**Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference**

# EXPLORATION OF A CABLE-DRIVEN 3D PRINTER FOR CONCRETE TOWER STRUCTURES

Jesse J. Heineman*, Randall F. Lind*, Phillip C. Chesser*, Brian K. Post*, Alex M. Boulger*, Alex Roschli*, Lonnie J. Love*, Katherine T. Gaul*

*Oak Ridge National Laboratory, Manufacturing Demonstration Facility, 2350 Cherahala Blvd, Knoxville, TN 37932

## Abstract

Researchers at Oak Ridge National Laboratory's Manufacturing Research Demonstration Facility (MDF) are currently developing a cable-driven concrete additive manufacturing (AM) system called SKYBAAM. This system is a novel solution for 3D printing large structures using concrete. The current research focuses primarily on proof of concepts for the cable driven system, material selection, material pumping solutions, and the concrete extruder design. Looking forward from the success of the current research, this paper investigates the feasibility of using the SKYBAAM on a larger scale, specifically for extremely tall tower structures. The current system design presents challenges at a larger scale, and so the primary focus of this paper is to investigate new designs of a platform that would support large-scale SKYBAAM operations. Additionally, this paper will discuss the resulting deflections that can be expected due to machine operation and wind-loading. Excessive structural deflections could lead to loss of printing accuracy, or even a complete failure of the print, so it is important to establish that acceptable deflections can be reasonably achieved on these large-scale tower structures.

## Introduction

A novel solution for 3D printing large structures out of concrete is currently being developed at the MDF [1]. This cable-driven platform, called SKYBAAM, utilizes a mobile crane to support the extruder above the workspace, and four cable tension stations that are located on the ground to control the movements of the extruder in the X, Y, and Z directions. The original vision for SKYBAAM is presented here (Figure 1), as well as the layout of a mid-scale prototype system that is currently being used at the MDF (Figure 2).

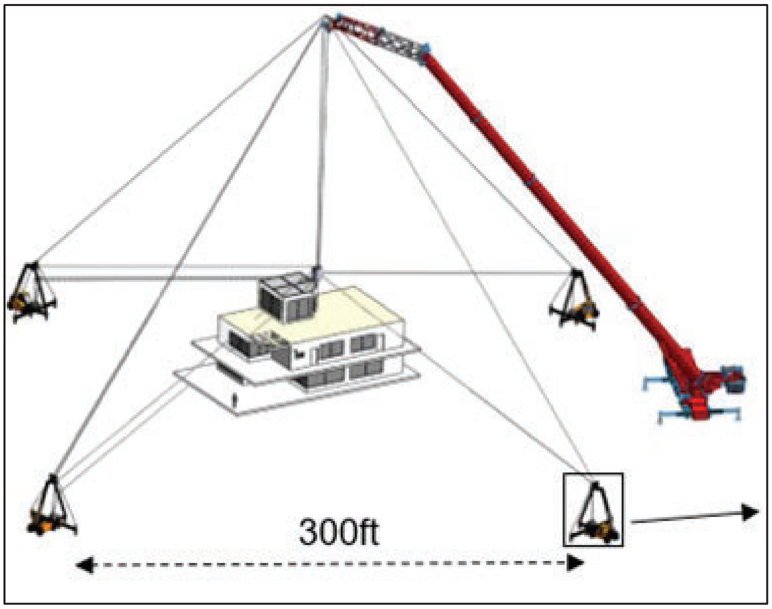


*Figure 1: Potential Application for SKYBAAM*

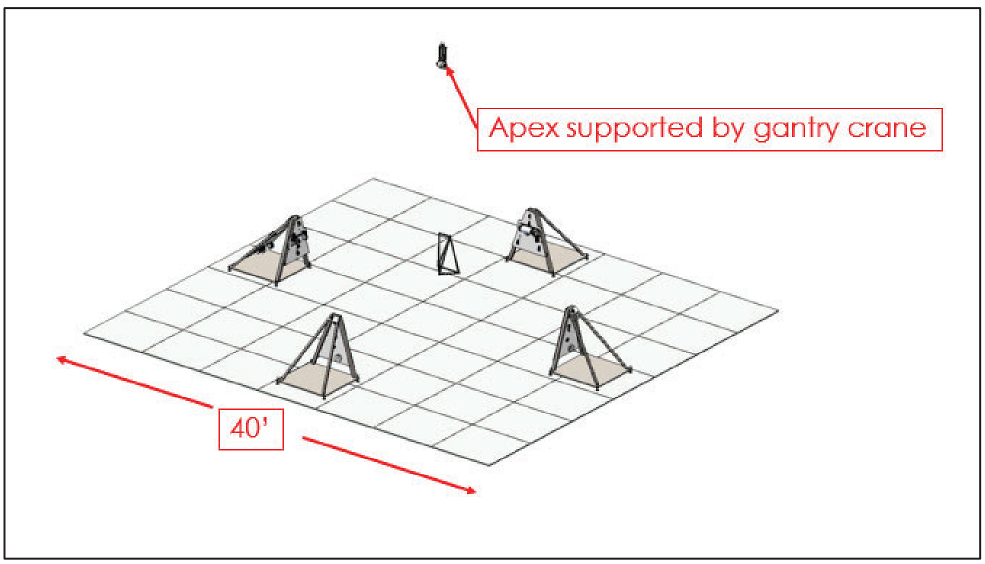


*Figure 2: Mid-Scale Prototype Platform at the MDF*

In order to maintain stiffness in the X and Y directions and to keep the requisite crane loads to a reasonable level, the SKYBAAM architecture requires minimizing the cable angles from the cable tension stations to the extruder. However, minimizing this angle causes the overall footprint of the workspace to grow in the XY plane, and results in workspaces that are several times larger than the height of the structure being printed. Scaling the current SKYBAAM platform up to a scale large enough to fabricate a tower structures in excess of 200 feet would require a very wide footprint, which would likely not be practical for most jobsites. In addition, a very large workspace footprint would necessarily require excessively long cables to connect the tension stations to the extruder. These longer cables would also need to be much thicker and maintain much higher tensions to keep the system stiffness to an acceptable level.

The higher cable tensions would lead to higher loading requirements for the mobile crane supporting the extruder, as well as higher power requirements from the cable tension stations. This paper will explore a new application for the SKYBAAM system that could be used to manufacture tower structures while reducing the workspace footprint, minimizing cable deflections, and reducing the cable station loading requirements compared to the traditional SKYBAAM arrangement.

## SKYBAAM for Tower Structures

The basic design concept of SKYBAAM system has been preserved, with the primary difference being the implementation of a superstructure that supports the weight of the extruder instead of a mobile crane. In addition, the cable tension stations would be mounted to the legs of the superstructure and would travel upward during a build instead of remaining stationary on the ground (Figure 3). This concept allows for a much smaller workspace footprint, which means that the cable lengths will be much shorter, which in turn will help minimize the cable deflections and tension station power requirements. However, with this design, there will also be deflections of the tripod structure due to print head movements and wind loading. The primary focus of this paper is to ensure that we can reasonably achieve small enough structural deflections to maintain high print accuracy with this type of superstructure.

The primary superstructure design that was investigated was a tripod-like structure, with each of the legs made from a square-profile truss beam. Two different types of tripod structures were analyzed. In each case, the dimensions of the leg truss structure and the sizes of the main load-carrying elements were optimized to achieve roughly 1/8 in. deflection due to the variable print head loads and roughly ½ in. deflection due to an evenly distributed 30mph wind load. All the following structural analysis was performed in SOLIDWORKS simulation.

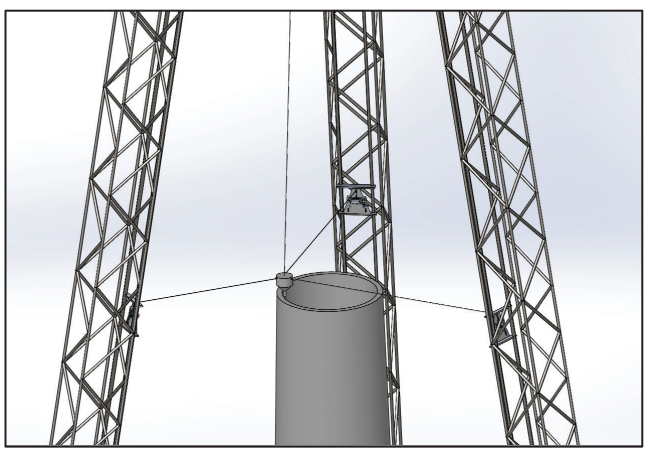

*Figure 3: Tension Station Arrangement*

## Angled tripod legs

The first type of tripod structure that was analyzed was made up of angled tripod legs that are spread out at the base and meet at a single point at the apex (Figure 4). The resulting optimized truss size for this design was a 72” square profile made up of 4” x 3.5” round tubes as the main structural elements. The overall weight for this type of structure is approximately 100,000lb.

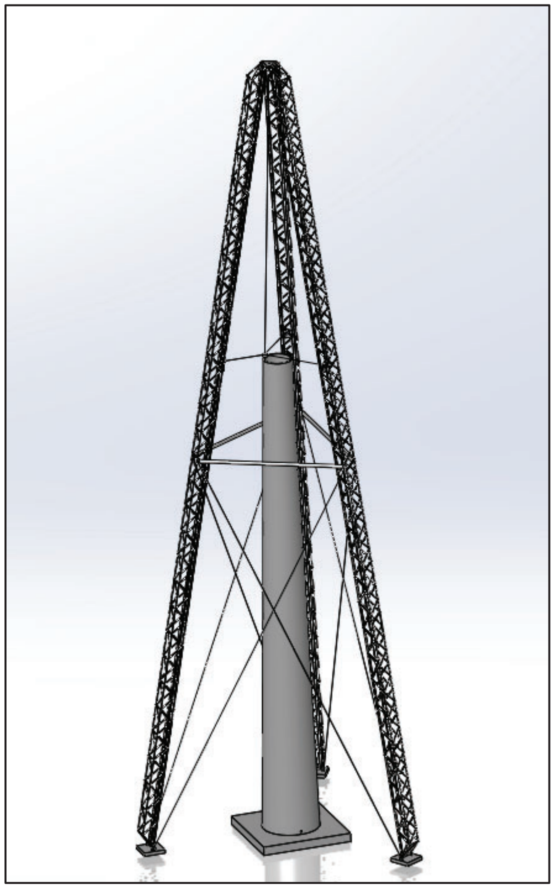

*Figure 4: Angled Leg Tripod Structure*

Deflection due to gravity

This type of design requires long truss legs to achieve the required clearance above the printed part due to the angle of the truss legs. In addition, due to the angle of the legs, there is a component of gravity acting perpendicular to the truss leg, which causes a static deflection as shown in Figure 5.

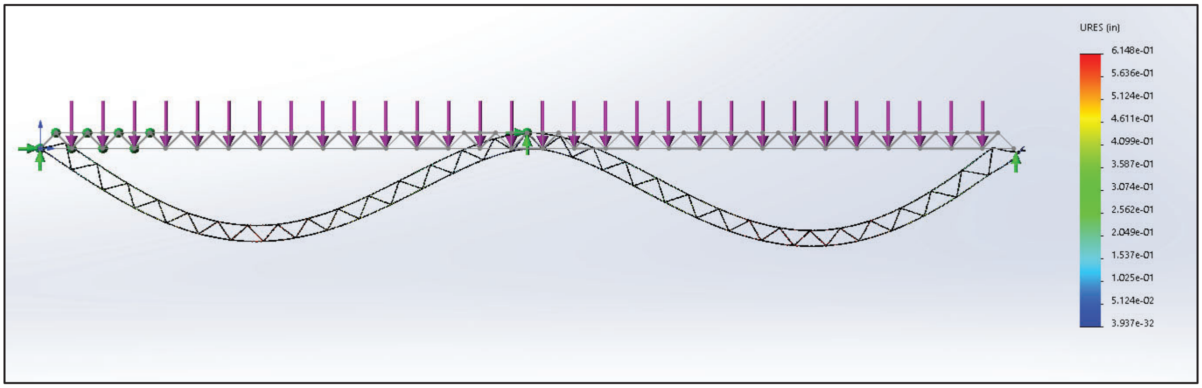


*Figure 5: Deflection of Angled Leg Truss Due to Gravity*

<u>Deflection due to combined loads</u>

The maximum load acting on a truss leg is composed of gravity, the acceleration of the print head, and tension from the opposing tension stations. The geometry of each of the loads was analyzed to determine the components that act perpendicular to the truss leg, which were used for the simulation. The print head loads were applied mid-way between supports to simulate the maximum deflection situation. The deflection is shown in Figure 5.

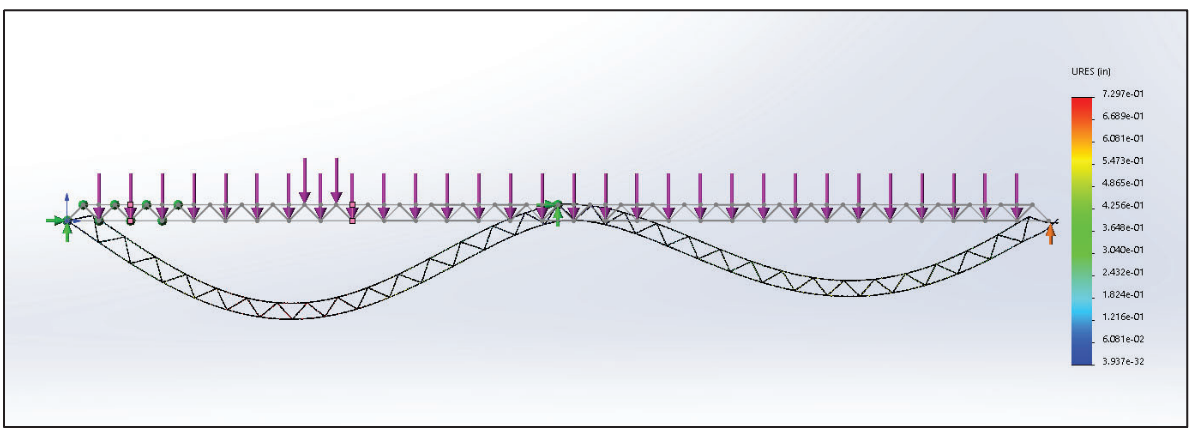


*Figure 6: Deflection of Angled Truss Leg Due to Combined Loads*

<u>Deflection due to print head loads</u>

The static components of the deflection can be easily predicted and managed, so it is the varying loads due to the print head movements that we are primarily interested in. These movements can be variable during a build cycle and are not as easy to manage. The variable deflections can be calculated by subtracting the static gravitational forces from the total deflection due to the combined loading. The maximum deflection for this structure is shown to be within desired range of approximately 1/8" (0.73"[Figure 5] – 0.61"[Figure 6] = 0.12").

<u>Deflection of angled leg tripod structure due to wind loads</u>

Deflections from the wind loading simulation are shown in Figure 7, with the maximum deflection of 0.36" occurring at the top of the tower. A more meaningful deflection location would be at approximately 3/4 height, where the maximum build height would occur. This location has a deflection closer to 1/4", which is within the desired range of 1/2".

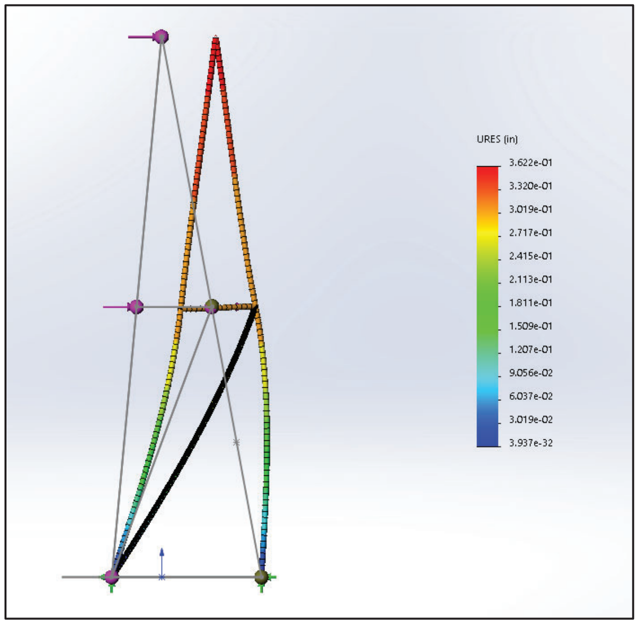


*Figure 7: Deflection of Angled Leg Tripod Structure Due to Wind Load*

## **Vertical tripod legs**

The second type of tripod structure that was analyzed included a large roof structure at the top, which allows the truss legs to be shorter and completely vertical as shown in Figure 8. The optimized truss size for this design was a 36" square profile made up of 3" x 2.5" round tubes as the main structural elements. The overall weight for this type of structure is approximately 60,000lb.

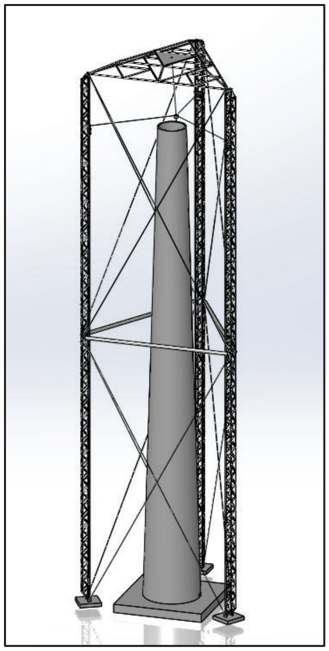

*Figure 8: Vertical Leg Tripod Structure*

Deflection due to print head loads

The print head loads were applied mid-way between supports to simulate the maximum deflection situation (Figure 9). The maximum deflection is shown to be 0.13", which is very close to the target value of 1/8".

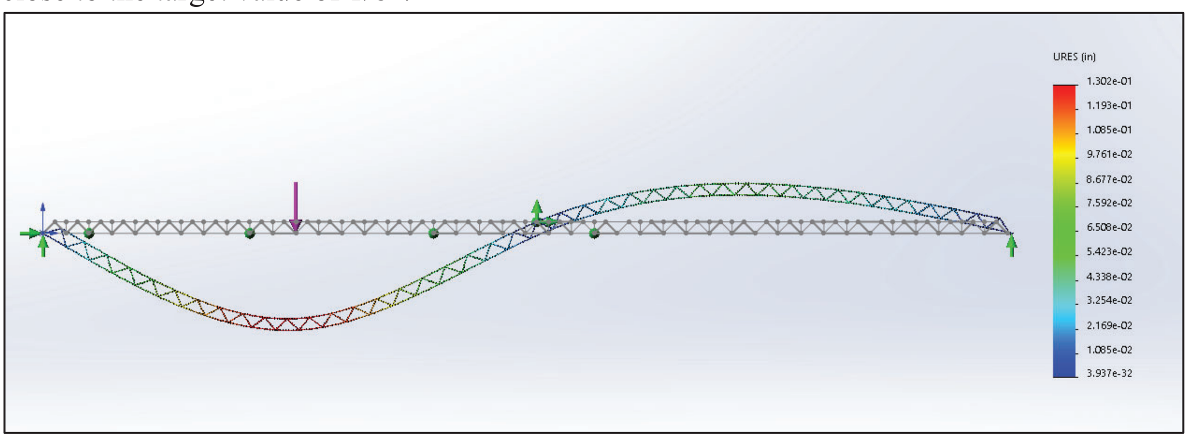


*Figure 9: Deflection of Vertical Leg Truss Structure Due to Print Head Loads*

Deflection due to wind load

Deflections from the wind loading simulation are shown in Figure 10, with the maximum deflection of 0.54" occurring at the top of the tower. A more meaningful deflection location would be slightly below the top of the tower, where the maximum build height would occur. This location has a deflection closer to 0.45", which is within the desired range of 1/2".

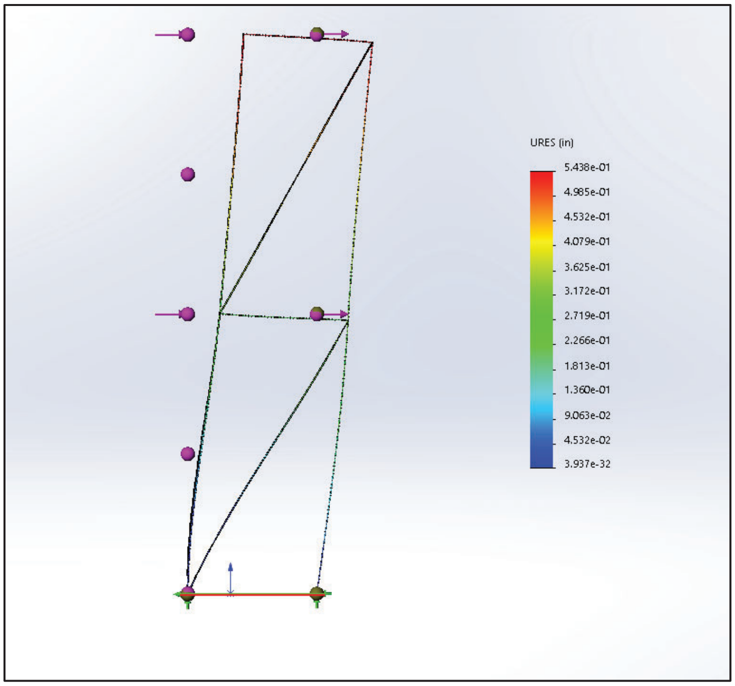


*Figure 10: Deflection of Vertical Leg Tripod Structure Due to Wind Load*

## Conclusion

Both types of structures have achieved our target deflection values for both print head and wind loads. The angled tripod structure has fewer components and a simpler assembly which could have a relatively lower installation time and cost. However, it would require a taller and higher capacity crane. On the other hand, the vertical tripod structure has a significantly lower weight but requires more tensioning elements between the truss legs, which could increase the installation time and cost. Further analysis should be performed to compare the installation costs of each type of structure, as well as any other jobsite logistics to help guide the future design of these structures.

## References

[1] Chesser, P., Post, B., Roschli, A., Lind, R., Boulger, A., Love, L., Gaul, K., Fieldable Platform for Large-Scale Deposition of Concrete Structures. Solid Freeform Fabrication Symposium. Austin, TX, 2018.