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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

On-site 3D Concrete Printing for Next-generation Low-cost Wind Plants

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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 purpose of this project was to design, demonstrate, and test wind turbine tower sections and offshore wind energy components that are manufactured on-site using three-dimensional concrete printing (3DCP) technology to facilitate the deployment of large land-based and offshore wind turbines in California. The project combined structural design and analysis by WSP USA, with material development and testing, lifecycle assessment, laboratory structural testing, and finite element modeling by the University of California, Irvine, and with technoeconomic analysis, prototyping, and large-scale 3D concrete printing demonstrations by RCAM Technologies. The project team successfully designed a 3D-printed concrete tower and foundation for a 7.5-megawatt wind turbine in California, validated the design through large-scale structural testing of 3DCP tower subassemblies under simulated fatigue and seismic loading, quantified the lifecycle costs and environmental impacts of a 3DCP tower and identified routes to reduce them, completed a large-scale outdoor tower printing demonstration, and assessed the feasibility of using 3DCP to fabricate anchors and subsea energy storage systems for offshore wind energy. These findings support California's clean-energy and climate goals by reducing the cost of wind energy to reach net zero carbon emissions while creating good paying jobs and using existing, local supply chains.

Keywords: 3D concrete printing, additive manufacturing, wind energy, floating offshore wind, renewable energy, wind turbine towers

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Background

California has set ambitious clean energy and climate goals, aiming to transition to carbon neutrality by 2045 (Executive Order B-55-18, 2018) and mandating that renewable energy and zero-carbon resources supply 100 percent of electric retail sales by 2045 (Senate Bill 100, De León, Chapter 312, Statutes of 2018). Wind energy, both onshore and offshore, can play a significant role in helping California reach its ambitious renewable energy mandates. As required by Senate Bill 525, the California Energy Commission adopted planning goals of 2 to 5 gigawatts of offshore wind energy by 2030 and 25 gigawatts by 2045. On-site three-dimensional concrete printing (3DCP) can advance California's renewable energy objectives by streamlining wind plant construction. This on-site additive manufacturing model can mitigate the limitations associated with transporting large land-based and offshore steel wind turbine towers.

Project Purpose and Approach

The purpose of this project was to design, demonstrate, and test land-based wind turbine tower sections and offshore wind energy components manufactured on-site using 3DCP. The project advanced scientific knowledge in 3DCP materials, manufacturing methods, and structural testing of 3D-printed concrete components to facilitate the deployment of large land-based and offshore wind turbines in California.

The project aimed to advance the technology readiness level of wind turbine towers and foundations manufactured using 3DCP from technology readiness level 4 to technology readiness level 6, and to assess the feasibility of using 3DCP to manufacture components for offshore wind and subsea energy storage. The project approach included:

- Developing a preliminary design, manufacturing plan, and cost estimate of a 140-meter 3DCP tower and foundation for a 7.5-megawatt wind turbine to be installed in California.
- Validating the design via dynamic structural testing of tower sub-assemblies.
- Quantifying the lifecycle environmental impacts of 3DCP tall towers and foundations.
- Assessing the use of waste materials in 3D-printed concrete to reduce carbon footprint.
- Demonstrating on-site 3DCP at large scale in a relevant outdoor environment.
- Assessing the feasibility of using 3DCP to manufacture offshore wind suction anchors and hybrid offshore energy storage systems.
- Developing research and commercial capabilities for 3D concrete printing in California.

The key project performance metrics were: (1) a reduction in the capital cost of a 140-meter tower compared to a conventional rolled steel tower, (2) extended service lifetime of the tower, and (3) reduced embodied carbon dioxide emissions from the manufacture of the tower and foundation.

The research produced data on the design, performance, cost-effectiveness, and lifecycle impact of 3D-printed concrete wind turbine towers and offshore wind energy components. These results can be used by academic institutions to further advance early-stage research and development of 3DCP technology and by project developers to gain an understanding of the technology's potential in real-world applications.

Key Results

The project combined structural design and analysis performed by WSP USA with material development and testing, lifecycle assessment, laboratory structural testing, technoeconomic analysis, and prototyping and printing demonstrations at both the University of California, Irvine (UCI), and RCAM Technologies, Inc., DBA Sperra (RCAM) facilities.

Conceptual and Preliminary Design of a 3DCP Tower and Foundation

WSP USA and RCAM designed a 7.5-megawatt 3D-concrete-printed wind turbine tower and foundation and performed structural analyses demonstrating the sufficiency of the design for seismic load conditions in California. The design was subjected to a risk assessment workshop that incorporated feedback from wind energy, design, and construction experts. The project team developed a manufacturing and assembly plan, estimated manufacturing costs, and modeled the levelized cost of energy (LCOE) generated using the proposed tower and foundation design. The LCOE was determined to be $55 per megawatt-hour, which is significantly lower than the California LCOE target of approximately $90 per megawatt-hour for conventional 140-meter towers established by the National Renewable Energy Laboratory. A lower LCOE benefits electricity ratepayers in California by reducing costs.

Development of a Closed-loop Cycle Approach for a Next-generation 3DCP Tower

UCI analyzed the lifecycle impacts of 3DCP compared to conventional steel towers. The best performing 3D-printed concrete tower design had the smallest embodied carbon dioxide emissions, which were 24 percent lower than a steel tower designed for the same wind turbine. The embodied carbon dioxide emissions result primarily from the construction materials. Therefore, further efforts should focus on optimizing the design to reduce material mass and develop concrete material formulations with lower embodied carbon dioxide emissions.

Laboratory Printing, Pilot-testing, and Analysis of a 3DCP Tall Tower Sub-assembly

UCI developed a 3D-printable concrete mixture with an ultra-high compressive strength exceeding 100 megapascals. UCI then performed structural testing of a 3D-printed tower assembly under fatigue and seismic loading, simulating operational and extreme conditions. The assembly maintained its stiffness and showed no damage after extensive fatigue loading and resisted intensive seismic loading without structural failure.

Outdoor Testing and Demonstration of On-site 3D Concrete Printing

RCAM conducted indoor printing trials with two tower specimens to verify build height and layer quality. The first specimen was a section of a full-scale tower wall, and the second was a scaled prototype of a tapered cylindrical tower. Both trials demonstrated successful 3D concrete printing, enabling outdoor trials. Subsequently, RCAM printed a 3-meter tall tower outdoors that was reinforced every 300 millimeters and avoided collapse or deformities.

Feasibility Analysis and Concept Fabrication of Offshore Components

RCAM designed and fabricated a 3D-printed concrete subscale prototypes of its floating offshore wind anchors and subscale underwater energy storage system. RCAM performed feasibility analyses and manufacturing studies to assess the viability of manufacturing these components in California ports. The findings demonstrated that 3D concrete printing provides a feasible approach to manufacturing concrete anchors in California ports using existing supply chains and currently available printing technology, thereby benefitting local economies.

Development of 3DCP Research and Development, Education, and Supply Chain Capabilities in California

RCAM established a port-side 3DCP facility at AltaSea, a blue economy incubator at the Port of Los Angeles, and expanded its staff from 2 to 10 full-time employees. UCI enhanced its capabilities with new 3DCP equipment and trained 10 students in 3DCP. RCAM assessed the material supply chains, the workforce, and the technology development steps needed to commercialize 3D-printed concrete wind turbine towers and offshore energy components in California. The study showed that California’s existing concrete workforce and supply chain capabilities can provide sufficient capacity to satisfy the growing demand for 3D-printed concrete renewable energy components.

Knowledge Transfer and Next Steps

RCAM Technologies conducted outreach for its 3DCP tower technology to interested commercial wind turbine manufacturers, wind plant construction firms, and developers. Project commercialization and deployment was facilitated through research and industry publications and by including key technology end users in the Technical Advisory Committee, which comprised Mortenson Construction, WSP USA, Catalina Sea Ranch, Siemens Gamesa, Equinor, and Boulder Windpower Consulting. The UCI helped ensure replicability of the developed manufacturing processes to the research community and other applicable 3DCP end users.

To share project information and foster adoption of 3D concrete printing technologies for renewable energy applications, RCAM hosted tours and community outreach events for over 900 people at its research and development printing facility at AltaSea at the Port of Los Angeles. Stakeholders include investors, philanthropic entities, workforce and community organizations, K-12 students, elected officials, and the public. The project team also presented findings at over 12 industry events and academic conferences, including the North American Wind Energy Academy, the American Society for Testing and Materials International Conference, and the Global Offshore Wind Conference. The project team has seven publications published or planned for high-impact journals such as *The Journal of Ocean Technology,* the *Journal of Cleaner Production, Cement and Concrete Research,* and *Wind Energy*.

RCAM recommends the following next steps:

- Advance, certify, and qualify 3DCP materials for marine applications and develop codes and standards for 3D-printed concrete structures.
- Create or incentivize education and training programs through trade schools or community colleges to develop a trained 3DCP workforce.
- Support publicly funded 3DCP demonstration projects in partnership with state/federal organizations to increase awareness of and demand for 3DCP technology.
- Consider 3DCP in ongoing and future studies of floating wind port infrastructure.
- Study the long-term jobs and economic benefits of 3DCP technologies.

With these actions, 3D concrete printing technology can help California reach net zero carbon emissions while minimizing costs for ratepayers and maximizing in-state economic benefits.

CHAPTER 1: Introduction

Project Purpose

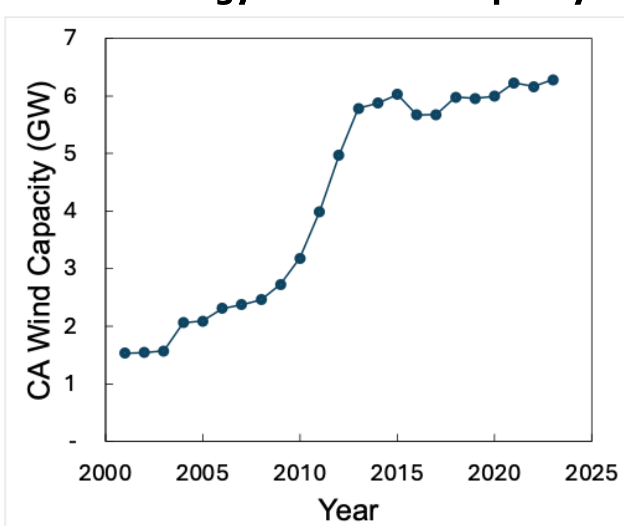
This project aimed to design, demonstrate, and test wind turbine towers and offshore wind energy components, including energy storage manufactured using three-dimensional concrete printing (3DCP) technology. It expanded knowledge of 3DCP materials, manufacturing, and structural performance to support wind energy in California. The project aligned with California's climate goals by reducing wind energy costs, creating jobs, and using existing supply chains to achieve net zero carbon emissions.

Background

Land-based Wind Energy Generation

Wind power, generating 1,870 terawatt-hours or 23 percent of all renewable energy in 2021, is the world's leading renewable energy technology after hydropower (IEA, 2022). In the U.S., wind energy is a crucial part of the national renewable energy portfolio and was the largest source of electric-generating capacity additions in 2020 (Wiser et al., 2021). California has set ambitious clean energy and climate goals, aiming to be carbon neutral by 2045 per Executive Order B-55-18 (2018). Senate Bill 100 (De León, Chapter 312, Statutes of 2018) mandates that renewable energy and zero carbon resources supply 100 percent of electric retail sales to end-use customers by 2045. To help reach these ambitious renewable energy mandates, California set planning goals for offshore wind energy of 2 to 5 gigawatts (GW) by 2030 and 25 GW by 2045. However, despite having the 6th-highest installed wind capacity, California has seen stalled growth in wind energy since 2013, as shown in Figure 1.

Figure 1. California Wind Energy Generation Capacity From 2001 to 2023

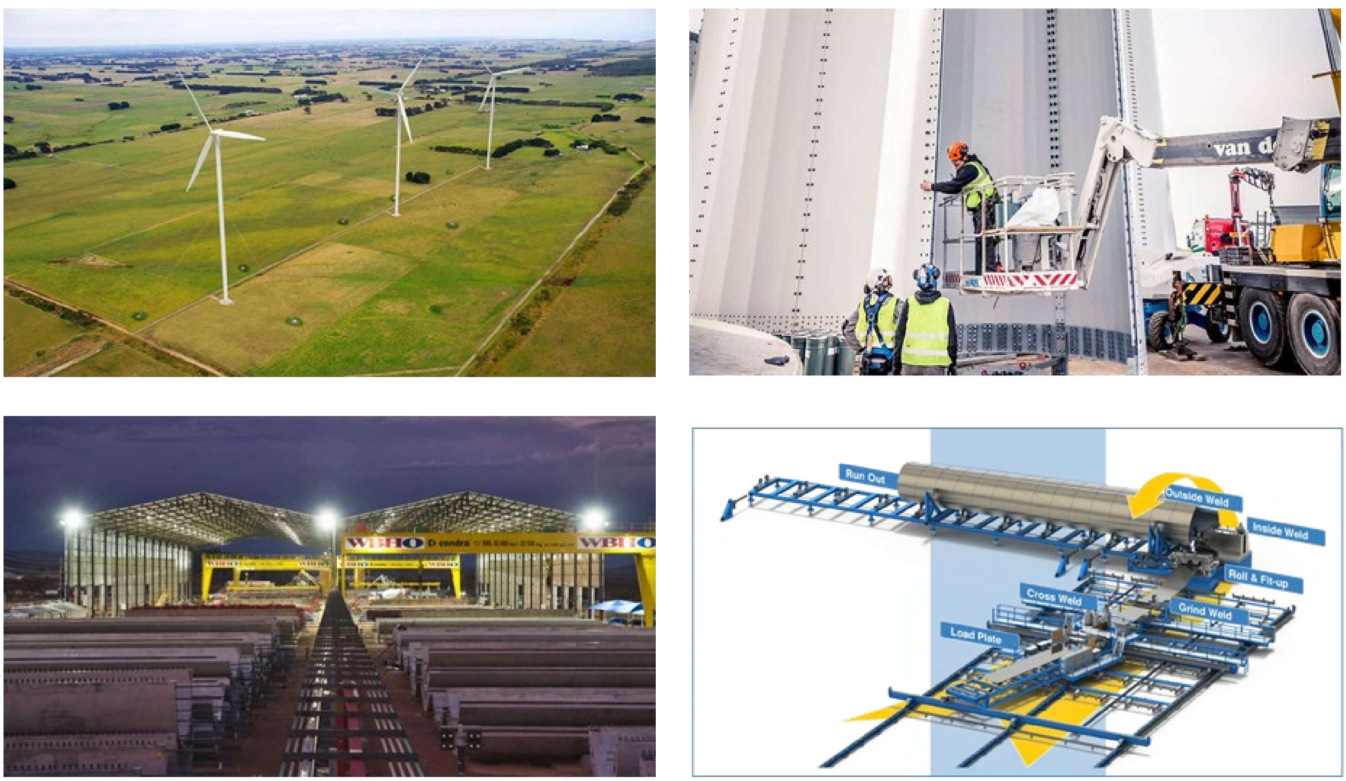


Source: RCAM Technologies, from California Energy Almanac data (CEC, 2023)

Wind turbines convert wind energy into electricity using blades that spin a rotor connected to a generator, creating electricity through electromagnetism. The power harvested from wind is proportional to blade length and the cube of wind speed. Advances in technology have increased blade size and turbine capacity, producing more energy at lower costs and requiring taller towers. Taller turbines are more efficient, as wind speed and consistency increase with height; for instance, a 140-meter (m) tower can boost energy production by over 21 percent compared to an 80-m tower (NREL, 2015).

Conventional towers are made from rolled and welded steel in centralized U.S. facilities and transported to wind plants by truck or rail. However, transportation constraints limit tower diameter to 4.3 m, resulting in sub-optimal tower designs with limited height. New tower designs, such as guyed towers, modular steel towers, on-site spiral wound steel towers, and precast concrete towers (Figure 2), can overcome these limits by allowing the cost-effective manufacturing of taller towers. These designs either extend transportable tower heights using modular systems or use on-site manufacturing to avoid transportation restrictions.

Figure 2. 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 advantages and disadvantages. Modular towers require more assembly time for bolting and grouting, and stakeholders often criticize their aesthetics. On-site steel tower manufacturing involves high startup costs, making it less cost-effective for smaller wind plants with fewer large turbines. However, on-site concrete tower manufacturing can overcome the limitations of current tower technologies, aiding in the continued cost reduction of land-based wind energy.

Offshore Wind Energy

Offshore wind is an alternative to land-based wind energy. For waters over 60 m deep, offshore turbines are installed on floating platforms anchored to the seafloor, usually using large steel platforms and anchors. California prioritizes floating offshore wind (FOSW) to achieve net zero goals, aiming for 5 GW by 2030 and 25 GW by 2045. However, FOSW faces high capital costs, supply chain gaps, and limited port space and infrastructure. Utilizing domestic material content and manufacturing labor is critical to maximize the economic benefits of offshore wind projects. RCAM Technologies, Inc., DBA Sperra (RCAM) has developed 3D-printed concrete suction anchors for FOSW plants, which can reduce costs and enable local manufacturing.

Energy Storage

To achieve net zero emissions, the grid requires long-duration energy storage (LDES) to match energy generation with demand. Currently, pumped storage hydropower is the dominant LDES, providing about 93 percent of US energy storage. However, pumped storage hydropower expansion faces permitting challenges and a lack of suitable sites. New cost-effective LDES technologies are needed. The Fraunhofer Institute for Energy Economics and Energy Systems (Fraunhofer IEE) has developed a subsea energy storage technology called Stored Energy in the Sea (StEnSea) (Puchta et al., 2017) that addresses these deployment barriers. Figure 3 shows photographs of Fraunhofer IEE's 2.5-m StEnSea prototype, which was tested in a 100-m-deep lake (Dick et al., 2021). The technology was demonstrated to be technically feasible but needs further cost reductions to be competitive with other technologies like batteries.

Figure 3. Demonstration of StEnSea Energy Storage by Fraunhofer IEE

Source: Fraunhofer IEE (Puchta et al., 2017; Dick et al., 2021)

Project Goals and Metrics

The goals of the project were to:

- Advance the on-site manufacturing technology and 3DCP tall towers and foundations through design, demonstration, and laboratory structural testing.
- Assess and reduce the environmental lifecycle impacts of 3DCP manufacturing of tall towers and foundations.
- Assess the feasibility of 3DCP anchors and energy storage systems for offshore wind.
- Evaluate and expand California's research and development (R&D) and commercial 3DCP capabilities and the workforce potential needed to manufacture 3DCP wind energy components in California.

The key project performance metrics were: (1) a reduction in capital cost of a 140-m tower compared to a conventional rolled steel tower, (2) the service lifetime of the tower, and (3) embodied CO_2 emissions from the manufacturing of the tower and foundation. These metrics will determine the competitiveness of the 3DCP tower against conventional steel towers.

Audience and Market

The research results provided novel data on the design, performance, cost-effectiveness, and lifecycle impact of 3D-printed concrete wind turbine towers and offshore wind components. Academics and innovators can use this data to advance 3DCP technology and concrete materials, while project developers and construction companies can understand its potential, fostering market acceptance due to cost-effectiveness and the ability to manufacture tall towers on-site. The materials performance data and laboratory structural testing results generated in this project can be used by standards organizations to improve understanding of the behavior of 3D-printed concrete towards the development of codes for and standards specific to 3D-printed concrete structures.

CHAPTER 2: Project Approach

Technology and Research Objectives

The project aimed to advance the technology readiness level (TRL) of wind turbine towers and foundations manufactured using 3DCP from TRL 4 to TRL 6, and to assess the feasibility of using 3DCP to manufacture components for offshore wind and subsea energy storage. The project approach for technology advancement and research included:

- Developing a preliminary design, a manufacturing plan, and a cost estimate for a 140-m 3DCP tower and foundation for a 7.5-megawatt (MW) wind turbine to be installed in California.
- Validating the design via dynamic structural testing of tower sub-assemblies.
- Quantifying the lifecycle environmental impacts of 3DCP tall towers and foundations.
- Assessing routes to incorporate waste materials in 3D-printable concrete to reduce the environmental impacts of 3D-printed towers and foundations.
- Demonstrating on-site 3DCP at large scale in a relevant outdoor environment.
- Assessing the feasibility of using 3DCP to manufacture offshore wind suction anchors and hybrid offshore energy storage systems.
- Developing research and commercial capabilities for 3D concrete printing in California.

Project Partners and Advisors

RCAM was the prime recipient on the project. The project team included University of California, Irvine (UCI), WSP USA, Verdical Group, and Fraunhofer IEE (cost-share partner). The Technical Advisory Committee included Sandy Butterfield (Boulder Wind Consulting), Ole Havmøller (Equinor), Seth Price (Principle Power), Todd Bell (Pattern Energy Group), Emil Moroz (UL), and Kirk Morgan (Barr Engineering).

Project Methods

The project combined structural design and analysis, material development and testing, lifecycle assessment, laboratory structural testing, technoeconomic analysis, and prototyping and printing demonstrations at both UCI and RCAM facilities.

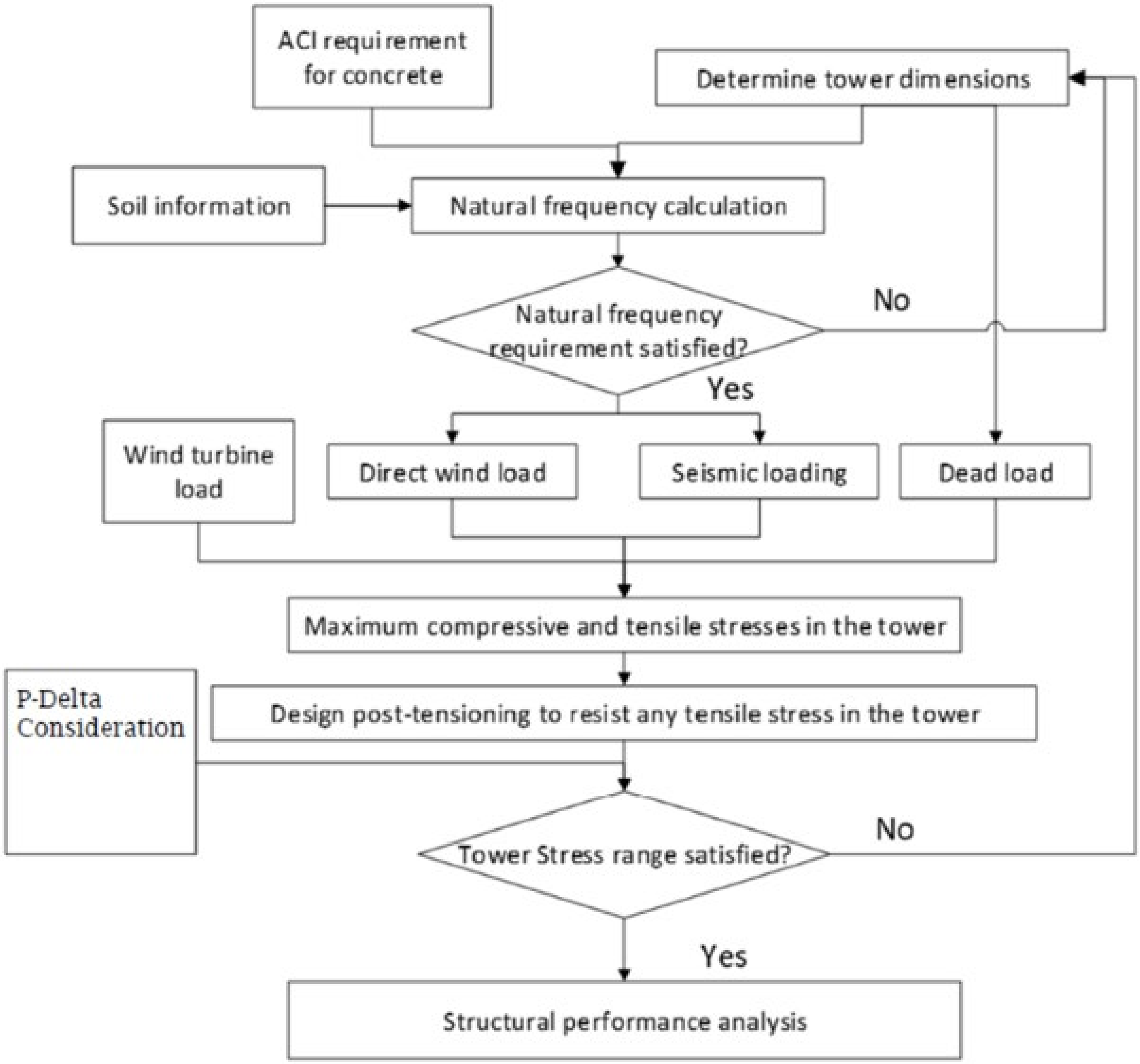
3DCP Tower and Foundation Design

WSP USA performed the design of the 3DCP tower and foundation. The tower was designed for operational and extreme-level wind load events based on load and resistance factor design (LRFD) service and strength design principles and industry-accepted wind load factors. The tower design flowchart shown in Figure 4 was followed for the preliminary design. The design methods for reinforcement and post-tensioned concrete structures followed reinforced concrete and prestressed concrete design codes. In addition, the dynamic behavior of the towers and the seismic performance were evaluated using corresponding service level loads. Fatigue life was not checked, as this load case is typically not governing the design of post-tensioned concrete towers.

The LRFD method was used with strength-reduction factors to consider different loads and load combinations on the tower. The loads included wind turbine load, direct distributed wind load, seismic load, and dead load. The direct wind load on the tower was calculated following American Society of Civil Engineers (ASCE) methods. Seismic load consideration followed design documents from the American Concrete Institute (ACI) and ASCE (ACI Innovation Task Group 9, 2016; ASCE, 2017). The static equivalent earthquake load acting on the tower was calculated based on spectra accelerations determined from the available U.S. seismic design maps, assuming the tower is in an existing wind plant near Palm Springs, CA.

Under the combined loading conditions, the ultimate strength of and the stresses for the structural components (tower and foundation) are obtained. The maximum tensile stress in the tower should be canceled out by the prestress applied, that is, exhibiting zero tension under the service condition. The maximum compressive stress in the tower should be lower than the compressive strength of the 3D-printable concrete. It should be noted that, during the calculation, the second order effect was considered since the high slenderness ratio of the tower significantly magnified the calculated moment distribution along the tower height. Finite element analysis (FEA) was performed to validate and refine the tower cross section and the tower foundation.

Figure 4. Design Flowchart for 3D-printed Concrete Wind Turbine Towers



Source: WSP USA

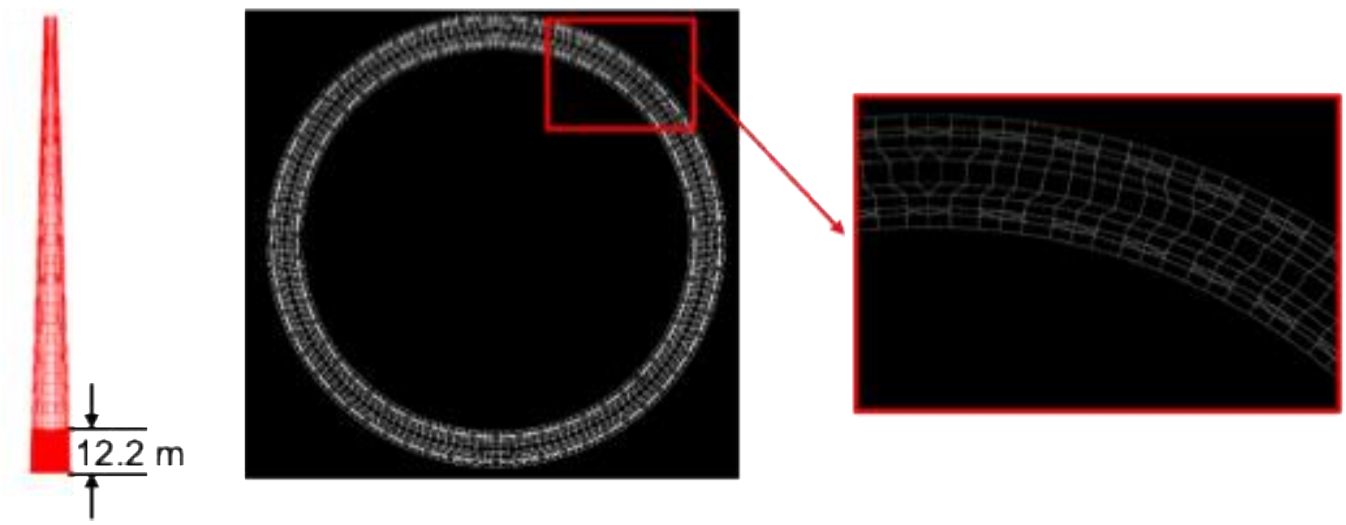
3D FEA of Tower

A finite element model, a method for numerically solving differential equations in engineering and modeling, was created in SAP2000 (a structural engineering software tool) to further analyze the behavior of the 3D-printed concrete tower. The objectives of the finite element model were to:

1. Compare the internal stresses at the interfaces between different materials having different compressive strengths and moduli of elasticity.
2. Compare the effect of concrete material properties (for example, UCI's 3D-printed concrete and conventional concrete) on tower performance.
3. Analyze the effects of thermal loading on the tower.

Due to the vast number of elements and limitations of the program, only a 12.2-m section, shown in Figure 5, was modeled in depth to represent four 3D-printed tower segments at the tower base. The finite element model consists of three different elements: the 3D-printed concrete tower, the grouted concrete, and the vertical reinforcement bars described by using solid elements and frame elements, respectively. Mesh discretization was carried out, as depicted in Figure 5. The solid elements have eight nodes, with each node having three degrees of freedom. Because of the complex geometry and the mesh of the tower, wedge-shaped solid elements with six nodes were also used. The cross section was meshed into 2,260 elements across the XY plane, with a maximum mesh size of 0.25 m. Mesh convergence that was used to validate the selected mesh size produced satisfactory results.

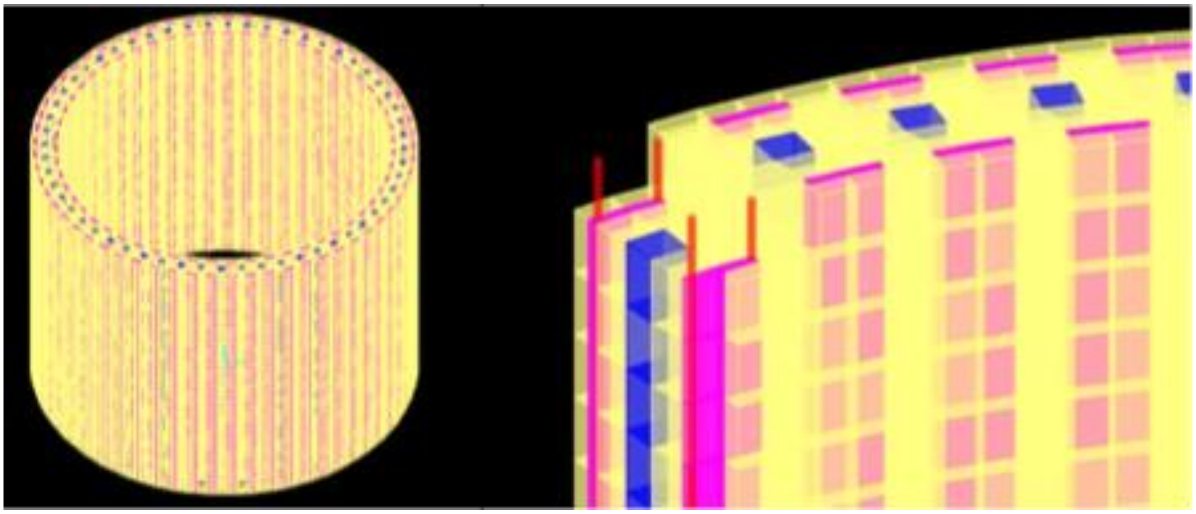
Figure 5. FEA Tower Segment and Wind Turbine Tower Cross Section Mesh Elements



Source: WSP USA

The cross section was extruded vertically to 12.2 m to replicate three segments of the 3D-printed concrete tower, with a maximum vertical mesh size of 305 millimeters (mm). The model is shown in Figure 6. In total, 93,404 solid elements and 6,930 frame elements were created to complete the finite element model. The pink solid elements are the grouted concrete for the vertical reinforcement bars. The blue solid elements are the grouted concrete for the prestressing tendons. The yellow solid elements represent the 3D-printed concrete. The frame elements representing the vertical reinforcement are shown in red.

Figure 6. 3D Finite Element Model of the Wind Turbine Tower



(Left) Wind turbine finite element model and (right) frame elements connected to solid elements.

Source: WSP USA

Foundation Design and Analysis

Foundation Design Assumptions

The foundation was designed assuming the installation location was Palm Springs, CA. The following soil properties were assumed for the foundation design:

1. Soil type: Medium dense to dense sand
2. Density of soil: γ = 18.85 kilonewtons per cubic meter (kN/m^3)
3. Soil shear modulus: Gs = 18,410 kilonewtons per square meter (kN/m^2)
4. Cohesion: c = 0
5. Soil Poisson's ratio: ν = 0.3
6. Interfacial friction angle: δ = 20

The ultimate bearing capacity was calculated using a safety factor of 2.5, which was selected using engineering judgment and standard guidelines (Bowles, 1988).

Footing Bearing Capacity Check and Stability Check

The bearing capacity of the soil was calculated with the assumptions that the settlements were tolerable and shear failure of the soil would control the design. The Terzaghi method was used for calculating the bearing capacity of the soil (Bowles, 1988). The depth of the foundation in the Terzaghi equation is assumed as 0.91 m (that is, the depth of only the circular raft foundation). A SAP2000 model was used to check the bearing capacity of the foundation.

Reinforced Concrete Foundation Strength Check

To obtain force output from the SAP2000 solid model, the elements and the associated nodes at the critical design locations were grouped together and section cuts were made. SAP2000 calculates the section-cut forces by summing the forces acting on member joints within solid objects that define the section cut. The critical design location for the bottom mat of the foundation was assumed as the face of the tower for the flexural steel design.

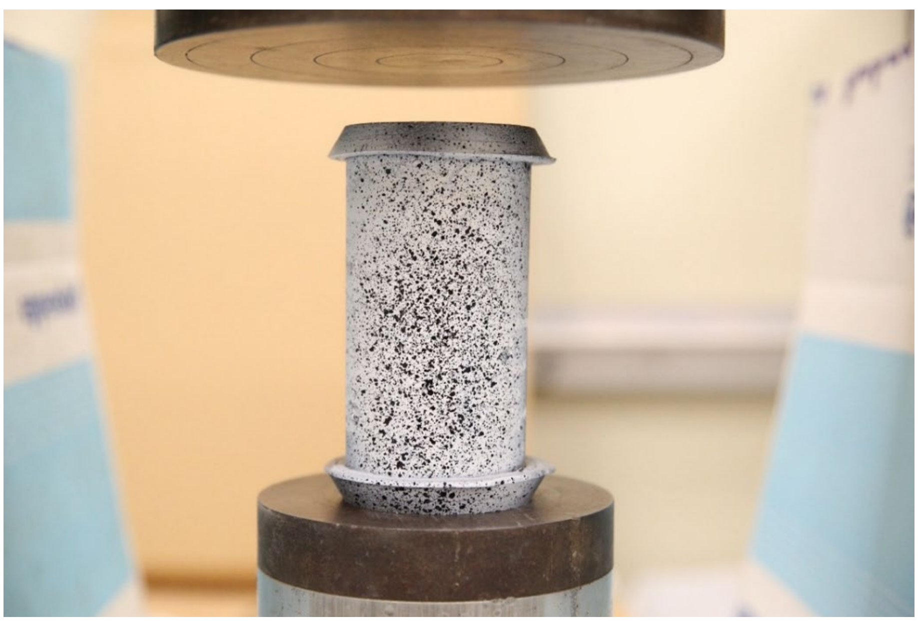
Lifecycle Assessment of 3DCP Towers and Foundations

The UCI team conducted a lifecycle assessment of a 3DCP tower and foundation considering the entire lifecycle, from material acquisition to disposal, following ISO 14040 and ISO 14044 (Jones and Li, 2024). The study examined 3D-printed towers, 3D cast towers, and standard tubular steel towers. The manufacturing methods, concrete mix designs, transportation distances, erection times, and maintenance requirements were analyzed. The end-of-life phase assessed varying levels of material recycling and landfill scenarios, considering the potential reuse of steel and concrete materials. SimaPro version 9.0.0 was used to carry out emissions calculations using the Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1 V1.05/ US 2008) analysis framework.

Laboratory Testing of 3DCP Materials

UCI tested the mechanical properties of the tower materials including the 3D-printed concrete, cast concrete, and grout. UCI conducted uniaxial compressive testing on 3D-printed concrete cylinder specimens with a diameter of 76.2 mm and a height of 152.4 mm, at the age of 28 days, following ASTM standard C39 (Figure 7).

Figure 7. Photograph of 3D-printed Concrete Cylinder in Compressive Strength Test



Source: University of California, Irvine

Tower Prototype Laboratory Structural Testing and Analysis

UCI designed a 3D-printed concrete tower assembly to resist both service and extreme loads. As shown in Figure 8, the assembly consisted of four 3D-printed concrete tower segments that were placed on top of one another, connected by horizontal wet joints, and tied by external and unbounded post-tensioning steel rods. Each segment had a 3D-printed formwork made of ultra-high-strength concrete, and ultra-high-strength concrete cast inside the UCI 3DPC formwork. The overall height of the tower, including the foundation and the loading blocks, was approximately 4 m. The tower's outer diameter was 0.51 m and the inner diameter was 0.36 m.

Figure 8. 3D-printed Concrete Tower and Test Setup

Source: University of California, Irvine

The horizontal wet joints, made of ultra-high-strength grout, provided a strong bond between the segments to prevent flexural opening and shear sliding at the joints under service and extreme loads. In addition, unbonded 25.4-mm-diameter post-tensioning steel rods were placed through the hollow core of the tower assembly. UCI applied 280 kilonewton (kN) post-tensioning force to each rod, resulting in a total post-tensioning force of 840 kN. This resulted in 8.14 megapascals (MPa) of prestressing in the 3D-printed concrete segments.

3D-printed Concrete Tower Manufacturing

UCI manufactured the tower assembly in the UCI Advanced Multifunctional Materials and Manufacturing Research Lab. As shown in Figure 9, UCI first mixed the concrete material and then charged the fresh concrete into a continuous pump to print the formwork of each tower segment. After curing the UCI 3DPC tower formworks, UCI mixed the same type of concrete and cast it into the 3DCP formwork to make a complete segment. The segments were covered with wet cloths and plastic sheets for curing before assembly and post-tensioning.

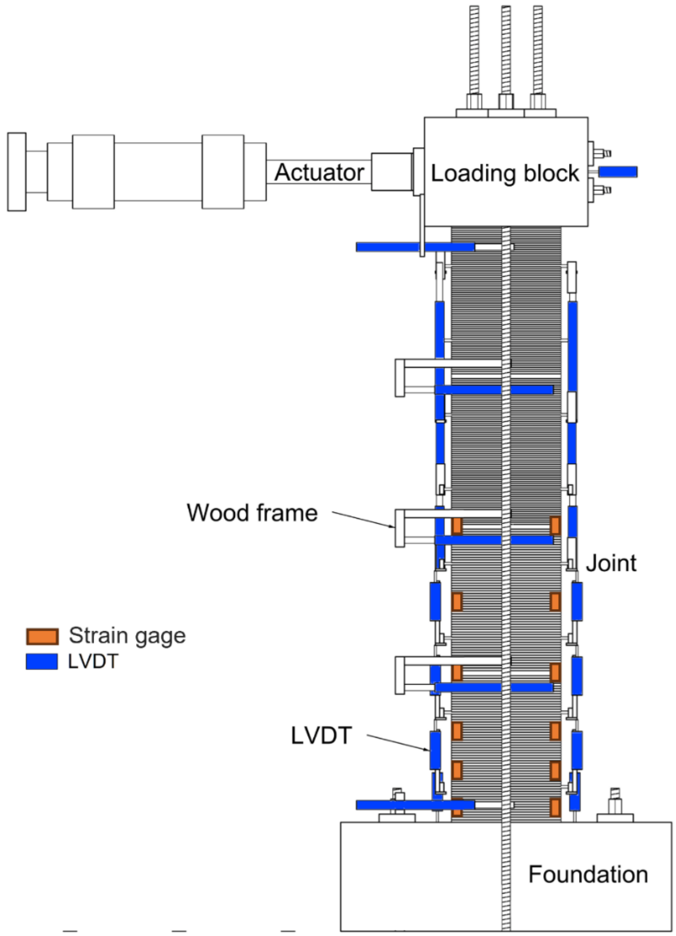
Figure 9. The Mixing, Casting, and Curing Process of the Tower Segment

Source: University of California, Irvine

Instrumentation and Calibration

UCI installed linear variable displacement transducers and strain gages to capture the tower structural response under dynamic and quasi-static loading. Figure 10 shows the sensor locations.

Figure 10. Instrumentation of 3D-printed Concrete Tower Assembly



Source: University of California, Irvine

Loading protocol

Table 1 shows the loading protocol for the 3DCP tower assembly. First, fatigue loading was applied under force control as a 1.5-Hertz (Hz) sinusoidal wave. The maximum force for each cycle was up to 50 percent of the decompression point of the 3DCP tower. The R factor, which is the ratio of the minimum to the maximum applied force for each fatigue cycle, was -1. One million loading cycles were applied at this loading level during phase I of the fatigue testing. During phase II of the fatigue testing, the maximum force for each cycle was increased to 100 percent of the decompression point of the 3DCP tower. The R factor remained -1.

Table 1. Loading Protocol for Fatigue Testing of Tower Assembly

Load Type	Description	Cycles (x106)
Fatigue (Phase I)	50% of decompression point	1.0
Fatigue (Phase II)	Up to decompression point	1.0
Quasi-Static Cyclic	Up to failure	Two cycles for each drift level

Source: University of California, Irvine

After the fatigue test, quasi-static cyclic loading was applied to the tower under displacement control, until failure. This test aimed to examine the loading capacity, the damage pattern, and the failure mode of the tower after being subjected to high-cycle fatigue. The test was applied by increasing the lateral drift ratio, that is, the lateral displacement divided by tower effective height, every two cycles.

Fatigue Testing of 3DCP Beams

Fatigue tests were performed on 3D-printed concrete beams to evaluate their fatigue behavior under flexural loading. Table 2 summarizes the testing variables and the number of beam specimens for each testing scenario. Two types of 3D-printed concrete materials were tested: ultra-high-strength 3D-printable concrete developed at UCI (named as UCI 3DPC), and normal-strength 3D-printable concrete commercially available from Quikrete.

The beam specimens were 305 mm in length, 50.8 mm in width, and 50.8 mm in height. All beams were cured for 28 days. The fatigue tests involved a four-point flexural bending setup, applying sinusoidal loading at a frequency of 2 Hz to simulate dynamic stresses. This testing was force-controlled, cycling from a calculated maximum stress (S_{max}) to a minimum stress (S_{min}). A digital image correlation system was utilized to provide precise and detailed measurements of displacement, deformation, strain, and damage, offering valuable insights into the crack initiation, crack progression, and overall deformation behavior of 3D-printed beams in comparison to cast beams under cyclic stress.

Table 2. Number of Beam Specimens Tested for Flexural Fatigue

UCI 3DPC, Cast							
Max. stress/flexural strength	100%	95%	90%	85%	80%	75%	70%
Number of specimens	9	4	4	4	4	3	3
UCI 3DPC, Printed							
Max. stress/flexural strength	100%	95%	90%	85%	80%	75%	70%
Number of specimens	9	4	4	4	4	3	3
Quikrete, Cast							
Max. stress/flexural strength	100%	95%	90%	85%	80%	75%	70%
Number of specimens	5	2	3	4	4	4	3
Quikrete, Printed							
Max. stress/flexural strength	100%	95%	90%	85%	80%	75%	70%
Number of specimens	5	3	3	5	3	4	3

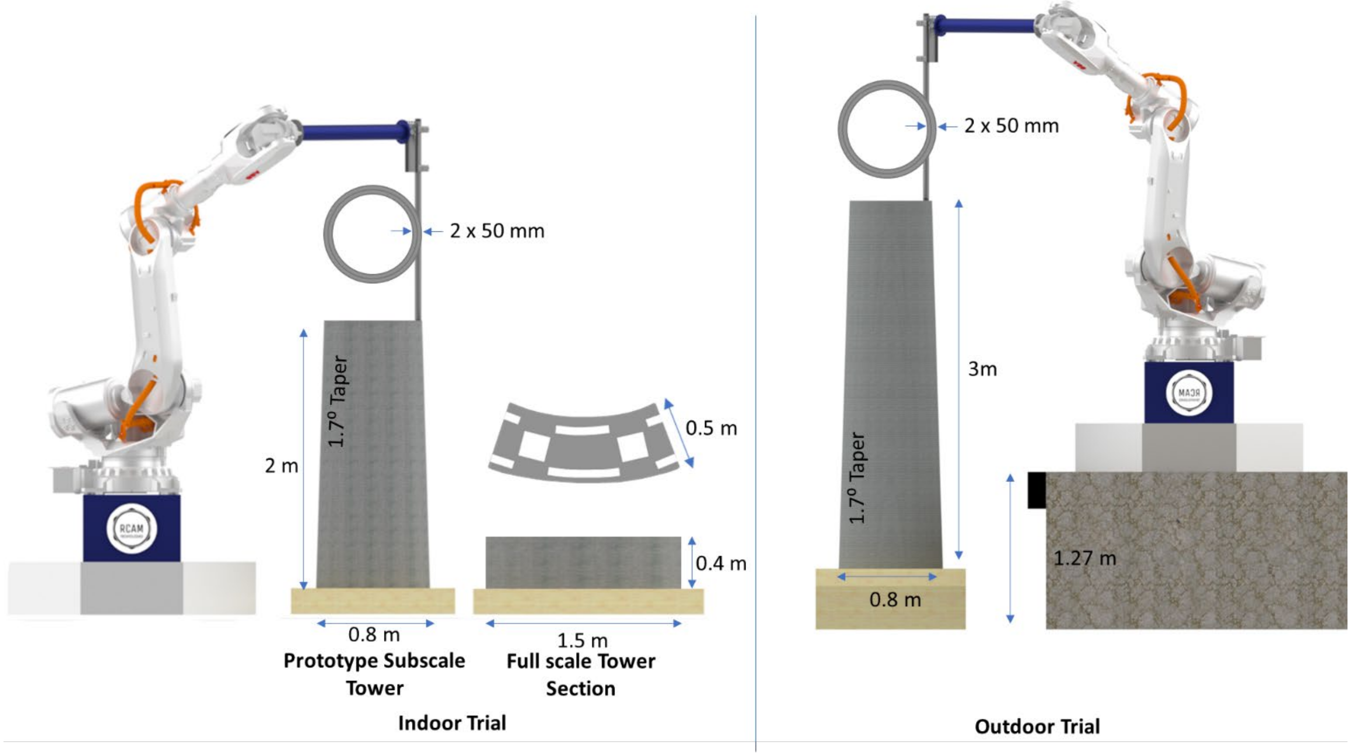
Source: University of California, Irvine

3D Concrete Printing at AltaSea at the Port of Los Angeles

During the project, RCAM established a 3DCP R&D facility at AltaSea, a blue economy incubator at the Port of Los Angeles. RCAM operationalized and commissioned its robotic-arm 3D concrete printing system at AltaSea. The system consists of a mobile ABB 6700 robotic arm installed on a concrete and steel gravity base, and a digitally controlled concrete mixer and pump system. The robotic arm provides up to a 3.89-m reach when using the available extensions. For all printing tasks in this project, RCAM used Quikrete® commercial grade 3D printing mix concrete, which is supplied in pre-batched dry mix 22-kilogram (kg) bags. The materials have a manufacturer specified 28-day compressive strength of 34.4 MPa and air cured length change (shrinkage) of greater than or equal to -0.10 percent.

RCAM planned and executed a series of indoor and outdoor printing trials to demonstrate the feasibility of printing large-scale tower sections, and to investigate the impacts of outdoor printing and curing of the tower prototypes compared to production and curing in an indoor environment. The trials included two tower specimens, shown in Figure 11: a representative section of a full-scale tower wall and a scaled prototype tower representing the bottom portion of a tapered cylindrical tower section. Following indoor trials, RCAM mobilized a robotic arm in an outdoor area of its facility on a 1.27-m high dock. RCAM printed a 3-m-tall variation of the indoor trial tower, reinforcing every 300 mm. To prevent shrinkage cracking, water was misted on the tower during and after printing.

Figure 11. Renderings of the Indoor and the Outdoor Tower Prints



Source: RCAM Technologies

Both cast and printed 50 mm by 50 mm cube samples were taken during the indoor and the outdoor printing trials and tested as per ASTM C109. Cast samples were made by directly filling cube molds with material extruded by the printer. Cast specimens were cured in water to provide the maximum-strength baseline. While printing was underway, separate beams were printed and cut into 50-mm cubes to prepare the printed specimens. Printed specimens were subject to three curing conditions: air cured, water cured, and field cured. The field-cured specimens were misted with water in the first 24 hours of curing to mimic likely curing conditions in a practical application. Testing was performed on specimens ranging from 1 to 28 days in age to establish the strength gain over time. A minimum of 3 specimens were tested per condition/age. Additional testing for shrinkage was performed following ASTM C157.

Technoeconomic Analysis

The levelized cost of energy (LCOE) of onshore and offshore wind power plants was estimated in this project using the System Advisor Model (SAM) software (Blair et al., 2018) 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 (megawatt-hour [MWh]/year)

SAM was used to calculate AEP_{net} based on turbine characteristics, plant size and layout, and the most recently available weather data file. FCR, CapEx, and OpEx assumptions were developed from internal cost models, default data in SAM, and literature data.

RCAM calculated the levelized cost of storage of subsea energy storage technology using a spreadsheet model based on NREL's Offshore Balance of System model (NREL, 2017).

The following assumptions were made for the LCOE analysis:

- The San Gorgonio Farms wind farm was selected as a representative wind plant site.
- The wind plant was assumed to consist of fourteen 7.5-watt (W) turbines at a 140-m hub height, yielding a plant with 1-GW nameplate capacity.
- The turbines were assumed to follow a simplified arrangement, comprising an array of two rows of seven turbines each, with both turbine and row spacings set to 8 rotor diameters and with an offset of 4 rotor diameters between each row.
- The selected wind turbine was the Enercon E-126 turbine, with a 7500-kW rated output.
- The rotor diameter was 127 m, the hub height was selected as 140 m, and the shear coefficient was 0.14.
- Wind plant construction was assumed to utilize on-site 3D concrete printing to manufacture both towers and foundations.
- Construction was assumed to utilize multiple gantry-based 3D concrete printing systems.

Key Project Milestones

The key project milestones were:

1. Completion of the preliminary tower and foundation design report.
2. Completion of the tower and foundation life cycle assessment.
3. Structural testing of the tower subassembly.
4. Outdoor tower printing demonstration.

CHAPTER 3: Results

Conceptual and Preliminary Design of a 3DCP Tower and Foundation

Conceptual Design of 3DCP Tower and Foundation

RCAM and WSP USA reviewed the latest advancements in 3D concrete printing technologies. Four primary tower cross section concepts were assessed, and two concepts were selected for further analysis, after review of technology risks and feasibility by the project team and advisors. The first concept uses on-site 3D concrete printing to create the cross section and form cavities for vertical reinforcement and prestressing. In the second concept, the 3D concrete printing is performed offsite at a concrete plant and is used to create stay-in-place formwork for the tower cross section. These segmental panels can be shipped to the construction site, where cast-in-place concrete would be filled in to improve the strength of the cross section for the tower, as needed.

A baseline tower design of 140 meters tall with a 3.37-MW wind turbine was selected for the study. Structural analysis and service-level checks confirmed the feasibility of the tower, demonstrating that it could withstand operational and extreme wind loadings without cracking.

Manufacturing and Assembly Plan

WSP USA and RCAM developed a manufacturing and assembly plan for the tower and foundation using both manufacturing concepts. The process for on-site printing is listed below:

1. **Mobilization and Setup:** Equipment, materials, and printers are set up at the job site. Volumetric mixing trucks and concrete pumps supply material to the printers.
2. **Printing Tower Sections:** Printers are operated to create tower sections of up to 3 meters in height. Steel hoop reinforcement is manually installed at specified intervals.
3. **Installation of Post-tensioning Ducts and Vertical Reinforcement:** Post-tensioning ducts, anchors, and vertical reinforcement are placed in the voids and grouted.
4. **On-site Curing:** Printed tower sections are cured before assembly under wet burlap cloths to maintain high humidity.

After manufacture of the tower segments, the assembly process consists of three stages: foundation construction, tower erection, and installation of the rotor-nacelle assembly.

Risk Assessment Workshop and Mitigation Measures

The project team convened a risk assessment workshop that included Technical Advisory Committee members and project advisors. Table 3 lists three of the primary risks identified.

Table 3. Risks and Mitigation Measures

No.	Risk	Mitigation Measures
1	Use of conventional concrete foundations incur high costs.	Further investigate the design of 3DCP tower foundations.
2	The design for California's seismic loading may unduly limit the competitiveness of this concept in other regions.	Explore the sensitivity of tower costs to design load without seismic loads, to ensure that benefits can be provided not only to California but also to other regions in the United States.
3	There is uncertainty in the mechanical behavior of 3D-printed concrete materials.	1. Develop a comprehensive 3DCP material dataset. 2. Optimize tower design as a function of concrete compressive strength. 3. Assess fatigue behavior and anisotropy of 3D-printed concrete.

Source: RCAM Technologies

As a result, the following actions were incorporated in the project:

1. Design and analysis of 3D-printed concrete foundations.
2. Design and estimation of tower costs without seismic requirements.
3. Investigation of the effect of 3DCP concrete strength on tower design and cost.

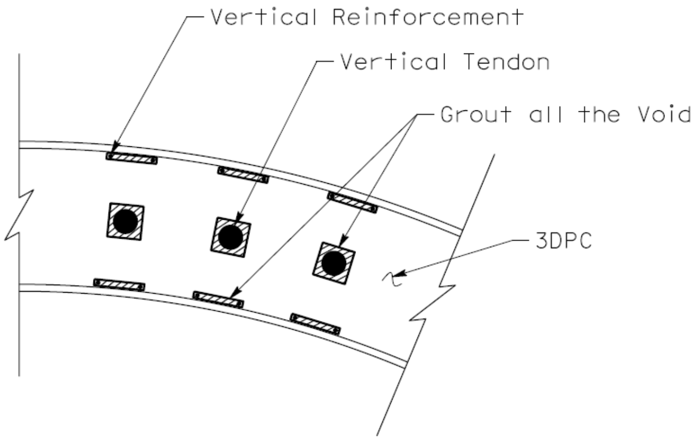
Turbine Scaling Study

WSP USA and RCAM completed an upscaling analysis of the 3DCP wind turbine tower design from a 3.4-MW to a 7.5-MW turbine, maintaining a 140-m hub height. The team used the design loads from the NREL's BAR3 turbine as estimated loads for the 7.5-MW turbine (Bortolotti et al., 2021). The upscaled tower design called for thicker tower walls and a larger foundation due to the increased wind load, leading to a rise in material quantities ranging between 11 percent and 39 percent. However, the crane capacity required for assembly remained unaffected. The total tower cost increased by approximately 13 percent, while the power-specific CapEx dropped by nearly 50 percent.

Preliminary Design of Tower and Foundation

WSP USA conducted the preliminary design of a 3DCP 7.5-MW concrete tower and foundation, focusing on the tower section as shown in Figure 12. WSP USA performed finite element analyses using material properties representative of conventional and high-performance 3D-printed concrete. The analyses confirmed that tower drift at the top complies with ASCE 7-16 Table 12.12-1 limits and that the design meets requirements under the predominant loading conditions.

Figure 12. Tower Cross Section



Source: WSP USA

WSP performed an analysis of the dynamic properties and natural frequency of the towers, which verified that the towers have natural frequencies within the desired working frequency range. WSP demonstrated the sufficiency of both designs under seismic loading.

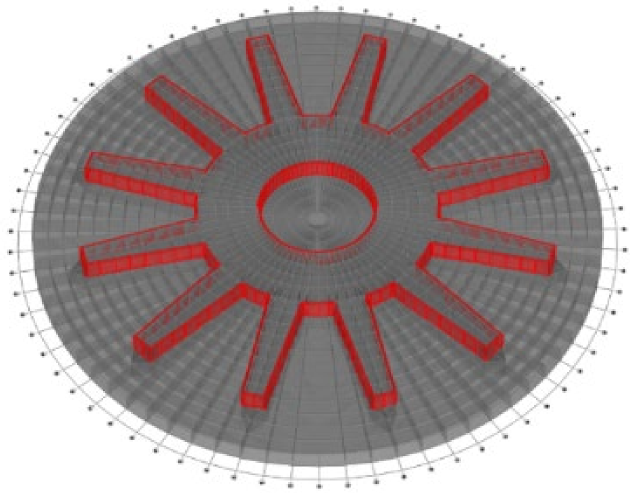
WSP designed the post-tensioning for the concrete towers, specifying the required stress level and properties of steel post-tensioning tendons. Figure 13 shows the maximum joint stress (tension in "+", compression in "-") within the tower under the applied load case. The figure shows that the 3DCP tower is under zero tension and the compressive stress (f'c) is less than 0.45f'c, as required by ACI 318-14 Section 24.5.4, indicating that the design is structurally adequate under service loading.

Figure 13. Maximum Joint Service Stress in 3D-printed Concrete Tower

f'c=specified compressive strength; kN/m2=kilonewtons per square meter; m=meter
Source: WSP USA

WSP analyzed a 3DCP foundation design called the short-ribbed beam foundation, shown in Figure 14. This design reduces material usage by 38 percent compared to a conventional gravity foundation, cutting the embodied carbon emissions by approximately 241 metric tons per foundation. The design was assessed to be sufficiently resistant to overturning and sliding failures.

Figure 14. 3D Model of Short-ribbed Beam Foundation



Source: WSP USA

Levelized Cost of Energy Analysis

RCAM estimated the capital expenditure (CapEx) for a 1-GW nameplate capacity wind plant at $1,809 per kilowatt (kW), translating to $13,567,500 per tower or $189,945,000 for the entire plant. These baseline tower CapEx estimates were comparable to breakeven costs for state-of-the-art steel towers estimated by NREL at $1,754/kW for 140-m hub height towers in California. RCAM identified several areas for cost reduction, including optimizing foundation design, reducing material costs, and optimizing tower design by utilizing higher strength materials and printing larger sections to streamline assembly time.

Based on the CapEx estimates above and the assumptions listed in the section of this report titled Technoeconomic Analysis, RCAM calculated the LCOE, shown in Table 4. The LCOE for 3D-printed concrete wind turbine towers was determined to be $55.10/MWh. Although this is higher than the national average LCOE for wind projects installed in 2020 ($33/MWh), the calculated LCOE is significantly lower than the California LCOE target for 140-meter towers established by NREL ($90/MWh). It should be noted that the analysis used conservative observations, including a higher fixed charge rate (9.8 percent compared to 8 percent in the NREL study) and a slightly higher OpEx value ($43/kilowatt-hour (kWh)/year versus $41/kWh/year).

Table 4. LCOE of 3DCP Towers in Comparison to Reference Data

LCOE of 3DCP Towers	National Average LCOE for Wind Projects Installed in 2020	California LCOE Target for 140-meter Towers Established by NREL
$55.10/MWh	$33.00/MWh	$90.00/MWh

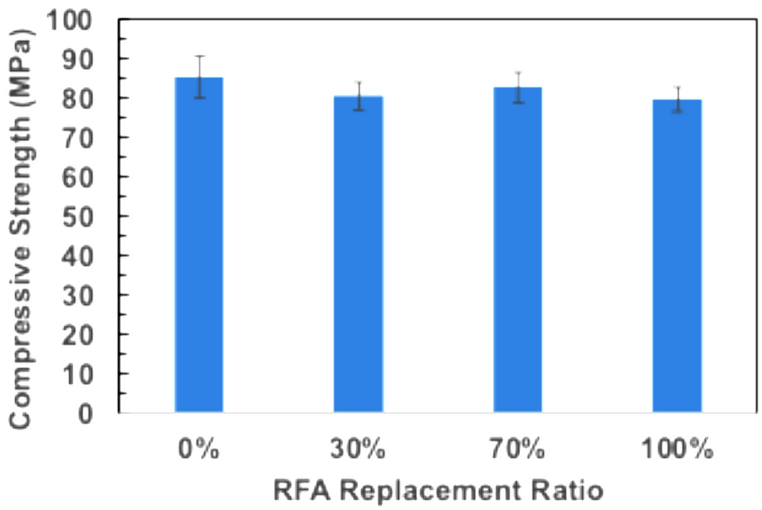
Source: RCAM Technologies

Develop a Closed-loop Cycle Approach for a Next-generation 3DCP Tower

Testing of Mixtures Containing Waste Materials

Figure 15 shows that replacing the natural fine aggregates in the UCI 3DCP with recycled fine aggregates by up to 100 percent decreased the compressive strength by only 6.5 percent (5 MPa).

Figure 15. 28-Day Compressive Strength of UCI 3DCP Mixture at 0 Percent, 30 Percent, 70 Percent, and 100 Percent RFA Substitution by Volume



RFA=recycled fine aggregate
Source: University of California, Irvine

Concrete 3D Printing With Recycled Concrete

Figure 16 shows the printing conducted with UCI 3DCP material that incorporates recycled fine aggregates by 30-percent volume of the total fine aggregates. The test successfully demonstrated the print quality of the material and the feasibility of concrete 3D printing with recycled fine concrete aggregate.

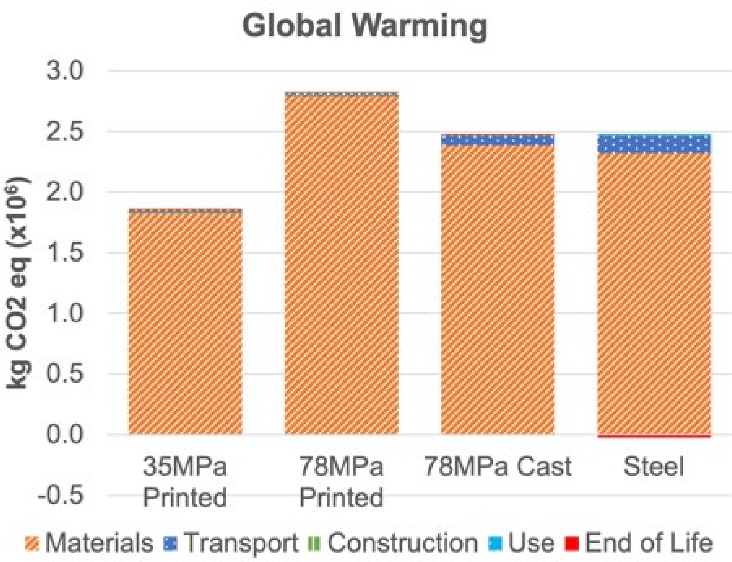
Figure 16. Printed Sample of 78-MPa Recycled 3D-printable Concrete

Source: University of California, Irvine

Lifecycle Analysis of 3DCP and Steel Towers

UCI analyzed the lifecycle impacts of 3DCP towers with concrete of varying compressive strength levels and conventional steel towers. Figure 17 shows the global warming potential (GWP) measured in kg of CO_2 equivalent, for the various tower designs. The 3D-printed tower using 35-MPa concrete had the lowest emissions in terms of global warming potential. The material stage is the dominant lifecycle stage in comparison to the use and end of life stages, responsible for 92.7 percent to 98.8 percent of GWP.

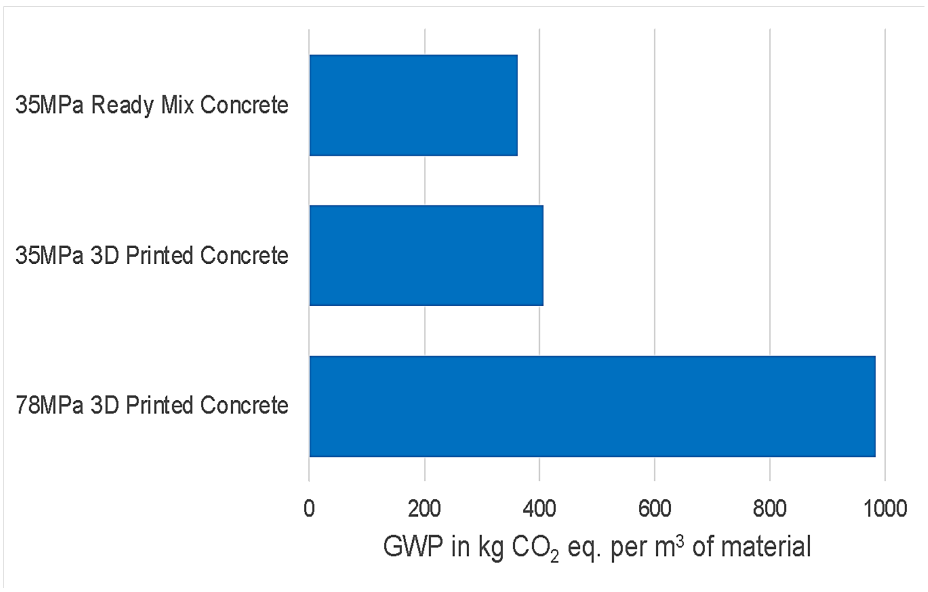
Figure 17. GWP Impact Categories for the 35-MPa 3D-printed, 78-MPa 3D-printed, 78-MPa 3D Cast, and Steel Wind Turbine Towers Broken Down by Life Cycle Stage Contribution



CO_2 eq.=carbon dioxide equivalent
Source: University of California, Irvine

As shown in Figure 18, for the same material volume, the 78-MPa mixture shows approximately 2.5 times the GWP of the 35-MPa printed concrete and CalPortland's average ready-mix concrete. The 78-MPa concrete does not use coarse aggregate, resulting in a higher amount of cement per unit volume. However, the higher compressive strength of the 78-MPa mixture presents opportunities for more efficient design of tall wind turbine towers, with reduced wall thickness and lower materials usage. This could potentially lower the overall tower GWP while offering structural and manufacturing advantages. This potential was not explored in this project and could be investigated in future studies.

Figure 18. One Cubic Meter of Conventional Ready-mix Concrete Compared to One Cubic Meter of 35-MPa (5 ksi) and 78-MPa (11 ksi) Printed Concrete in Terms of Global Warming Potential



ksi=kips per square inch; m^3=cubic meter
Source: University of California, Irvine

3D-printed towers have significantly lower transportation emissions than steel towers because their materials come from nearby ready-mix sites rather than from distant steel fabrication plants. The steel tower outperforms the concrete towers at end-of-life due to the greater recyclability of steel. This indicates that increasing the recyclability of concrete could further enhance the advantages of concrete towers over steel towers.

Laboratory Printing, Pilot-testing, and Analysis of a 3DCP Tall Tower Sub-assembly

Material Mechanical Properties

Table 5 shows the 28-day compressive strength of the 3D-printed and cast concretes. The UCI 3D-printed concrete exhibited an ultra-high compressive strength above 100 MPa, enabling rapid printing of thin-walled segments and reducing curing time before casting in-fill.

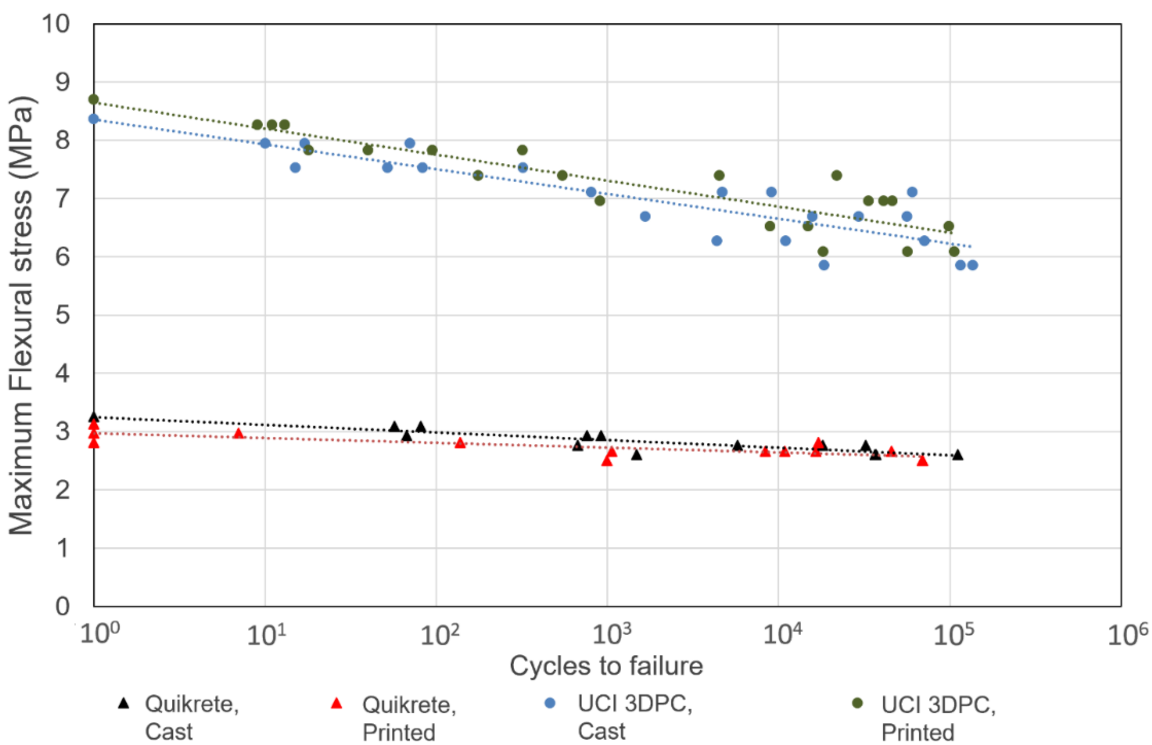
Table 5. Compressive Strength of Concrete Materials Used in the 3DCP Tower

Age	3D-printed Concrete	Cast Concrete	Grout
28 Days	104.7 ± 7.19 MPa	101.4 ± 9.04 MPa	101.4 ± 9.04 MPa

Source: University of California, Irvine

Figure 19 shows the measured fatigue curves of S_{max}-N_f curves, which depict the numbers of fatigue cycles to failure (N_f) under different maximum loading levels (S_{max}). Each data point corresponds to one beam specimen tested to failure. The trends of the S_{max}-N_f curves indicate that UCI 3DPC has a much longer fatigue life than Quikrete when subjected to the same applied maximum fatigue loading.

Figure 19. 3D-printed Concrete Material Fatigue Curves



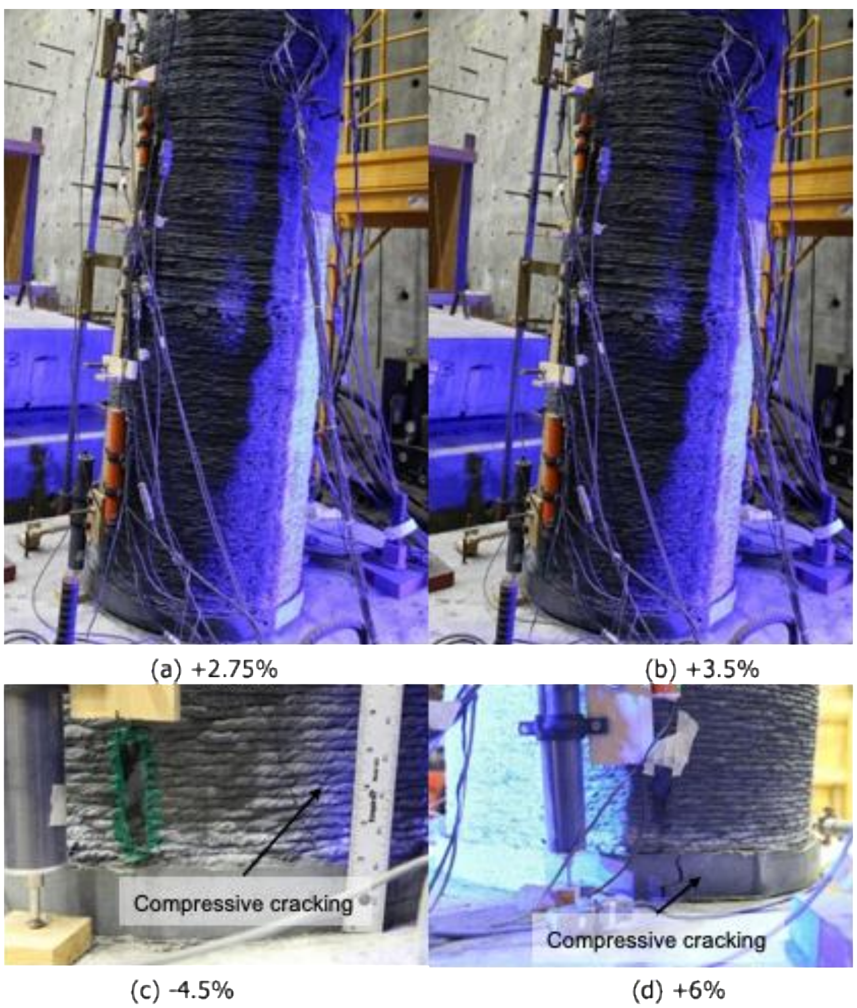
Source: University of California, Irvine

Structural Testing Results

The 3DCP tower was subjected to one million cycles of fatigue loading up to 50 percent of decompression, followed by another million cycles of fatigue loading up to 100 percent of decompression. The tower maintained a linear elastic response, and the stiffness after two million cycles appeared to be slightly lower than the initial stiffness, but the difference was insignificant. Also, the lateral displacement of the tower remained consistent during increasingly applied fatigue loading cycles. No damage or cracks were found in the tower assembly, either within the 3D-printed concrete segments, at the connections, or at the printed interlayers.

After completing the fatigue test, quasi-static reversed cyclic loading was applied to the 3D-printed concrete tower under displacement control. This test simulated extreme loading conditions, such as seismic events, and assessed the load-carrying capacity of the 3D-printed concrete tower. Figure 20 shows photographs of the 3D-printed concrete tower at different lateral drift levels. Initially, the tower exhibited a linear elastic response of up to 0.15 percent drift, after which it entered an inelastic stage as the applied lateral drift and load further increased. No significant damage was observed in the tower specimen up to 3.5 percent drift. Cracking began to form at the bottom segment, on the side far from the strong wall, at -4.5 percent drift, corresponding to a drop in the lateral load at -4.5 percent drift. Crushing of the concrete at the bottom segment, on the side near the strong wall, began at -6 percent drift, corresponding to a drop in the lateral load at +6 percent drift. The results indicate that the ultimate failure of a well-designed 3D-printed concrete tower is compression-governed. This suggests that using a 3D-printed concrete with significantly higher compressive strength, such as UCI 3DPC, can greatly improve the structural load-carrying capacity of the 3D-printed concrete tower.

Figure 20. Damage Pattern in 3D-printed Concrete Tower at Different Lateral Drift Levels

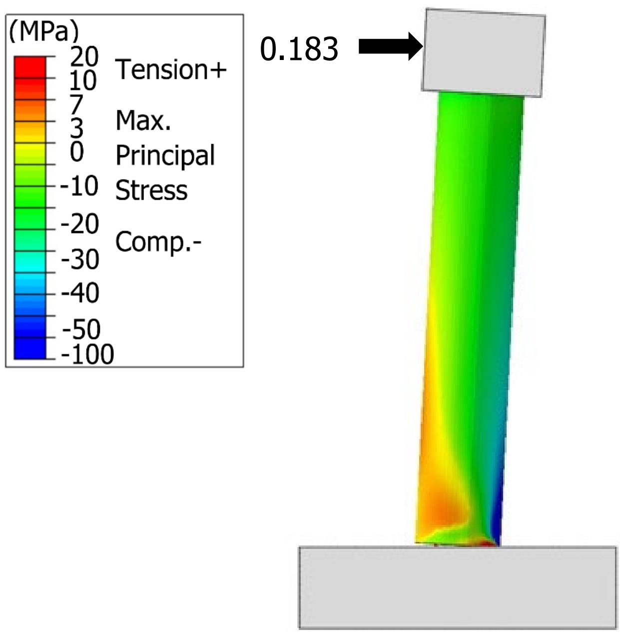


Source: University of California, Irvine

Finite Element Analysis Results

Finite element modeling was conducted using Abaqus to analyze the 3D-printed concrete tower, maintaining the same geometry, parameters, and boundary conditions as the experimentally tested specimen. Figure 21 shows that the maximum compressive stress occurs in the bottom region of the tower, while the maximum tensile stress occurs slightly away from the bottom of the tower, due to the gap opening between the tower and the base block at a high level of drift. The modeling results align well with experimental observations, confirming that the tower's failure was governed by the maximum compressive stress developed at the base at 6 percent drift. This compressive stress exceeded 100 MPa and reached the compressive strength of the UCI high-strength 3D-printed concrete material, which explains the observed concrete crushing on the compressive side. At this drift level, the maximum tensile stress on the opposite side of the tower remained below the tensile strength of the UCI high-strength 3D-printed concrete material, resulting in no significant cracking or damage in the concrete on the tensile side.

Figure 21. Maximum Principal Stresses Field at 6 Percent Drift



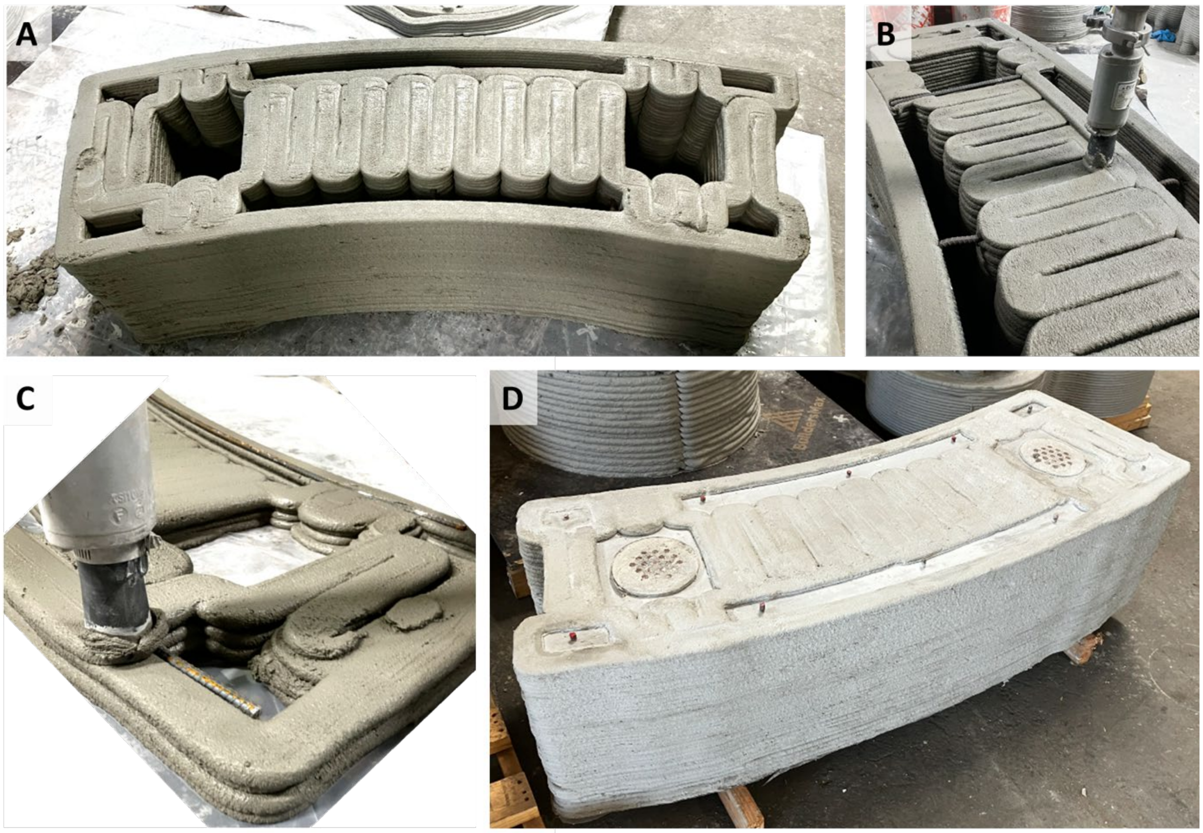
MPa=megapascal
Source: University of California, Irvine

This study validated the feasibility and successfully demonstrated the tower 3D printing and 3D casting processes, evaluated the flexure-governed fatigue behavior of 3D-printed concrete beams and large-scale 3D-printed tower assembly, and validated the structural design and load carrying capacity of the 3D-printed concrete tower assembly. The large-scale structural testing also examined the mechanical capacity of the 3D-printed concrete tower assembly under operational fatigue loading as well as extreme loading conditions such as earthquakes.

Outdoor Testing and Demonstration of On-site 3D Concrete Printing

Figure 22 shows the print representative of a full-scale tower wall, designed as a one-eighth portion of the top tower segment. The print operation was completed without issues.

Figure 22. Representative Full-scale Tower Segment Section Printed Indoors



(A) Finished printed shell, (B-C) printing over the horizontal reinforcement, (D) final reinforced and grouted section.

Source: RCAM Technologies

Figure 23 shows the subscale tower specimen, a cylindrical tower with a base diameter of 0.8 m, a height of 2 m, and a 1.7° taper. Reinforcement hoops were inserted every 300 mm in height.

Figure 23. Indoor Printing Process of the Subscale Cylindrical Tower

(A) Printed 2-meter tower prototype and sample beams, (B) top view of the double wall print path over reinforcement hoop (C) close-up of printing over reinforcement, and (D) laying a reinforcement hoop.

Source: RCAM Technologies

The outdoor-printed tower used the same dimensions but with a total height of 3 m, as shown in Figure 24. Printing was executed in approximately 2.5 hours. The tower had a mass of approximately 1.5 metric tons. There were no physical effects noticed on the printed tower due to the heat or sunlight.

Figure 24. Outdoor Printing of the 3-m-tall Reinforced Tower

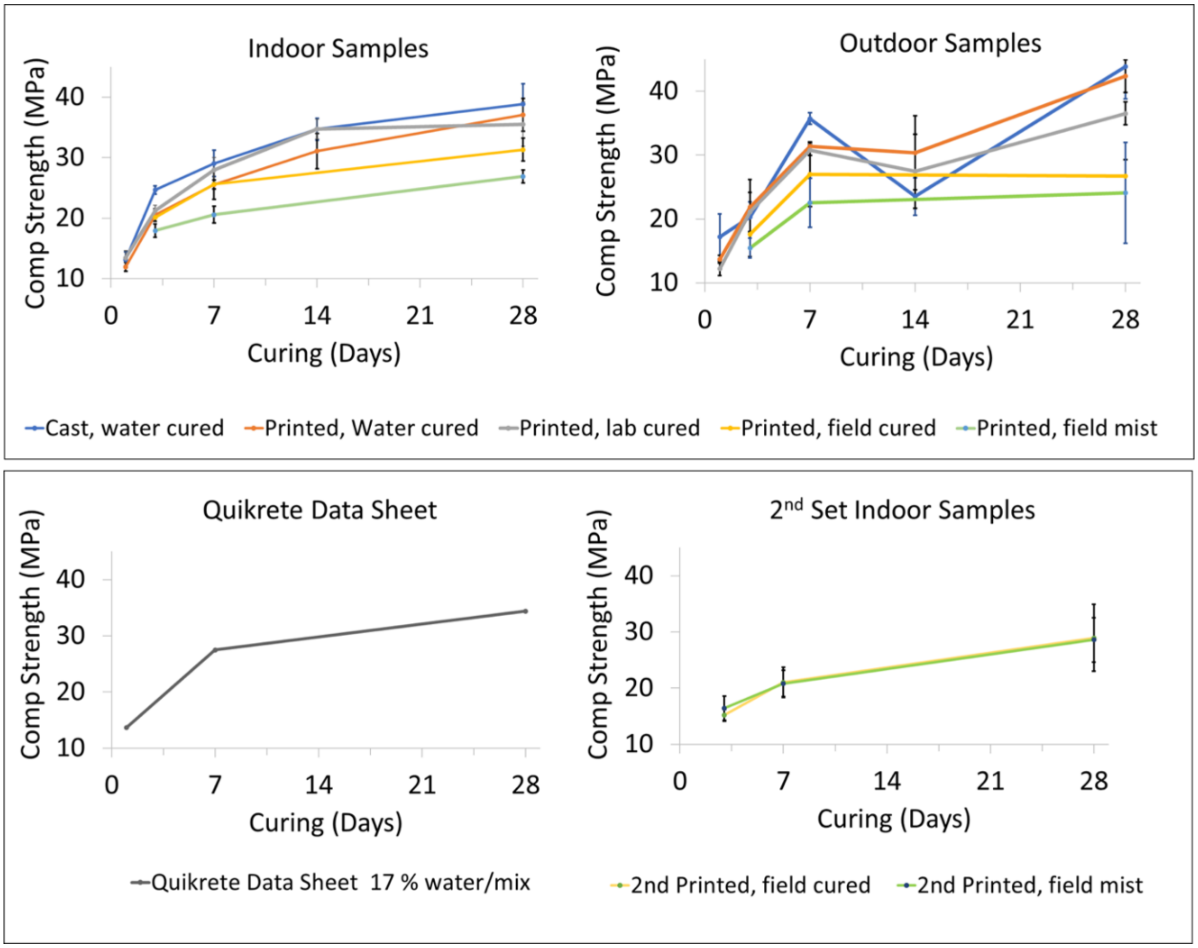
Source: RCAM Technologies

Figure 25 shows the layered beams printed using the same parameters. The printed beams did show small shrinkage cracks on the top layer due to drying. Figure 26 shows the measured compressive strength of the printed specimens and the cast specimens. It is difficult to draw fully conclusive evidence between the printed field-cured samples due to the large standard deviation. However, field samples indicate an average similarity of a 6-MPa-lower to a 13-MPa-lower 28-day strength than lab-cured samples.

Figure 25. Printed Beam Samples for Quality Testing

Source: RCAM Technologies

Figure 26. Graphical Representation of Average Compressive Strength Test Results



Source: RCAM Technologies

Additional testing of 7-day and 28-day compressive strength (ASTM C109 on 3" by 6" cast cylinders), shrinkage (California modified ASTM C157), modulus of elasticity (ASTM C469 & C39) and rapid chloride permeability (ASTM C1202) was performed by an independent material testing laboratory. Table 6 shows the average results of each test. The 28-day strength was above the specification and comparable to the results RCAM obtained in the testing of cast samples. Shrinkage was within the -0.10-percent tolerance for the printable mixtures. Chloride permeability was negligible (less than 100) for the printable mixtures and very low (100 to 200) for the 20-percent mixture, indicating high chloride resistance and durability.

Table 6. Third-party Testing Results of Quikrete Material

	Water/Dry Mix			
	Fluid Mix	**Printable Mix**		
Test	**20%**	**18%**	**16.5%**	**15%**
7-day Compressive Strength (ASTM C109) (MPa)	14	18	23	24

Test	Water/Dry Mix			
	Fluid Mix	Printable Mix		
	20%	18%	16.5%	15%
28-day Compressive Strength (ASTM C109) (MPa)	34	41	44	47
28-day Modulus of Elasticity (ASTM C469) (MPa)	22	31	36	41
28-day Shrinkage (ASTM C157) (%)	-0.215	-0.166	-0.139	-0.130
56-day Rapid Chloride Permeability (ASTM C1202) (Coulombs)	112.77	72.98	48.77	50.67

Source: RCAM Technologies

Feasibility Analysis and Concept Fabrication of Offshore Components

RCAM demonstrated the fabrication of 3DCP suction anchors and energy storage spheres. Figure 27 shows photographs of the printed anchor models. The printed sections featured a single cylindrical wall (5 centimeters wide) with an outer diameter of 46 centimeters.

Figure 27. 3D-printed Concrete Anchor Prototypes

(Top left and bottom left) Photographs of the 3D-printed concrete prototype with spiral post-tensioning channels, and (right) photograph of the 1:8-scale 3DPA models showing the bolted and studded plate pad eye concepts.

Source: RCAM Technologies

3D-printed Concrete Underwater Energy Storage

The subsea pumped hydro energy storage technology functions by cycling water in and out of large concrete spheres on the seafloor to release and store energy on demand. A reversible pump/turbine unit is used to pump water out of the spheres and into the surrounding ocean water, charging the system. To release energy back to the grid, a valve is opened, allowing water to re-enter the spheres, turning the turbine and generator to generate electricity. Figure 28 shows photographs of the completed sphere proof of concept prints. Spheres were printed in three ways: (1) as hemisphere shells with grout poured in between, (2) over a temporary support of crushed lightweight aggregate, and (3) using a set accelerator injected at the nozzle. All variations successfully manufactured spheres without collapse.

Figure 28. Photographs of the Prototype 3D-printed Concrete Underwater Energy Storage Spheres

Source: RCAM Technologies

Development of 3DCP R&D, Education, and Supply Chain Capabilities in CA

3DCP construction projects will create new construction roles and broaden access to construction careers due to their use of automation. 3DCP can utilize existing concrete supply chains. Printing equipment is becoming more available from domestic suppliers. RCAM identified seven key challenges associated with the use of 3DCP in marine applications:

1. The availability of qualified and certified 3DCP materials
2. A lack of data on the marine durability of 3DCP materials
3. Limited experience in using 3DCP, particularly in the United States
4. Insufficient knowledge and experience in printing in marine environments
5. Further development and testing of methods for reinforcing 3DCP structures
6. A limited understanding of the fatigue and vibration performance of 3DCP
7. A lack of awareness within the wind industry regarding 3DCP

Technical Barriers and Challenges

The first technical challenge was the lack of load data for 7.5-MW wind turbines, as this rating was beyond the state of the art at the project's start. RCAM and WSP successfully overcame this barrier by using a scaling study approach. However, industrywide competitiveness and a reluctance to share load data remain barriers to developing new tower technologies.

The second challenge was the absence of reference designs for ultra-tall steel wind turbine towers for 7.5-MW turbines, complicating the establishment of baseline designs for cost and lifecycle emissions impacts. The UCI team addressed this by consulting industry experts, using NREL data, and developing a detailed bottom-up steel tower design. National labs and universities can mitigate future challenges by developing reference models for ultra-tall towers and high-capacity turbines.

The final challenge was the lack of data on 3D-printed concrete material behavior for structural design. The project team overcame this barrier by performing detailed characterizations of the material properties of the 3D-printed concrete, with support from RCAM, UCI, and third-party materials laboratories. This is an active area of study.

Market and Policy Barriers

Barriers to deploying 3DCP wind turbine towers and foundations include a lack of data, limited industry familiarity with 3D concrete printing, the absence of construction codes for 3D-printed concrete, and resistance to new land-based wind plants in California. RCAM addressed these by generating structural testing data, engaging in business development and outreach, and focusing on repowering projects within existing permitted wind areas. During the project, new state and federal policies accelerated offshore wind energy deployment, creating favorable conditions for developing manufacturing technologies.

Outreach Activities

RCAM hosted several community and stakeholder outreach activities at its R&D printing facility at AltaSea at the Port of Los Angeles, welcoming over 905 visitors since RCAM began 3D concrete printing operations in October 2022. Figure 29 shows photographs from three of these events. Focusing on education, RCAM welcomed a total of 390 students and 45 teachers from local high schools and community colleges.

Figure 29. Photographs of Outreach Events at RCAM's Facility at AltaSea at the Port of Los Angeles

Source: RCAM Technologies

RCAM and UCI disseminated project findings in academic journal articles and trade publications. The team's published, submitted, and planned publications are listed in Table 7.

Table 7. Summary of Project Publications

Publication Type	Publication Status	Title	Author(s)	Year of Publication
Trade Journal: Article *Journal of Ocean Technology*	Published	Stored Energy in the Sea: Combining 3D Printed Pumped Hydro Energy Storage Systems with Floating Offshore Wind in California	Christian Dick, Jonas Sprengelmeyer, and Gabriel Falzone	2023
Journal Article: *Journal of Cleaner Production*	Published	Life cycle assessment of ultra-tall wind turbine towers comparing concrete additive manufacturing to conventional manufacturing	Kathryn Jones and Mo Li	2023
Journal Article: *Cement and Concrete Research*	Published	Role of thixotropy in interlayer microstructure and properties of additively manufactured cementitious materials	Yun-Chen Wu, Xinbo Wang, and Mo Li	2024

Publication Type	Publication Status	Title	Author(s)	Year of Publication
Journal Article: *Wind Energy*	In Press	Life Cycle Assessment of Wind Turbine Concrete Foundations Comparing Concrete Additive Manufacturing to Conventional Manufacturing	Kathryn Jones and Mo Li	2024
Journal Article	Planned	3D printed concrete incorporating recycled aggregates	Kathryn Jones and Mo Li	2024
Journal Article	Planned	3D printed concrete column under fatigue and seismic loading	Wei Geng, Young-Jae Choi, Amadeu Domenech, and Mo Li	2024

Source: RCAM Technologies

RCAM and the UCI team also presented project findings at industry events and academic conferences, including the following:

- North American Wind Energy Academy (NAWEA)/WindTech 2022, 2023 and 2024
- American Ceramics Society (ACerS) 12th and 13th Advances in Cement-Based Materials
- American Society for Testing and Materials (ASTM) International Conference on Advanced Manufacturing 2023
- International Partnering Forum 2022 and 2023
- Digital Concrete 2022
- Global Offshore Wind 2022
- 7th Offshore Energy & Storage Symposium
- TechConnect World Innovation Conference & Expo

The project team has been excited to share project findings with industry and inspire the next-generation renewable energy workforce.

CHAPTER 4: Conclusion

The project demonstrated the feasibility of using 3D concrete printing technology to cost-effectively manufacture ultra-tall wind turbine towers, offshore wind energy components, and subsea energy storage systems that can be used in California. On-site 3D concrete printing was demonstrated to be a feasible method for manufacturing towers for 7.5-MW wind turbines, which can unlock new potential wind energy areas for development in California to increase generation of renewable energy. In addition, 3D concrete printing can be used to repower existing wind plants by replacing older low-capacity wind turbines with fewer, more efficient turbines that generate the same amount of electricity while reducing visual disturbance and avian mortality. 3D concrete printing technology can be used to manufacture concrete anchors and energy storage systems in California ports, which can help California reach its goals for offshore wind deployment and net zero carbon emissions without unduly escalating electricity costs for California ratepayers. In addition, the team discovered new opportunities for 3D concrete printing of floating foundations for offshore wind and offshore solar, as well as wave energy and floating solar components. Together, deployments of these technologies have the potential to reduce the cost of renewable energy in California, increase the resilience and reliability of California’s grid, and create jobs and local economic benefits by enabling manufacturing of clean energy components in-state using local materials.

The project outcomes demonstrate that 3D concrete printing is a feasible method by which to manufacture concrete components for highly demanding structural applications in renewable energy and energy storage. The project results provide evidence that new ultra-tall wind turbine towers can be manufactured and installed in California using 3D concrete printing, enabling new high-efficiency, low-cost wind turbines to be economically viable in the state. This technology has the potential to open new opportunities for land-based wind energy deployments in California of larger, more cost-effective wind turbine towers and foundations. Compared to conventional manufacturing approaches relying on steel, 3D concrete printing can utilize existing supply chains within California, using domestically produced materials.

During the project, RCAM and the UCI team developed new 3D concrete printing research and development capabilities in California. RCAM and the UCI team generated significant new knowledge and lessons learned in 3D concrete printing technology through substantial trialing, prototyping, and testing efforts undertaken over the course of the project. Further, the collaboration with WSP USA generated new learnings by providing an experienced structural design and construction perspective in combination with the novel 3D concrete printing technology.

3D concrete printing technology has substantial market opportunity for construction in the renewable energy sector, the housing sector, and the construction industry at large, both within California and globally. 3D concrete printing is a versatile technology that reduces the cost and increases the production rate of complex concrete components using automation. The rapidly growing renewable energy sector requires innovative construction solutions to reduce costs. This is especially so within the offshore renewable energy industry, where current solutions have been largely repurposed from the oil and gas energy. RCAM developed designs for 3D-printed concrete wind turbine towers and foundations, fixed bottom offshore wind foundations, subsea energy storage systems, and anchors and foundations for floating solar, wave energy, and offshore wind plants. Anchors for floating offshore wind alone comprise a multi-billion-dollar market in California.

To continue to advance 3D concrete printing technology and to develop the required workforce and market environment for 3D-concrete-printed renewable energy components, RCAM recommends the following next steps:

- Advance, certify, and qualify 3DCP materials and methods for marine applications.
- Survey, assess, and develop green 3DCP materials and reinforcements.
- Develop a materials standard for 3D-printable cementitious materials and codes for concrete 3D-printed structures.
- Invest in research and development to study the mechanical strength and performance of 3D-printed structures.
- Further optimize the tower design.
- Develop and demonstrate the use of 3DCP to reduce the cost of subsea energy storage.
- Assess the suitability and benefits of using a versatile additive manufacturing platform and floating dry docks to fabricate different floating wind turbine substructure configurations.
- Invest in development of smaller 3DCP products for beachhead markets adjacent to floating wind, such as anchors for floating solar farms and wave energy converters, that can help accelerate 3DCP learning curves and de-risk the first 3DCP technologies and products.
- Create or incentivize education and training programs through trade schools or community colleges to develop a trained workforce familiar with 3DCP technology and materials.
- Support publicly funded 3DCP demonstration projects in partnership with state/federal organizations to increase the awareness of and demand for 3DCP technology.
- Consider the needs and benefits of 3DCP in ongoing and future studies of floating wind port infrastructure requirements.
- Conduct a more detailed study of the long-term job and economic benefits of 3DCP technologies.

With these actions, 3D concrete printing technology will reach the required technology and commercial readiness to help California reach its net zero carbon emissions goals while minimizing costs for ratepayers and maximizing economic benefits in the state.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
3D	three-dimensional
3DCP	three-dimensional concrete printing
ACI	American Concrete Institute
AEP_{net}	net annual energy production
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CapEx	capital expenditures
CO2 / CO_2	carbon dioxide
CO_2 eq.	carbon dioxide equivalent
EPIC	Electric Program Investment Charge
f'c	specified compressive strength
FEA	finite element analysis
FCR	fixed charge rate
FOCR	floating offshore wind
Fraunhofer IEE	Fraunhofer Institute for Energy Economics and Energy Systems
GW	gigawatt
GWP	global warming potential
Hz	Hertz
kg	kilogram
kN	kilonewton
kN/m^2	kilonewtons per square meter
kN/m^3	kilonewtons per cubic meter
ksi	kips per square inch (a unit of pressure equal to 1,000 pounds per square inch); kilopounds per square inch
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
LDES	long-duration energy storage
LRFD	load and resistance factor design
m	meter
mm	millimeter
MPa	megapascals

Term	Definition
MW	megawatt
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
OpEx	operational expenditures
R&D	research and development
RCAM	RCAM Technologies, Inc., DBA Sperra
RFA	recycled fine aggregate
SAM	System Advisor Model software
StEnSea	Stored Energy in the Sea technology
TRL	technology readiness level
UCI	University of California, Irvine
UCI 3DPC	three-dimensional printable concrete (developed at UCI)
W	watt

References

ACI Innovation Task Group 9. 2016. *Report on Design of Concrete Wind Turbine Towers.* ACI ITG-9R-16. American Concrete Institute, Farmington Hills, MI. Available at https://www.concrete.org/Portals/0/Files/PDF/Previews/ITG-9R-16_preview.pdf.

ASCE (American Society of Civil Engineers). 2017. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE Standard - ASCE/SEI 7-16).* ISBN: 0784414246. Available at https://sp360.asce.org/personifyebusiness/Merchandise/Product-Details/productId/233133882.

Blair, Nate, Nicholas DiOrio, Janine Freeman, Paul Gilman, Steven Janzou, Ty Neises, and Michael Wagner. 2018. "System Advisor Model (SAM) General Description (Version 2017.9.5)." National Renewable Energy Laboratory. Technical Report Number: NREL/TP-6A20-70414. Available at https://www.nrel.gov/docs/fy18osti/70414.pdf.

Bortolotti, Pietro, Nick Johnson, Nikhar J. Abbas, Evan Anderson, Ernesto Camarena, and Joshua Paquette. 2021. "Land-Based Wind Turbines with Flexible Rail-Transportable Blades – Part 1: Conceptual Design and Aeroservoelastic Performance." *Wind Energy Science* 6(5), 1277–1290. Available at https://doi.org/10.5194/wes-6-1277-2021.

Bowles, Joseph E. 1988. *Foundation Analysis and Design*. 5th ed. McGraw-Hill. ISBN: 0079122477. 1-1024.

CEC (California Energy Commission). 2023. "Electricity From Wind Energy Statistics and Data." Available at https://www.energy.ca.gov/media/7311.

Dick, Christian, Matthias Puchta, and Jochen Bard. 2021. "StEnSea – Results from the Pilot Test at Lake Constance." *Journal of Energy Storage*, 42, 103083. Available at https://doi.org/10.1016/j.est.2021.103083.

IEA (International Energy Agency). 2022. *Wind Electricity – Analysis.* International Energy Agency. Available at https://web.archive.org/web/20221024143914/https://www.iea.org/reports/wind-electricity.

Jones, Kathryn E.S., and Mo Li. 2023. "Life cycle assessment of ultra-tall wind turbine towers comparing concrete additive manufacturing to conventional manufacturing." *Journal of Cleaner Production*, 417, 137709. Available at https://doi.org/10.1016/j.jclepro.2023.137709.

NREL (National Renewable Energy Laboratory). 2015. "WINDExchange: U.S. Potential Wind Capacity Cumulative Area vs. Gross Capacity Factor." National Renewable Energy Laboratory). Available at https://windexchange.energy.gov/maps-data/327.

NREL. 2017. *NREL Offshore Balance-of-System Model*. National Renewable Energy Laboratory. NREL Publication Number: NREL/TP-6A20-66874. Available at https://research-hub.nrel.gov/en/publications/nrel-offshore-balance-of-system-model.

Puchta, M., J. Bard, C. Dick, D. Hau, B. Krautkremer, F. Thalemann, and H. Hahn. 2017. "Development and Testing of a Novel Offshore Pumped Storage Concept for Storing Energy at Sea – Stensea." *Journal of Energy Storage*, *On The Waterfront: Offshore and Seaside Energy Storage for Rapidly Growing Coastal Populations*, 14(Part 2), 271–275. Available at https://doi.org/10.1016/j.est.2017.06.004.

Wiser, Ryan, Mark Bolinger, Ben Hoen, Dev Millstein, Joe Rand, Galen Barbose, Naim Darghouth, Will Gorman, Seongeun Jeong, Andrew Mills, and Ben Paulos. 2021. *Land-Based Wind Market Report: 2021 Edition*. Report Number: DOE/GO-102021-5611. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Publication and Product Library, Washington, D.C.; Lawrence Berkeley National Lab, Berkeley, CA. Available at https://doi.org/10.2172/1818841.

Project Deliverables

The Project Deliverables are listed below:

Task 2: Conceptual and Preliminary Design of a 3DCP Tower and Foundation

- 2.1 Conceptual Tower Design Report
- 2.2 Conceptual Manufacturing and Assembly Plan Report
- 2.3 Turbine Scaling Study Report
- 2.4 Risk Management Report
- 2.5 Load Table for Basis of Design
- 2.6 Preliminary Tower and Foundation Design Report
- 2.7 LCOE Report

Task 3: Develop a Closed-loop Cycle Approach for a Next-generation 3DCP Tower

- 3.1 Final Economic and Environmental Life Cycle Assessment Report

Task 4: Laboratory Printing, Pilot-testing, and Analysis of a 3DCP Tall Tower Sub-assembly

- 4.1 3DCP Pilot Test, Demonstration, and Validation Report

Task 5: Outdoor Testing and Demonstration of On-site 3D Concrete Printing of Wind Energy Components

- 5.1 Outdoor On-site Demonstration Plan
- 5.2 Large-Scale On-site 3DCP Demonstration Report

Task 6: Feasibility Analysis and Concept Fabrication of Offshore Floating Wind Plant Components

- 6.1 Feasibility Analysis of 3DSA and 3DStEnSea Fabrication Concepts Report

Task 7: Development of 3DCP R&D, Education, and Supply Chain Capabilities in CA

- 7.1 3DCP Technical Report
- 7.2 3DCP Commercial Promotional Brochure and Webpage

All project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.