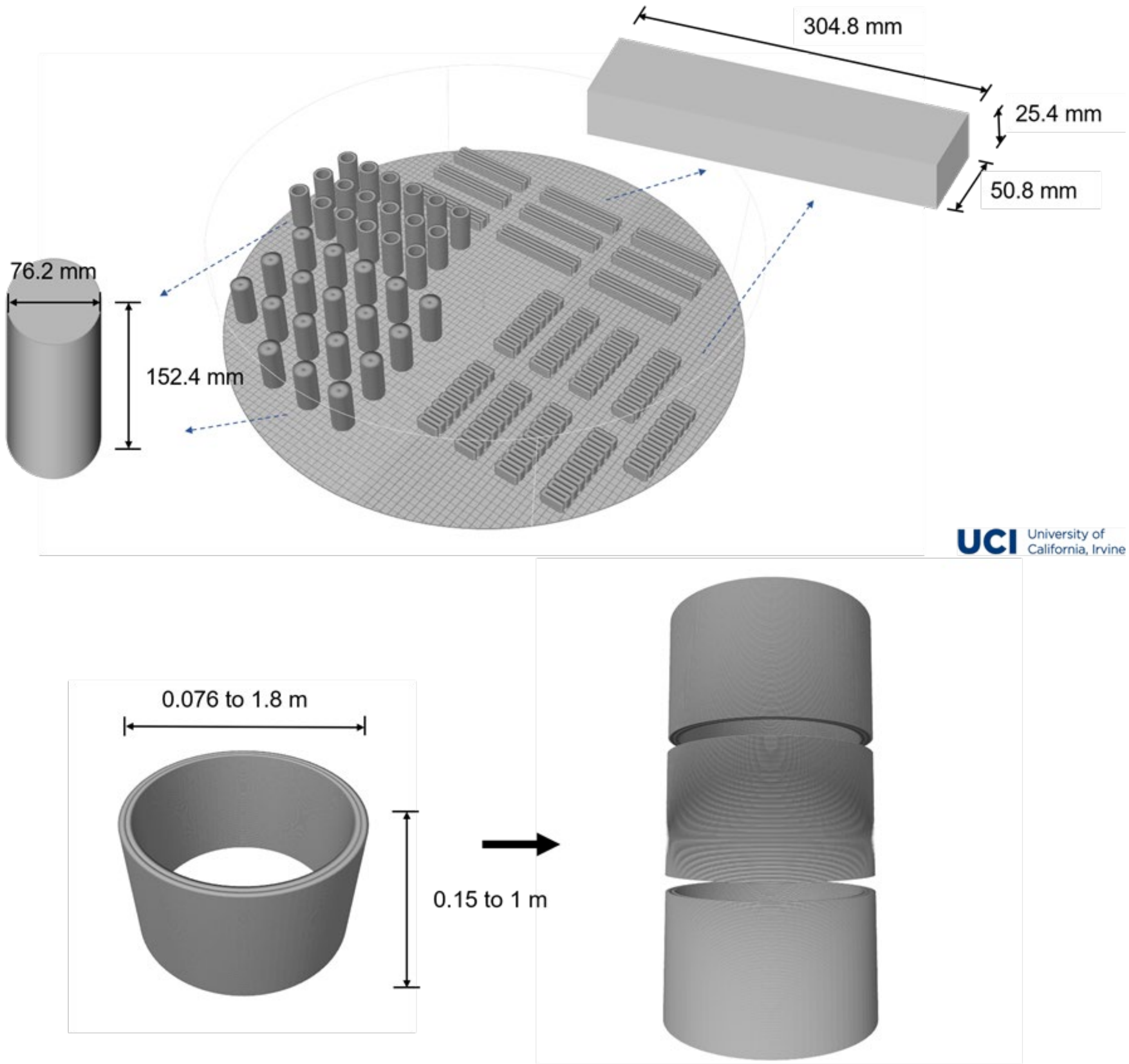
Figure 23: Components of UCI's Printing System

Source: University of California, Irvine

Specimen Printing

The project team printed specimens at the UCI AM^3 Lab to (1) test the printer head and printing system for continuously printing concrete specimens for typical structural geometries; (2) evaluate and optimize the UCI 3D printing concrete mix designs to accommodate the continuous printing process at a larger production quantity; and (3) perform further mechanical and durability testing on the successfully printed concrete specimens. Figure 24 shows models of the 3DCP specimens, including beams, solid cylinders and hollow cylinders similar to the tower sections. The specimens were printed using the continuous pumping capacity of the printer. Figure 25 shows an example test print from UCI.

Figure 24: Example Material Test Specimen Print Paths at UCI



Printed concrete segment

Assembly of 3D printed segment for tower geometry

Source: Figure generated using Simplify3D at UCI (2019).

Figure 25: Example Test Print at UCI

Source: University of California, Irvine

Although the Potterbot printer had been successfully used by UCI to begin printing, improve mix designs, and fabricate small scale specimens, UCI identified limitations in the print quality, especially for larger scale prints. These limitations appeared to be caused primarily by the light-weight construction of the 3D Potterbot. There was flexure of the arm when it was carrying more than half of the extrusion tube capacity and when extended, and larger prints resulted in poor repeatability in the radial and axial print bead dimensions that caused the print to collapse prematurely. Additional challenges with the Potterbot included the inability to use rectangular print nozzles for large beads (there was no nozzle degree of freedom) and the inability to add machine vision to compensate for uneven surfaces. Additionally, the 3D Potterbot did not allow for future expandability or degrees of freedom, such as a robotic track for larger prints or multiple prints.

RCAM and UCI have procured and operationalized an industrial robot to enable larger-scale 3D concrete printing with higher precision. A moderately more expensive, substantially higher-capacity (up to 150 kg) and longer-reach (up to a 3.2-meter radius) robotic arm was recommended to ensure that the robot capacity and reach were sufficient for the project and for follow-on RCAM/UCI 3DCP research and development (R&D) and commercialization. These specifications are expected to appreciably improve dimensional repeatability, enabling larger specimens that are approximately three times as large as with the Potterbot. Table 3 shows the key metrics and targets for printing systems informed by the project's prototype printing and market research efforts.

Table 3: Key Metrics and Targets for Printing Systems

Parameter	3D Potter	Industrial Robotic Arm ABB 6700 150-3.2	Full-Scale Gantry Equipment Field Deployed Targets
Maximum print diameter	1.8 m	6.4 m	10 m
Maximum cylinder height	1 m	3 m	10 m

Parameter	3D Potter	Industrial Robotic Arm ABB 6700 150-3.2	Full-Scale Gantry Equipment Field Deployed Targets
Maximum horizontal print speed	100 mm/s	300 mm/s	300 mm/s
Maximum vertical print rate (not pump-limited)	0.9 m/h	2.7 m/h	3 m/h
Path repeatability	Varies with arm load	0.08 mm to .12 mm	TBD
Compressive strength of 3D cast structure	30 MPa	30 to 60 MPa	30 to 60 MPa
Durability (design life)	N/A	N/A	25 to 50 years
Approximate cost in 2019 for one printer (without the pump or discounts)	$18,000	$80,000	Less than $300,000

Source: RCAM Technologies and University of California, Irvine

Properties of 3D Printed Concrete Specimens

Rheological Behavior

Two types of 3D printing concrete were employed in this project. One was suitable for smaller-scale printing using the 3D Potterbot SCARA with a lower extrusion force and rate. The other was tailored toward the larger-scale printing of the tower assembly using the continuous flow pump-robot system that had a much higher extrusion force and rate. The large-scale printing concrete achieved the higher yield stress and better buildability and resistance to shape deformation needed for 3D printing larger and taller structural segments. Furthermore, the higher complex viscosity of the large-scale printing concrete allowed a much higher pumping force and pumping rate for extrusion during the large-scale 3D printing process. The technical details of this study on the 3D printing concrete rheological behavior, compressive strength development, and fracture behavior will be reported in a journal paper.

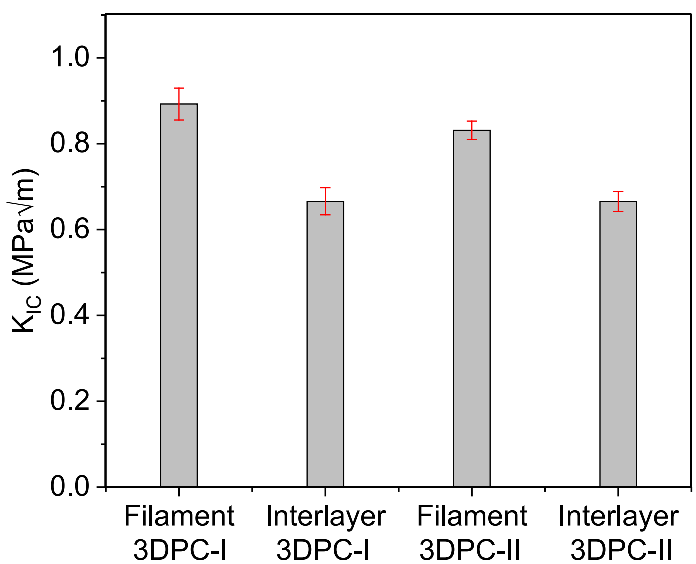
Compressive Strength

The compressive strength testing results showed that both the 3D printing concrete mixtures UCI developed achieved high early-age and late-age strengths. The small-scale 3D printing concrete achieved 24-hour compressive strength of 20.11 megapascal pressure units (MPa) on average and 28-day compressive strength of 53.65 MPa on average. Notably, through further improved material design, the large-scale 3D printing concrete achieved 24-hour compressive strength of 30.65 MPa on average and 28-day compressive strength of 73.77 MPa on average. These results validated the feasibility of using 3DCP with high early-age and late-age mechanical strength specifications for ultra-tall tower structures resisting large loads.

Fracture Behavior

Based on the fracture testing results from notched 3D printed concrete beam specimens, the plane-strain fracture toughness (K_{IC}) was calculated based on the peak load on the load vs. a crack-mouth opening displacement curve and the critical effective crack length measured by digital image correlation. Figure 26 compares interlayer and filament fracture toughness K_{IC} values for the beams made of two different types of 3D printing concrete. For beams made of 3DPC-I, the interlayer K_{IC} was 25.4 percent lower than the filament K_{IC} on average. For beams made of 3DPC-II, the interlayer K_{IC} was 20.0 percent lower than the filament K_{IC} on average.

Figure 26: Fracture Toughness of 3DPC Specimens



Source: University of California, Irvine (Wu et al., 2020)

The outcomes of the fracture testing included the following:

- Unlike conventional cast concrete beams, the fracture behavior of 3D concrete printed beams strongly depended on the location of notch or stress concentration due to the new additive manufacturing process.
- The interlayer tended to develop a shorter process zone at the crack tip before fracture compared with the filament, due to less aggregate bridging.
- Concrete mix designs also affected the maximum process zone size and critical effective crack length, indicating that the chemical bond of the cementitious binder at the crack tip also contributed to the process zone behavior.

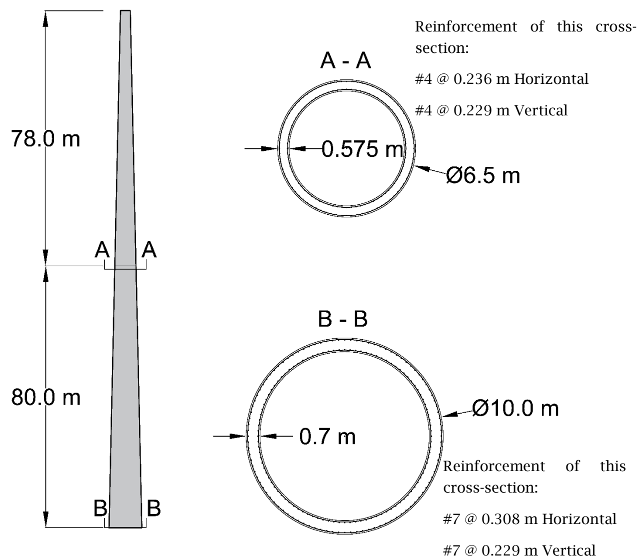
Preliminary Design of Wind Turbine Towers

Preliminary Design and Analysis of Baseline Concrete Wind Turbine Tower

The preliminary design of the baseline concrete tower was performed as described in the Project Approach section.

Figure 27 shows the tower geometry and reinforcement details at two typical sections of the baseline tower. The tower was a linear tapered tower. Two layers of vertical reinforcement were placed in the tower for temperature and shrinkage reinforcement. Note that this tower geometry was the finally determined tower geometry.

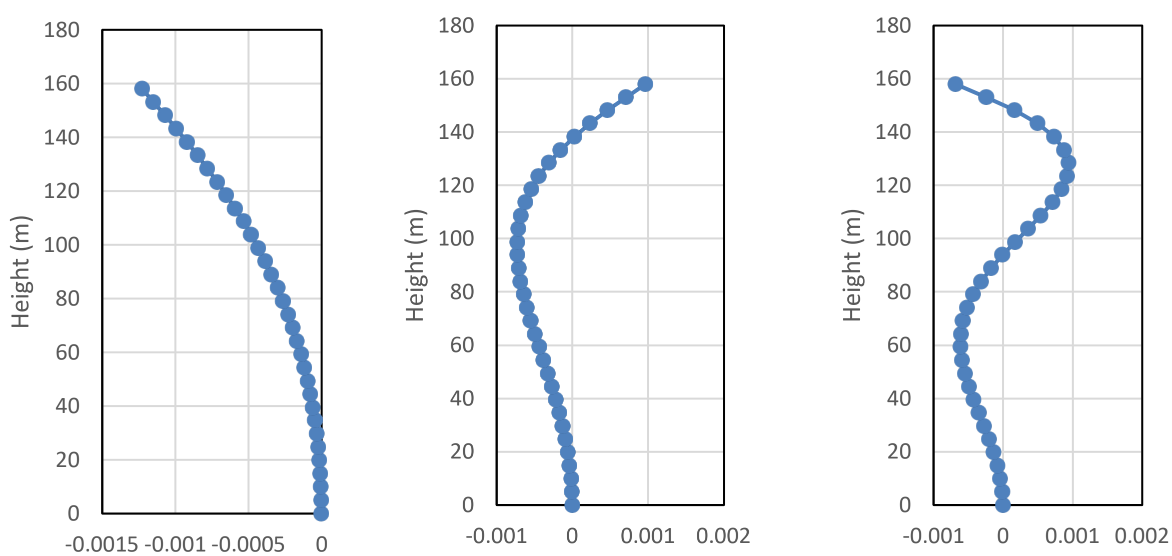
Figure 27: Baseline Tower Geometry and Representative Cross Sections



Source: University of California, Irvine

Figure 28 shows the natural frequencies and mode shapes of the baseline tower. The first natural frequency of the tower was 0.305, which was the same as the natural frequency of the IEA tower for the IEA 3.35 wind turbine. The natural frequency of the baseline tower design satisfied the natural frequency requirement.

Figure 28: Natural Frequency and Mode Shape of the Baseline Tower

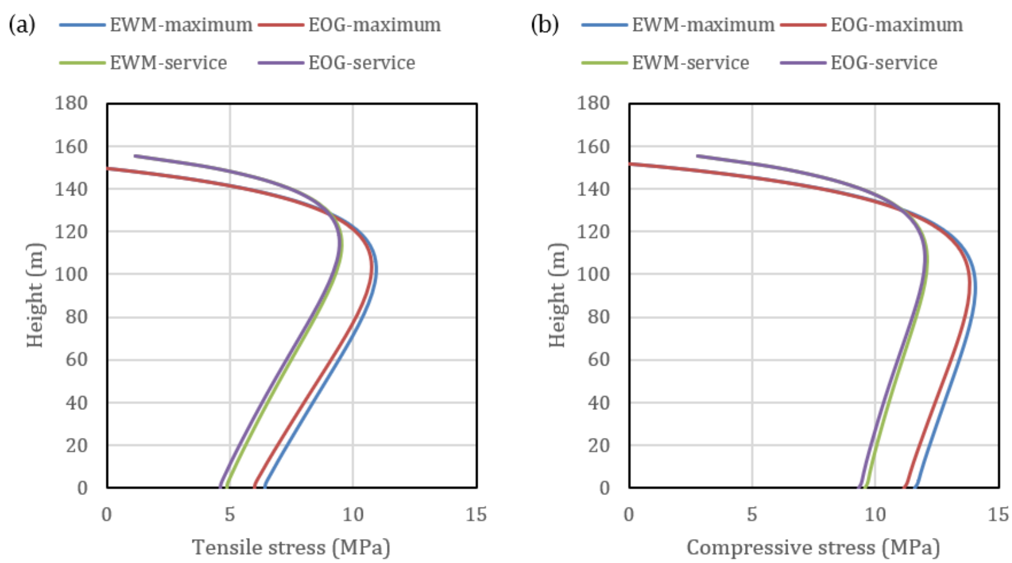


(Left) 1st mode shape, (center) 2nd mode shape, and (right) 3rd mode shape

Source: University of California, Irvine

The wind velocity and wind load along the tower height were calculated for both EWM and EOG models and used to compute the moment, axial load, and deflection of the tower as a function of its height. The analyses considered the P-delta effect and various construction errors. The tensile stress and compressive stress along the tower height were calculated as shown in Figure 29. The maximum tensile and compressive stresses occurred with the maximum factored wind load combination using the EWM model.

Figure 29: Maximum Stresses in Baseline Tower Design



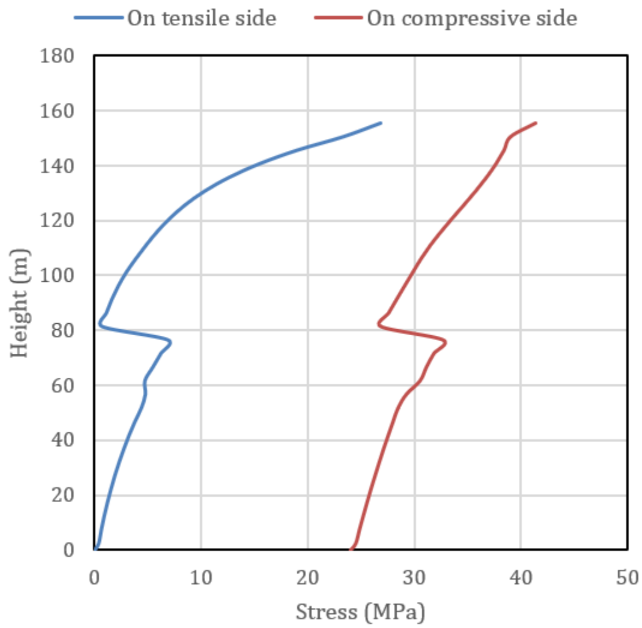
Source: University of California, Irvine

The stresses in the tower were also calculated under the construction wind load case. There was no tensile stress developed in the tower under this loading condition, and the maximum compressive stress was 3.95 MPa, much lower than the compressive strength of concrete, ensuring safety under construction wind load. Seismic design was performed following ASCE 7-10. The moment and shear force on the tower were calculated while considering the P-delta effect. The tower deflection and maximum tensile stress in the tower were then calculated.

The initial post-tensioning (PT) design was specified, including the 160 PT tendons. The design criterion was to use prestress to cancel out any tensile stress due to seismic load or wind load in the tower. The refined PT design reduced the number of PT tendons from 160 to 140 in the lower section of the tower and to 70 tendons in the upper half of the tower.

Figure 30 shows the stress in the tower after applying prestress following the refined design. Positive values indicated compressive stresses and negative values indicated tensile stresses. There was no tensile stress in the tower under seismic loading due to the prestressing force.

Figure 30: Maximum Stress on the Tensile Side and Compressive Side of the Baseline Tower After Applying Prestress

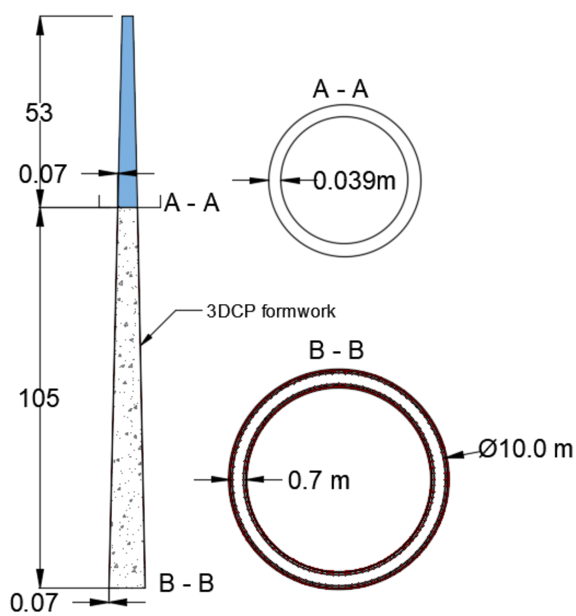


Source: University of California, Irvine

Preliminary Design and Analysis of 3DCP Wind Turbine Tower

Figure 31 shows the geometry of the hybrid 3DCP tower. The external dimension of the concrete and steel part was the same as the baseline tower. In the concrete section, two layers of vertical reinforcements were placed in the tower as temperature and shrinkage reinforcements, the same as in the baseline tower.

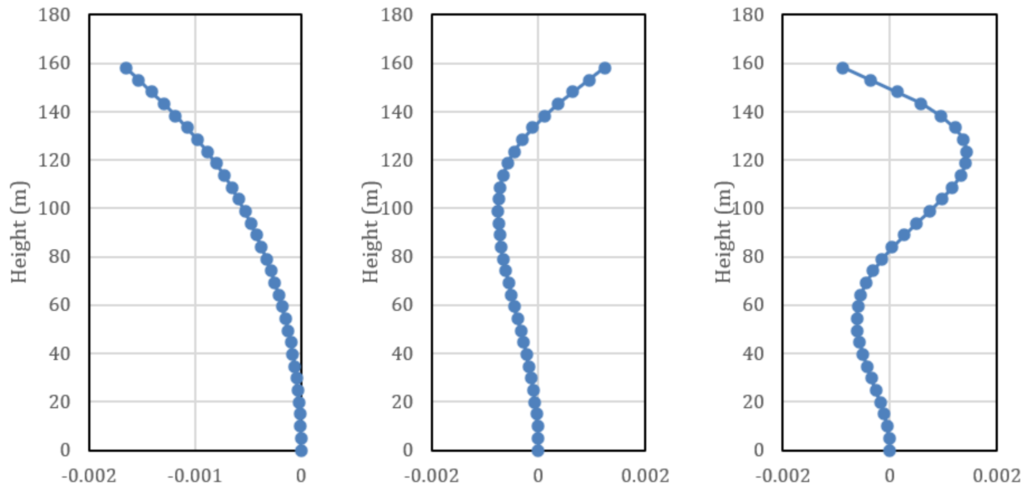
Figure 31: Geometry of Hybrid 3DCP Tower



Source: University of California, Irvine

The 3DCP tower design was also validated by natural frequency analysis. Figure 32 shows the mode shape analysis results for the 3DCP hybrid tower. The design load combinations for the 3DCP tower were the same as for the baseline tower. The main difference was that the weight of the 3DCP formwork was included in the dead load for the design of the 3DCP tower.

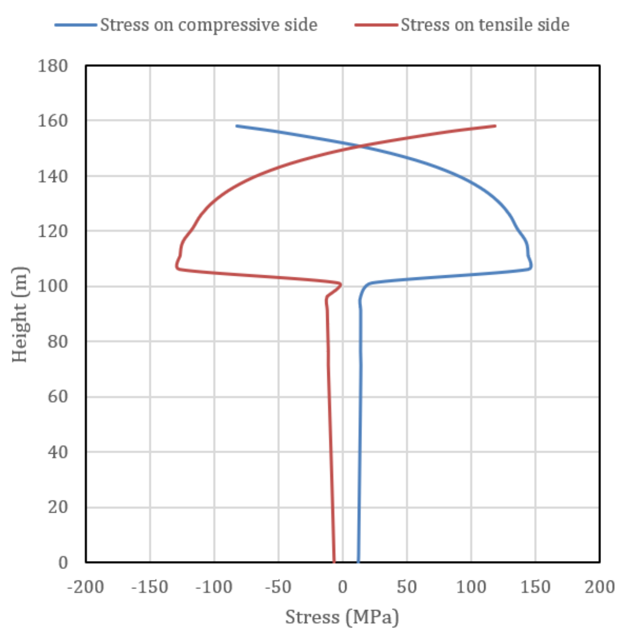
Figure 32: Mode Shape Analysis of 3DCP Hybrid Tower



Source: University of California, Irvine

The maximum factored wind load was the dominating load combination and the EWM model showed larger moments at different sections of the tower. Figure 33 shows the calculated tensile stress and compressive stress in the tower. In the steel section, tensile stress and compressive stress were within the safe range. For the concrete section, the tensile stress (- 12.08 MPa) was higher than the concrete cracking strength; therefore, prestress was necessary to cancel out the tensile stress in the tower.

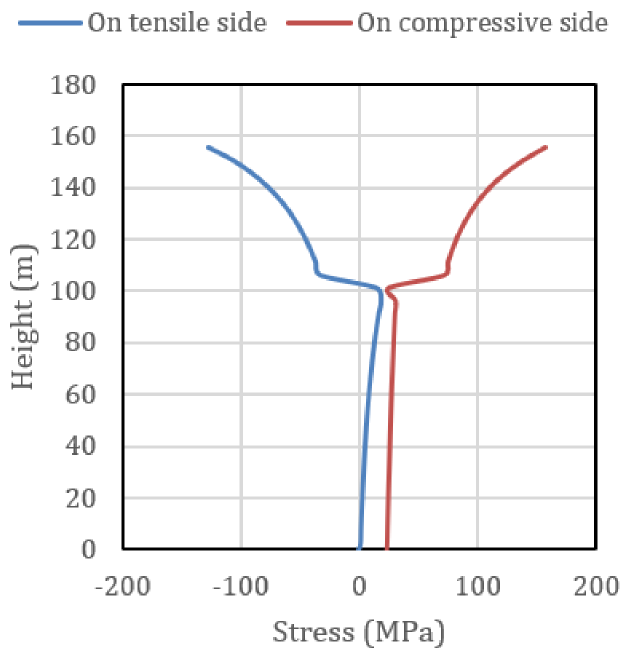
Figure 33: Maximum Compressive and Tensile Stresses in 3DCP Tower



Source: University of California, Irvine

Post-tensioning design was performed based on the maximum tensile stress in the 3DCP tower. The PT design used 110 tendons in the concrete tower section. Figure 34 shows the maximum tensile and compressive stresses after applying prestress. Negative values indicate tensile stress, and positive values indicate compressive stress. With this PT design, there was no tensile stress in the concrete part of the tower. The tensile stress in the steel part of the tower was within the allowable range.

Figure 34: Maximum Stress on the Tensile Side and Compressive Side of 3DCP Tower After Applying Prestress



Source: University of California, Irvine

The construction wind load design for the 3DCP tower, considering the direct wind load on the tower, the weight of the steel part and the concrete part of the tower, and the weight of the 3DCP formwork, verified the safety during construction.

Structural Testing and Analysis of Tower Assembly

The UCI team completed the first-ever study on the structural design, manufacturing, structural testing, and analysis of a large-scale 3D printed concrete tower subassembly.

Figure 35 shows the fabricated tower subassembly and the AM^3 Lab team at UCI. The large-scale structural testing examined the mechanical capacity of the 3D printed concrete tower subassembly under service loading as well as extreme loading conditions.

Figure 35: Completed Tower Assembly

The UCI team completed the design, 3D printing, fabrication, assembly, and instrumentation of the 3D printed concrete tower subassembly and test setup for performing large-scale structural testing. From left to right are AM3-Lab members Jianlei Wen, Amadeu Malats Domènech, Kathryn Jones, Dr. Mo Li (Lab PI and Director), Youngjae Choi, Xinbo Wang, Wei Geng, and Yun-Chen Wu, who contributed to this work.

Source: University of California, Irvine

The preliminary results from FEM numerical analysis were compared to the experimental data from testing the 3D printed concrete tower subassembly and showed good agreement. The FEM results slightly underestimated the initial stiffness of the 3D printed concrete tower assembly compared to the experimental results. The discrepancy in peak load was within 10 percent for the positive loading direction and was more than 20 percent for the negative loading direction. The damage in the 3D printed concrete tower subassembly under cyclic loading was revealed by evaluating the Von Mises stress criteria. The FEM simulation captured the damage pattern and failure mode in the 3D printed concrete tower subassembly well. The discrepancies observed between simulated and experimental results could have arisen from the variation in parameters of the material constitutive models, the geometrical variation introduced by the additive manufacturing process, and the interface cohesive model that possibly underestimated the interfacing bonding behavior. These aspects are key areas of research in the structural design and analysis of 3DCP structures to be investigated.

Outcomes of Structural Testing and Analysis

The large-scale testing of 3DCP tower subassembly validated the feasibility of 3D concrete printing and assembling tower segments at approximately 1:20 diameter scale. Further, the structural testing proved that the 3DCP tower subassembly achieved the designed structural load-carrying capacity under different loading conditions, thus validating the structural design approach for 3DCP towers. These outcomes were used to validate and calibrate a finite element model that can be used for accurate prediction of the full-scale structural behavior of

3DCP ultra-tall towers. These results are instrumental to the future design of 3DCP towers for field implementation. The detailed structural testing results and finite element analysis of the 3DCP tower assembly will be reported in a journal paper. The results are novel and instrumental to the future design of 3D printed ultra-tall concrete towers, to enable rational and wide field implementations.

Techno-economic and Market Analyses

Production Costs of a Full-scale Printer Configuration

The full-scale printing system is estimated to cost between $500,000 and $700,000 each. This estimate is based on vendor quotes from several 3D concrete printing equipment developers currently offering commercial systems. Figure 36 shows a representative large-scale gantry 3D concrete printing system (Berlin-1) presently offered by Twente Additive Manufacturing. The system uses a 3-axis cartesian flying gantry and can be customized to feature build volumes from 10 meters (m) x 10 m x 4 m (length x width x height) up to 40 m x 15 m x 9 m (length x width x height). This system has: a maximum print speed of approximately 300 millimeters per second (mm/s); nozzle diameters ranging from 12 to 40 mm; a 3:1 nominal bead width-to-height ratio, with bead widths ranging from 20 to 68 mm; and a layer height ranging from 0 to 30 mm. Several other manufacturers such as COBOD and Black Buffalo offer similar printing systems.

Figure 36: Twente Additive Manufacturing's Berlin-1 Large Scale Gantry Printer

Source: Twente Additive Manufacturing

Levelized Cost of Energy Analysis

The San Gorgonio Farms Wind Farm was selected as a representative wind plant site for LCOE analysis. The site is located at approximately latitude: 33.92 N, longitude: -116.62 W near Palm Springs in Riverside County, California.

For this analysis, the wind plant was assumed to consist of 32 3.4 MW turbines at a 140-meter hub height, yielding a plant with a 108,800 MW nameplate capacity. The turbines were assumed to follow a simplified arrangement comprising an array of four rows of eight turbines each, with both turbine and row spacings set to a distance of eight rotor diameters, and an offset of four rotor diameters between each row. In practice, a more complex layout for the site may be required to optimize energy production for the specific site topography and wind resource.

The annual energy production AEP_{net} was calculated as 470 gigawatt hours (GWh), yielding a capacity factor of 49.3 percent. No degradation in annual performance was assumed for the purposes of this analysis. The FCR is defined as the amount of revenue per dollar of investment that must be collected annually to pay carrying charges on the investment as well as taxes. SAM's default FCR of 9.8 percent was assumed.

The OpEx includes the costs of operations and maintenance (O&M), expressed as average annual costs per kW nameplate capacity. Detailed assessments of operations and maintenance activities were not performed in this study. O&M was assumed as $43/kW/year per the NREL *2019 Cost of Wind Energy Review* (Stehly et al., 2020).

The wind plant construction was assumed to use on-site 3D concrete printing to manufacture both towers and foundations. The project CapEx was estimated as $1,465/kW. The cost was broken down as: turbine, $800/kW; tower and foundation, $278/kW; remaining balance of system costs, $267/kW; and financial costs, $120/kW.

Under these assumptions, the LCOE was calculated as $43/kWh. This is greater than the nationwide average LCOE for wind projects installed in 2020 ($33/megawatt-hour [MWh]), but it is expected to be acceptable in Southern California markets due to an approximately 50 percent higher cost of electricity there than the national average and the need to meet the Senate Bill 100 zero-carbon electricity goal by 2045. The results indicate that 3DCP tower technologies can feature market competitive costs even with currently available 3DCP technologies, which are rapidly improving.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The team placed a heavy emphasis on stakeholder discussions and workshop/conference presentations due to the bi-directional technology transfer opportunities provided by these avenues. RCAM Technologies plans to offer its 3DCP tower technology to commercial wind turbine manufacturers, wind plant construction firms, and developers. A summary of key activities is included below.

Preliminary Stakeholder Workshop at UCI

RCAM and UCI convened a stakeholder workshop at UCI on September 27, 2018, to discuss the project innovation and technology challenges, present preliminary results and subsequent planned work, and solicit feedback from TAC members, subject matter experts, and key stakeholders on the tower design and logistical considerations in tower construction. The feedback helped ensure the project plans were effective.

Stakeholder Discussions

During the project, RCAM and the UCI team facilitated discussions with stakeholders from more than 68 organizations (Table 4). The team's discussions with 3D concrete printing technology developers and concrete equipment vendors were critical to informing the equipment purchases for prototype manufacturing during the project, as well as analyses and cost modeling for future commercial manufacturing. Discussions with engineering and construction firms also helped refine the manufacturing and assembly plans and familiarize these firms with the capabilities of 3D concrete printing. The project team held discussions with the two leading wind turbine manufacturers in the United States, which are potential customers for RCAM's tower technologies. Several utilities and large diversified companies in the energy sector expressed an interest in RCAM's 3D concrete printing tower manufacturing technologies. RCAM and the UCI team also benefitted from bi-directional technology transfer with high profile members of project advisory panels from organizations such as Barr Engineering, Twente Additive Manufacturing, Mortenson, and UL.

Table 4: Stakeholder Interactions During Project Period

Organization Type	No. of Organizations	Examples
3D Concrete Printing Technology Developers and Equipment Providers	17	Vertico TAM Black Buffalo
Wind Turbine Manufacturers	2	GE Renewables Siemens Gamesa Renewable Energy

Organization Type	No. of Organizations	Examples
Construction and Engineering Firms	11	Mortenson Barr Engineering WSP USA
Utilities and Energy Companies	9	LADWP Southern California Edison Enel ENI
Startup Ecosystem Partners	4	Los Angeles Cleantech Incubator TVX-Boulder
Regulating/Certifying Bodies	2	AWS UL / AWS Truepower DNV GL
Universities	13	University of Nebraska Tufts University
National Labs and Funding Agencies	8	NREL Department of Energy US Army Corps of Engineers
Independent Consultants	2	Boulder Windpower Consulting
Total	**68**	

Source: RCAM Technologies, Inc.

Workshops, Conferences, and Committees

RCAM and the UCI team participated in several workshops and conferences during the project. These meetings gave the team the opportunity to present and share technical aspects of the 3D concrete printing technology for tall wind turbine towers, created networking opportunities with industry and academic stakeholders, and provided professional development opportunities for UCI students and post-doctoral scholars. The related conference presentations given by the project team included:

1. X. Li, "3D Printing of Tall Concrete Wind Turbine Towers," presented at the ACI Foundation Strategic Development Council, Denver, CO, September 5, 2018. [Online]. Available: https://www.acifoundation.org/Portals/12/Files/PDFs/SDC-Tech-Forum-44-Agenda.pdf
2. J. Cotrell, "Ultra-Tall Additively Manufactured Towers and Foundations," presented at the 7th International Conference Wind Turbine Towers, Bremen, Germany, August 24, 2018. [Online]. Available: https://windturbine-towers.iqpc.de/
3. Y. C. Wu and M. Li, "Interlayer Effect on Fracture Behavior of 3D Printing Concrete," presented at the Digital Concrete 2020, Eindhoven, Netherlands (Virtual), July 8, 2020. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-030-49916-7_55

4. M. Li, “Fracture Behavior and Testing Method of Additively Manufactured Concrete,” presented at the ASTM Symposium on Standards Development for Cement and Concrete for Use in Additive Construction, Virtual, December 7, 2020. [Online]. Available: https://www.astm.org/MEETINGS/SYMPOSIAPROGRAMS/C09ID3952.pdf
5. J. Cotrell, “3D Concrete Printed Wind Turbine Towers and Foundations,” presented at the NREL Industry Growth Forum, Denver, CO, May 9, 2019.
6. J. Cotrell, “15-MW Modular-Concrete, Suction Bucket Support Structure,” presented at the International Partnership Forum for Offshore Wind, Providence, Rhode Island, June 11, 2020.

Dr. Mo Li at UCI is actively involved with American Concrete Institution (ACI) technical committees, including ACI Committee 564 – 3D Printing with Cementitious Materials, ACI Committee 239 – Ultra-High Performance Concrete, and ACI Committee 378 – Concrete Wind Turbine Towers. Her work within the committees contributes to the development of guidelines and standards of materials and structural designs using 3DCP. Her committee work also aims to transfer the 3DCP knowledge and technologies to the broader community, including industry, researchers, practitioners, and policy makers.

Dr. Mo Li has been organizing and co-chairing four international and national conferences, gathering experts from research institutions, industry, government, and academia; these conferences contain sessions or discussions on how concrete technologies and advanced manufacturing can benefit the renewable energy industry and the overall infrastructure sustainability. These include:

- Co-organizing/chairing the 10th International Congress on Sustainability Science & Engineering (September 13–15, 2021). The conference included sessions on renewable and alternative energy.
- Steering Committee of the International Conference on Self-Healing Materials. The conference included technical sessions on advanced manufacturing of novel concrete materials and structures.
- Co-organizing/chairing the American Ceramics Society 12th Advances in Cement-Based Materials (July 11–13, 2022). The conference will include technical sessions on concrete 3D printing.
- Co-organizing/chairing the Telluride Innovation Workshop on Decarbonation of Cement, February 7–11, 2022.

RCAM and UCI team members also attended many conferences and workshops for networking opportunities.

Publications

The peer-reviewed journal articles published and in preparation by the project team include:

1. Y. C. Wu, J. Cotrell, and M. Li, "Interlayer Effect on Fracture Behavior of 3D Printing Concrete," *Second RILEM International Conference on Concrete and Digital Fabrication*, Springer, Cham, 2020, pp. 537–546. doi: 10.1007/978-3-030-49916-7_55.
2. Y. C. Wu and M. Li, "Fracture Behavior of Additively Manufactured Concrete," in preparation for *Cement and Concrete Research*, 2021.
3. Y. Choi, Y. C. Wu, W. Geng, and M. Li, "Structural Behavior of Large-Scale 3D Printed Concrete Tower," in preparation for *ASCE Journal of Structural Engineering*, 2021.

Web and Social Media

The project team recognizes the importance of online and social media in raising general awareness of the project and technology. RCAM created a company website featuring a page describing the project and a YouTube channel where RCAM posts videos that demonstrate the technology and applications. RCAM's website has more than 15,000 total lifetime views.

During the project, RCAM continued to communicate and interact with stakeholders in onshore and offshore wind energy and 3D concrete printing through LinkedIn, via the principal investigator's profile, which has 2,166 followers, and the RCAM Technologies account, which has 708 followers as of Oct. 26, 2021. RCAM also posts updates to its X account.

In addition, several news articles were published about the project including:

- J. Gerdes, "Is 3-D Printing the Solution for Ultra-Tall Wind Turbine Towers?," *Greentech Media*, November 28, 2017.
- David, "CEC awards $1.25M grant to RCAM Technologies for 3D printed concrete wind turbines", *3Ders,* December 4, 2017.
- "3D Concrete Printed Wind Turbine Towers and Anchors", *Construction Printing Technologies Worldwide.*

Education and Outreach

Dr. Mo Li has included concrete 3D printing content into her courses at UCI, such as in CEE 240 High Performance Materials and CEE 247 Structural Dynamics. Through teaching undergraduate students and training graduate students in concrete 3D printing and renewable energy, especially through hands-on experience, the project team is preparing the next generation workforce in this emerging field.

Additional R&D Funding Generated During Project

This project provided the landmark first funding for RCAM's 3D concrete printing technologies for renewable energy applications. The California Energy Commission's support in this project made it possible for RCAM to generate nearly $5 million in additional funding to further develop 3D concrete printing processes for complementary applications in fixed-bottom and floating offshore wind, amplifying the reach of RCAM's 3D concrete printing manufacturing technologies and facilitating commercialization.

Concrete Additive Manufacturing Stakeholder Workshop

A Concrete Additive Manufacturing Stakeholder Workshop was completed in combination with the project's second Technical Advisory Committee meeting. The meeting attendees included stakeholders in 3D concrete printing, wind plant engineering and construction, electric utilities, and certification organizations. The meeting focused on two primary topics: (1) presenting and discussing the results of prototype tower subassembly manufacturing, assembly, and laboratory testing performed by the UCI team, and (2) discussing the market outlook for 3D concrete printed wind turbine towers in California.

The meeting attendees voiced their support for the detailed and thorough presentation of material and structural subassembly results performed by Dr. Mo Li. Attendees agreed that the testing performed is a very valuable contribution to the state of the art in 3D concrete printing. The discussion motivated potential ideas for future laboratory structural testing. For example, it was suggested that the performance of 3D printed concrete assemblies be compared to the performance of conventional post-tensioned concrete columns. Demonstrating equivalent performance could facilitate future design activities and help gain acceptance of 3DCP products more quickly and cost effectively.

RCAM presented findings from its techno-economic and market analysis study. Overall, the attendees agreed with RCAM's assessment of onshore wind market trends, but they provided valuable insight informed by their experience and recent discussions with other industry stakeholders. Based on this data, the attendee outlook regarding the wind market was even more optimistic than RCAM's outlook, based primarily on market reports. Attendees cautioned against making conclusions from market reports, the publication of which is delayed, and from data of interconnection queues that may not always reflect actual projects completed. It was also suggested that looking only at averaged data should be avoided, because it can hide significant trends that vary by region, for example. Interest in onshore wind appears to be strong, judging by activity at a recent conference, which hosted more than 2,000 in-person attendees. A significant opportunity in onshore wind was noted, especially in California, based on the market for full repowering. Despite a current lull in wind projects in California, there are many aging wind plants in the state located in very attractive wind regions, and these should provide good opportunities for full repowering with tall towers and large turbines. Ultra-tall wind towers are expected to also open opportunities for wind plant development in regions such as the Southeastern United States, where the lower quality wind resource at conventional hub heights has made wind project development unattractive.

CHAPTER 5: Conclusions/Recommendations

Summary and Conclusions

RCAM Technologies and the University of California, Irvine, developed, demonstrated, and tested a 3DCP technology for building low-cost, ultra-tall wind turbine towers on site at California wind plants. The team completed a preliminary structural design of tall wind turbine towers made from 3D printed concrete, which proved that ultra-tall 3DCP towers can meet the structural performance characteristics required for California wind plants, including seismic loading. Structural performance analyses showed that, under service loading, with appropriately designed post-tensioned steel reinforcement, the 3DCP concrete tower can be prevented from cracking because tensile stresses are canceled out by the applied pre-stress.

The team selected and operationalized a 3DCP system to fabricate a concrete tower assembly in a laboratory. The laboratory printing demonstrated the feasibility of the 3D concrete printing manufacturing process for on-site segmental tower construction. Detailed structural testing of the tower assembly indicated that the 3D concrete printed tower specimen performed beyond the expected levels, validating the design methodology and manufacturing process. A finite element model was developed to scale the findings of the laboratory testing to analysis of full-scale towers. The project's laboratory work also contributed to the characterization of the rheological, mechanical, and fracture behavior of 3D printed concrete materials and components for use in wind turbine towers.

The project team developed a plan for on-site manufacturing of 3DCP wind turbine towers, assessed the land-based wind market in California, and performed techno-economic analysis of the 3DCP wind turbine towers. These analyses indicated that the 3DCP technology is feasible for on-site tower manufacturing of ultra-tall towers at market competitive costs and will result in additional benefits such as reduced viewshed disturbance and increased local economic benefits.

Recommended Future Research

Technology commercialization will entail continued laboratory research and development, including structural engineering and laboratory testing of 3DCP prototypes and on-site pilot demonstrations of 3DCP tower manufacturing.

This project supported some of the world's first laboratory R&D of 3D concrete printing technologies for manufacturing renewable energy structures. Continued laboratory R&D is planned through the team's follow-on California Energy Commission research project EPC-19-007, which will manufacture a higher-fidelity tower prototype and study performance under fatigue loading.

Reinforcement is a critical aspect for 3D printed concrete in structural applications such as wind turbine towers. In this project, RCAM decided to select more conventional and proven reinforcement methodologies (that is, manually installed hoops and rebar cages and post-tensioning tendons). While these systems are expected to provide sufficient performance and cost advantages compared to conventional construction, greater benefits could be derived from the use of advanced reinforcement systems, such as fiber reinforcement and automated embedment of reinforcement within 3D printed concrete layers. Development of such technologies is an active and critical area of ongoing laboratory research.

The preliminary finite element model developed during the project somewhat underpredicted initial stiffness and peak load in the 3D printed concrete tower assembly compared to experimental results. These discrepancies could have resulted from the variations in parameters of the material constitutive models, geometrical variation introduced by the additive manufacturing process, and/or the interface cohesive model that possibly underestimated the interfacing bonding behavior. These aspects are key areas of research in the structural design and analysis of 3DCP structures to be investigated. Developing accurate constitutive models for 3D printed concrete is a key area of research required for high-fidelity design of 3DCP towers. Further testing of 3D printed concrete materials and tower assemblies, including fatigue testing, must be carried out prior to market acceptance of 3DCP towers.

Minimizing the lifecycle emissions impact of tower manufacturing is an important objective for commercial production. Future research should explore approaches for reducing material usage, energy consumption, and environmental impacts of the 3D concrete printing technology by incorporating supplementary cementitious materials from industrial wastes, reusing the recycled concrete aggregates, and optimizing manufacturing processes.

On-site tower manufacturing demonstrations should be performed in a relevant outdoor environment to prove that field-printed 3DCP prototypes meet the quality standard requirements and specifications for the proposed wind tower.

The technological advancements developed during this research (including mixture designs, reinforcement strategies, manufacturing processes, and testing and analysis methods) will be cross-cutting and will support the advancement of 3DCP technologies for multiple applications in renewable energy infrastructure construction — for example, supporting the design and manufacture of anchors and substructures for floating offshore wind and RCAM's marine pumped hydroelectric long duration energy storage technology, both of which have the potential to help meet California's Senate Bill 100 goal of zero carbon electricity by 2045.

Outlook for Technology Commercialization

Commercializing RCAM's 3DCP tower manufacturing technology will require providing value to all relevant stakeholders in the ecosystem to alleviate their pain points and provide sufficient benefits over existing solutions to alleviate switching costs. These stakeholders include:

- Federal, state, and local governments and agencies that regulate and/or incentivize the construction of land-based wind plants.
- Utilities and other power purchasers such as large corporations.
- Wind turbine original equipment manufacturers.
- Electricity ratepayers, who generally desire reliable, low-cost renewable electric power.
- Communities that are potentially affected by noise or visual aspects of wind plants.

California 3DCP Tower Outlook

Given the trends in development of land-based wind in California, the most immediate target market of the 3DCP tower manufacturing technology is in repowering applications. The majority of California wind turbines are in six regions: Altamont, East San Diego County, Pacheco, Solano, San Gorgonio, and Tehachapi. Full repowering generally has the greatest potential in areas with high wind shear and existing turbines with short hub heights and small capacities, and where sufficient transmission infrastructure is available, which may be assessed via the U.S. Wind Turbine Database. More detailed analysis can be performed to identify optimal installation sites, but substantial opportunity for deployment of 3DCP towers exists in California.

The primary barriers to commercialization of the 3DCP manufacturing technology for wind turbine towers in California are related to the still-tepid market for onshore wind in California due primarily to (1) regulatory and environmental disincentives to develop new greenfield wind plants and (2) increased focus on offshore wind energy in lieu of land-based wind deployments. These are substantial challenges for which RCAM's influence and options are limited. However, wind energy has one of the smallest carbon footprints of any technology, is well proven in California and abroad, and is lower in cost than offshore wind and many solar installations. The increasing availability of larger onshore turbines, the urgency of meeting SB 100 goals and mitigating climate change, the increasing importance of local jobs in disadvantaged communities, and the rapid advancement of 3DCP technologies, combined with the advantages of onshore wind, provide both market push and pull mechanisms that make the mid-term and long-term prospects for wind energy in California promising. RCAM believes a resurgence in onshore wind will occur in the next several years, which RCAM's 3DCP technologies will be well suited to supply.

3D Concrete Printing Outlook

Although 3DCP was invented in the United States by Urschel and pioneered by Khoshnevis in California, in many cases during the last few years, foreign organizations have been faster to fund and develop 3DCP technologies compared to American universities, trade organizations, national laboratories, and federal grant agencies. However, the outlook for further development of 3DCP in the United States has brightened. Several key organizations, starting with the California Energy Commission, have taken important steps to support commercialization of the technology. The National Science Foundation, the National Institute of Standards and Technology, the Department of Energy, national laboratories NREL and Oak Ridge National Laboratory, the American Concrete Institute, the National Offshore Wind R&D Consortium, the New York State Energy Research and Development Authority, the Colorado Office of Economic Development and International Trade, and numerous premier universities are now involved with 3DCP development. Partnerships between the private and the public sectors are expected to continue to play a key role in the accelerated development and market adoption of reliable and robust 3D concrete printing technologies.

CHAPTER 6: Benefits to Ratepayers

Wind Capacity Deployment Potential

Regions with slow-to-moderate wind speeds and high wind shear in California have the most to gain from taller towers. NREL estimates that the California land area suitable for development (that is, exceeding a 35 percent threshold for gross capacity factor) increases from 3,000 square kilometers to 67,000 square kilometers when increasing the tower height from 80 meters with "2008 turbine technology" to a 140-meter tower with "near-future" technology (Lantz et al., 2019). This 64,000 square kilometer increase in land area can be considered to effectively unlock 128,000 MW (128 gigawatts) of new wind deployments (the new potential wind capacity) when using NREL's rule of thumb of 2 MW/km^2 of potential wind turbine capacity that could be installed on these lands. These new deployments can produce 336 million megawatt-hours (MWh) of electricity annually, assuming a net capacity factor of 30 percent. In general, about half of this increase, roughly 60,000 MW, is due to the increase in tower height alone.

Lifecycle Carbon Dioxide Emissions

Wind deployments avoid substantial emissions of greenhouse gases compared to fossil-fuel-generated electricity. Wind-generated electricity emits up to 120 times less carbon dioxide equivalent (CO_2e) than natural-gas-generated electricity and nearly 200 times less than coal on a lifecycle basis (5 g/kWh [grams per kilowatt-hour], 607 g/kWh, and 975 g/kWh, respectively). Although a conventional concrete wind turbine tower results in about 40 percent more CO_2e (7 g/kWh) than a 140-meter conventional steel tower, this CO_2 is inconsequential compared to the CO_2 emitted from electricity sources such as coal- and natural-gas-generated electricity. An RCAM 140-meter tower is projected to result in 85 times less CO_2 compared to natural-gas-fired electricity generation and 138 times less than coal-fired electricity generation on a lifecycle basis.

Levelized Cost of Energy

The LCOE enabled by the 3DCP tower manufacturing solution in California wind farm locations is estimated to be market competitive via NREL's System Advisor Model. Bringing this innovation to the commercial market will enable further use of wind plants in California without cost escalations to ratepayers and will support repowering of existing wind plants.

Economic Benefits to California

The project created near-term R&D jobs and is expected to create future jobs in wind turbine construction, operations, and maintenance if RCAM towers are successfully commercialized. One hundred percent of the project funding is budgeted to be spent in California (all EPIC funds are paid to individuals who pay California state income taxes on wages received for work performed under the agreement, and all business transactions, including material and equipment purchases, leases, rentals, and contractual work, are entered into with a business located in California).

The increased land-based and offshore wind deployments possible with RCAM's technologies will retain jobs and economic benefits in California. If the 3DCP technology is successfully commercialized, a large number of future jobs in wind turbine construction, operations, and maintenance are expected to be created in the deployment of new and repowered turbines on ultra-tall towers. These deployments will also provide lease and tax revenues in local California communities. Based on wind power projects installed between 2000 and 2008, the California job creation from deploying 50,000 MW would create 25,000 jobs while producing 336 million MWh of electricity annually, assuming a net capacity factor of 30 percent. In addition, successful near-term deployment of RCAM concrete wind turbine towers will build the additively manufactured concrete knowledge base that provides a commercialization path into substantially larger, but more conservative, markets such as construction.

Educational, Research and Development, and Supply Chain Benefits

This project supports California's capabilities in education, research and development, and commercial supply chain for 3D concrete printing for potential future energy, civil infrastructure, and housing applications. These technologies have numerous additional potential energy applications such as manufacturing low-cost components for future offshore wind energy plants, ocean energy storage, and solar thermal energy storage. For example, California has 112 GW of technical offshore wind resource potential along the coastline — enough to supply about 1.5 times the state's annual electric energy use. Combined with the 60 GW of land-based technical resource potential, California has enough wind energy potential to provide approximately twice the amount of electricity consumed in California. In addition, as California moves toward a zero-carbon electricity mix in 2045, land-based and offshore wind can provide value to the grid by balancing solar generation. The project also helps position California to lead the development of a rapidly emerging technology that has tremendous global potential for industrial applications such as civil infrastructure, commercial buildings, and construction of affordable housing.

Improved Turbine Aesthetics and Reduced Environmental Disturbances

Increasing the size of wind turbines will allow installation of a smaller number of turbines to reach a given wind plant nameplate capacity. These plants will create less ground disturbance and reduce visual impact compared to prior wind sites.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
3DCP	3D concrete printing
3DPC	3D printed concrete
ACI	American Concrete Institute
AEP_{net}	net annual energy production
ASCE	American Society of Civil Engineers
AM	additive manufacturing
AM^3	Advanced and Multifunctional Materials and Manufacturing for Structures
California ISO	California Independent System Operator
CapEx	capital expenditures
CERL	U.S. Army Corps of Engineers Construction Engineering Research Laboratory
cm	centimeter
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DTI	Danish Technological Institute
EOG	extreme operating gust
EWM	extreme wind speed model
FCR	fixed charge rate
FEA	finite element analysis
FEM	finite element modeling
GW	gigawatt
GWh	gigawatt-hour
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ISO	Independent System Operator
K_{IC}	fracture toughness
kW	kilowatt
LBNL	Lawrence Berkeley National Laboratory
LCOE	levelized cost of energy
mm	millimeter
MPa	megapascal

Term	Definition
m/s	meters per second
MW	megawatt
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OpEx	operational expenditures
RCAM	RCAM Technologies, Inc.
RP	recommended practice
SAM	System Advisor Model
TAC	Technical Advisory Committee
UCI	University of California, Irvine

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