AMIE 1.0:
Design of the Carbon Fiber Reinforced ABS Structure

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August 11th, 2015

Introduction

AMIE 1.0 is a demonstration project of a small building that uses Additive Manufacturing (3D printing) for the structure and enclosure along with Integrated Energy systems. The demonstration project was a joint effort by Oak Ridge National Laboratory (ORNL), Skidmore Owings & Merrill (SOM), Clayton Homes, General Electric, Alcoa, Nanopore, and Trudesign. The unique challenges presented by this project required each partner to share their knowledge and skillset, working together to find new solutions. This paper discusses the challenges associated with the 3D printed structure designed by ORNL and SOM. The design process relied on the materials science, 3D printing knowledge, and 3D printing capabilities of ORNL along with the building application, systems innovation, and project delivery experience of SOM.

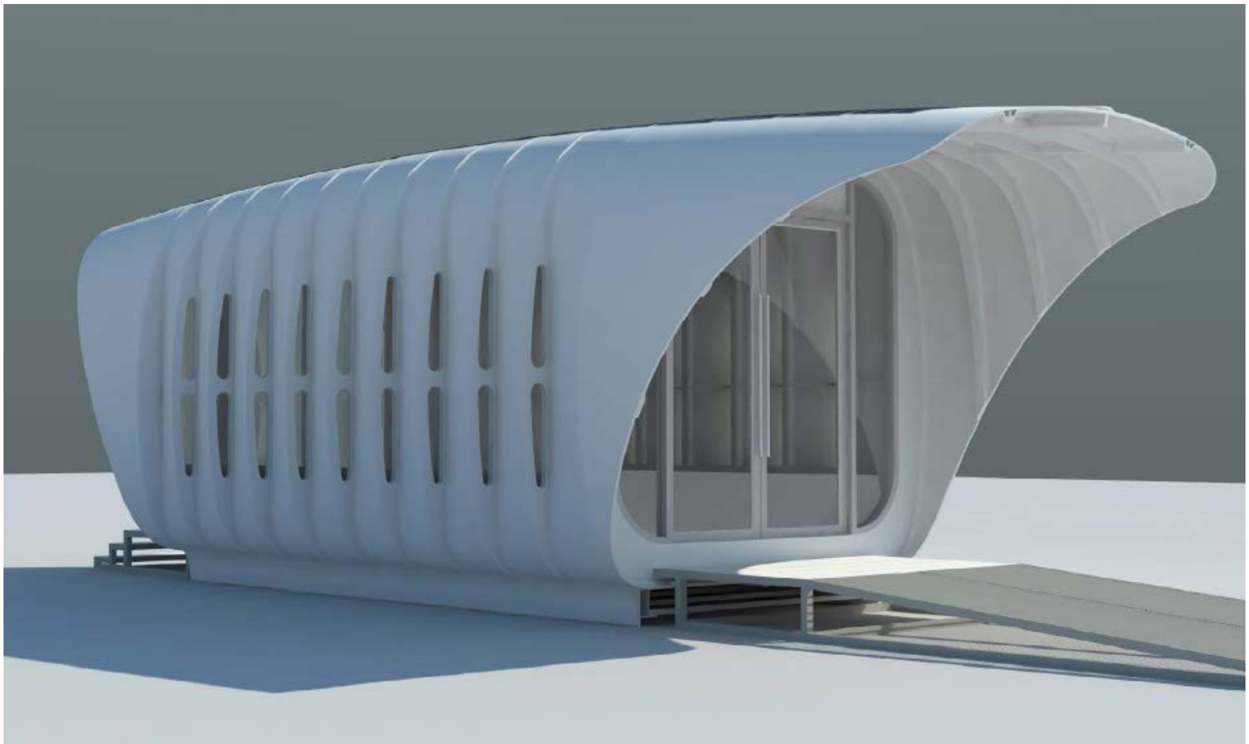

Figure 1: AMIE 1.0 Rendering

Material Properties

Additive manufacturing, or 3D printing, can use a variety of materials including plastics, concretes, and metals. For a structure of this size and with this print resolution, reinforced plastics make the most sense from a cost and performance perspective. Several materials were considered during the design process including glass and carbon fiber reinforced ABS plastic. The final material selection was a carbon fiber reinforced ABS plastic with approximately 20% of the material consisting of carbon fiber. The material properties of this type of material are provided below.

This material presents a number of engineering challenges not typically part of a building design. The material is highly anisotropic due to the printing process, which creates a “grain” to the material similar to wood. The direction “parallel to the grain” is referred to as the X and Y direction of the material. The direction “perpendicular to the grain” is referred to as the Z direction of the material. The material is 5 times stronger when loaded parallel to the grain and also more ductile. Loading the material in the Z direction is much less stiff and strong and is also prone to brittle cracking failures. Other factors to consider are the creep of the material which causes long term deflections as well as differential coefficients of the thermal expansion which can be 10 times more expansive than concrete or steel. Each of these aspects were considered in the design, resulting in the unique approach of the AMIE structure.

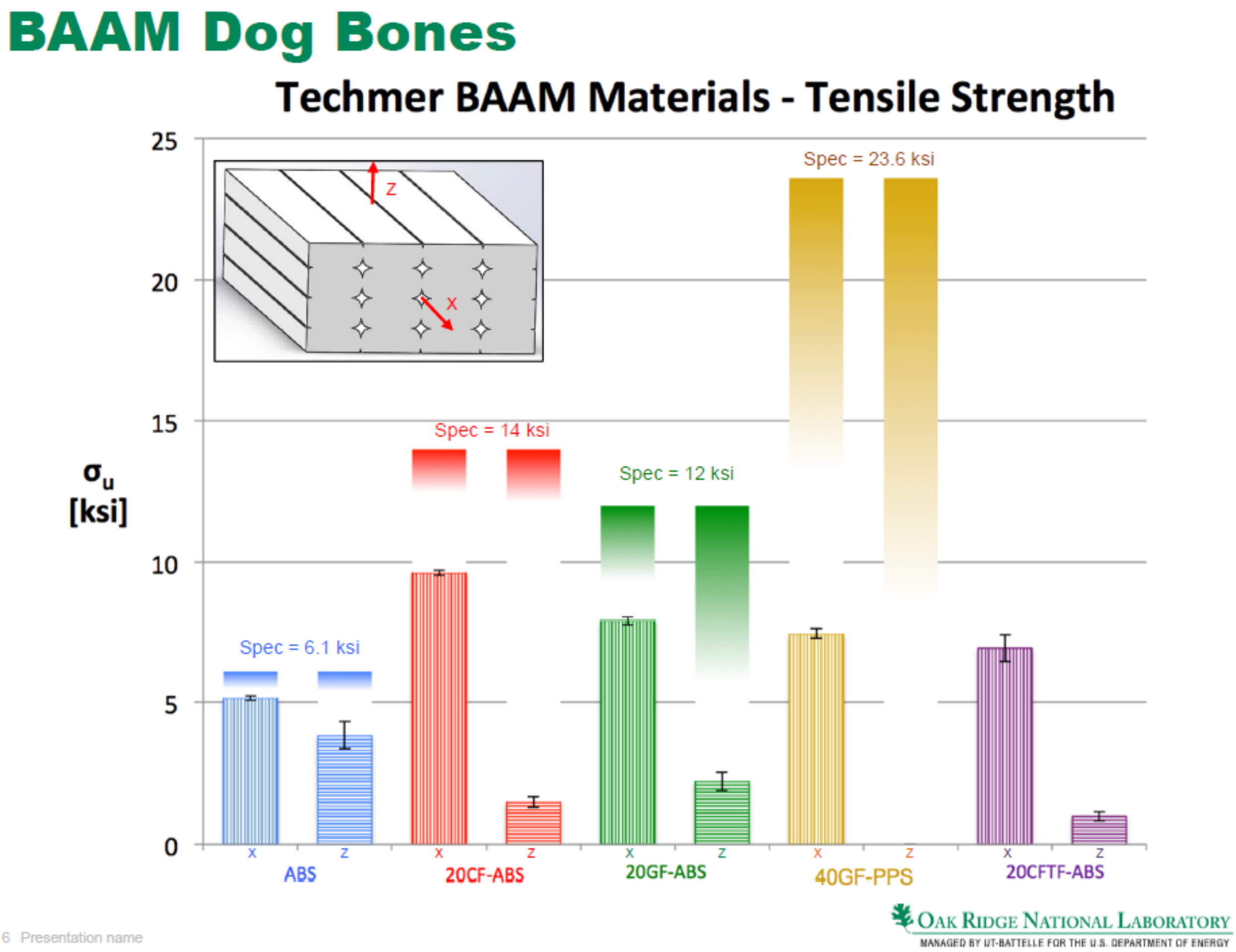
BAAM Dog Bones

Figure 2: Material Data provided by ORNL

AMIE 1.0 Structural Description

The structure of building can best be described as “channels and rings”. The size limits of the 3D printing bed required the building cross section to be printed in at least two prints. The design team chose to locate the joints between prints along the center of the building with one connection at the roof and one at the floor. Once connected, the two “channels” would form a 2ft wide “ring” of the building cross section. The building would then be assembled by connecting the 10 building rings and 8 canopy rings.

This approach was chosen by the design team for several reasons. First, printing the building in cross section allows the spanning elements of the building (roof trusses and floor joists) to be loaded primarily in the strong parallel to grain direction. Once the printing turns to the walls, the grains are oriented vertically to support gravity loads. The continuous nature of the floor, wall, and roof prints also create a moment frame which gives the building stability and resists wind loads.

The 2ft wide ring dimension was also a product of the constraints of the 3D printer. The machine selected to print a structure of this size was not able to also print “support material” which can allow for more complex shapes. Without the ability to print support material, the maximum angle that could be printed relative to the Z axis was 45 degrees, as confirmed by unsuccessful test prints. This constraint required the structure to be printed with the joists and trusses as the bottom of the print, followed by the walls of the building. The print would then be terminated at the next joist as the required angle was 90 degrees. The joist spacing of 2ft on center then caused each ring to be 2ft wide.

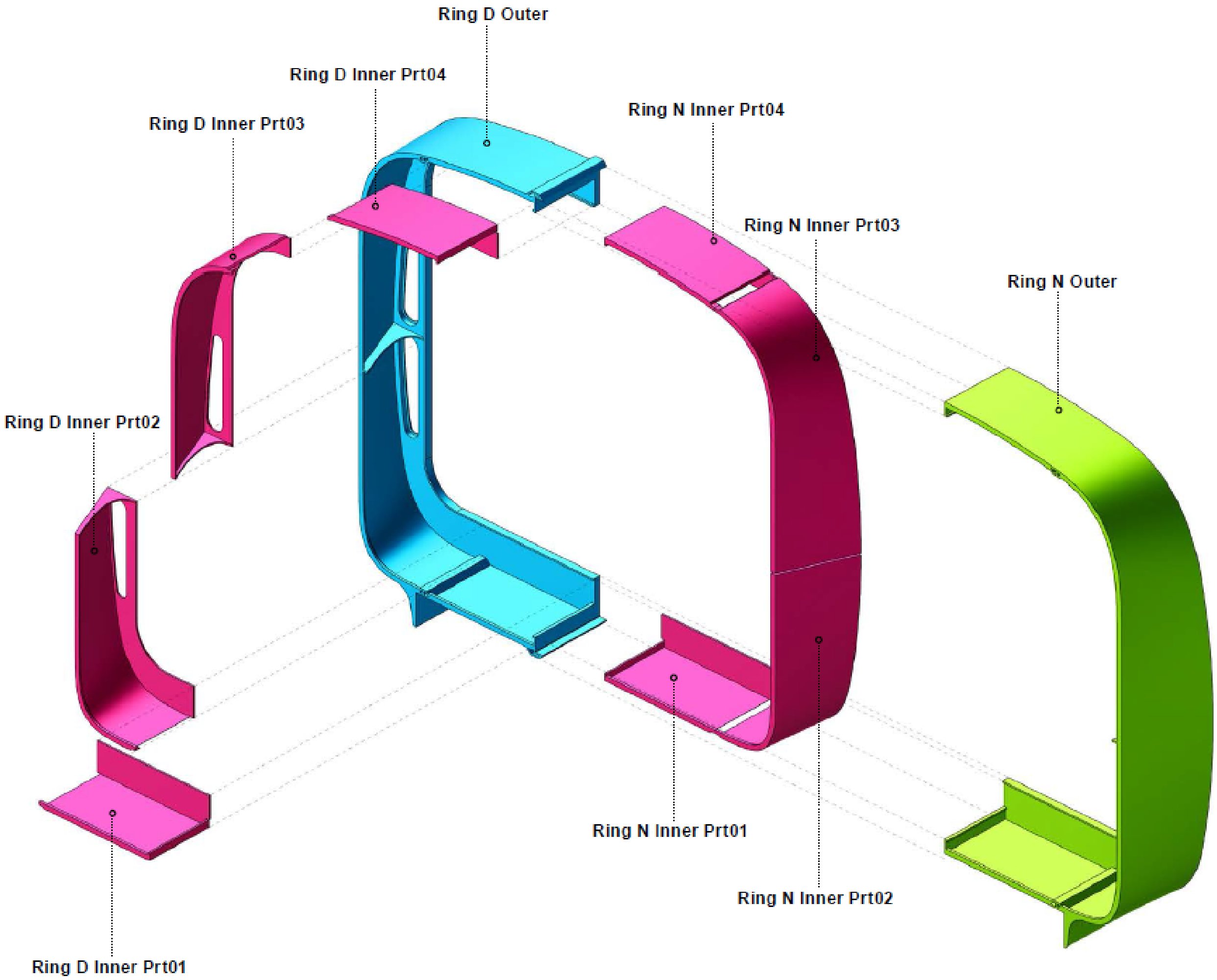

Figure 3: Individual 3D printed elements of the building

Main Structure Design

The structure of the main portion of the building was generally controlled by practical printing dimensions and minimum sizing for architectural coordination, due to the high strength (10,000psi) nature of the material. This also allowed the structure to be eroded at certain locations to showcase the abilities of the 3D printer, such as the roof “trusses”. The roof members are designed as a tied-arch structure. The top of the roof is designed to span gravity, snow, and rain loads to the side walls through compression arching. The bottom of the arch must be tied to avoid bending the walls outward from the trust. The bottom ABS tie is stressed parallel to the grain and is capable of resisting this load. The challenge of this system is the practical location of the 3D print splice in the middle of the roof. This connection was expected to be the weak point of the roof structure and so the print was enlarged to the full section depth to allow for a strong channel to channel connection. This connection was initially conceived to be a lapped ABS connection but was later revised to a side plate bolted connection for assembly purposes. The connection was sized based on first engineering principles and then tested by ORNL to confirm adequacy, given that there is no recognized standard for this application.

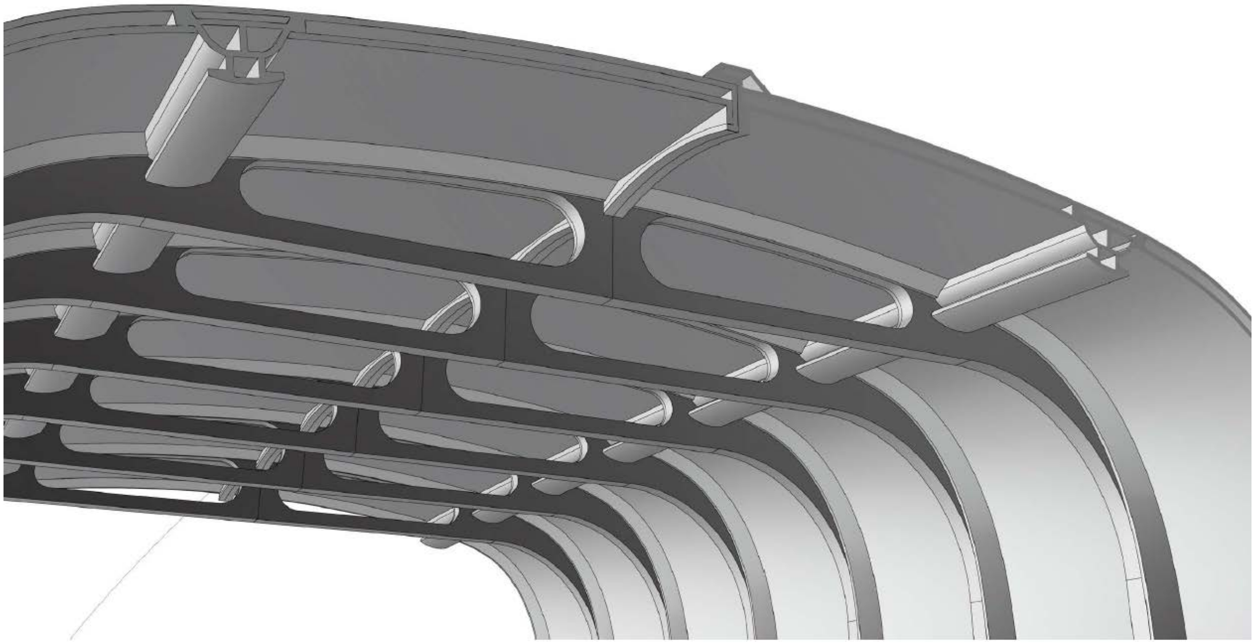

Figure 4: Roof Truss Rendering

Canopy Design

The main building structure was designed to avoid Z direction loads as it is less strong and less reliable in service. However, loading in the Z direction could not be avoided for the canopy structure which cantilevers from the building, causing a Z direction tension along the roof of the canopy. This type of loading is prone to cracking due to the tension in service. The design team studied this problem and applied a solution found in buildings to mitigate tension cracking: post tensioning. The design team suggested installing 4 post tensioning rods, one per corner of the building, which would pre-compress the building and reduce the potential for Z direction cracking. The sleeves for the PT tendons were then integrated with the 3D printed structure and expressed on the interior.

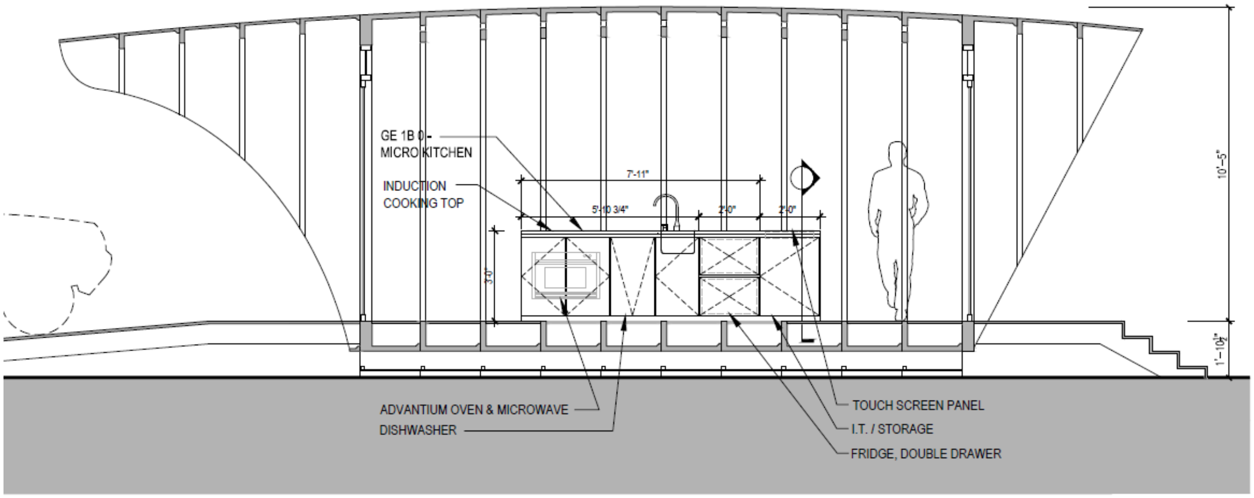

Figure 5: Section Showing Cantilevered Canopy

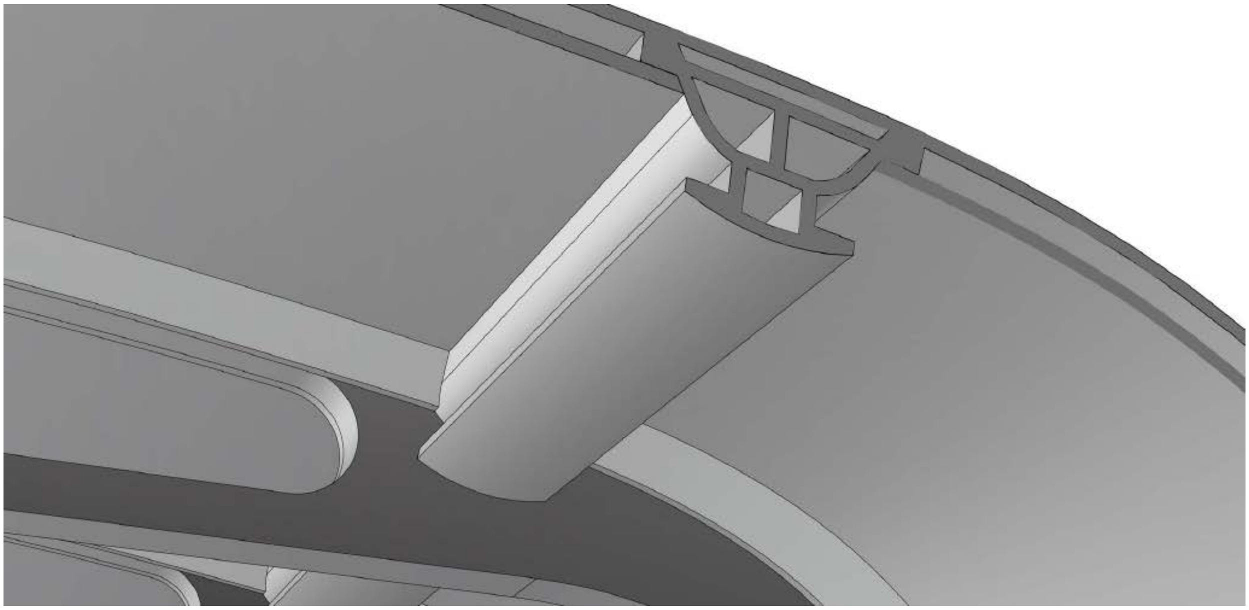

Figure 6: Rendering of Post-Tensioning Sleeve.

Thermal Load Design

The demonstration building will be exposed to atmospheric temperature fluctuations. Due to the high coefficient of thermal expansion in the Z direction for this material, it is predicted that the building could grow and shrink up to ½” in service. If the building is restrained against this movement it will surely cause significant Z direction cracking even with the provided post tensioning. The design team solved this issue two ways. First, the connections of AMIE to the steel support chassis are designed to be sliding connections with the exception of several fixed connection near the center of the building. These connections allow AMIE to slide along the chassis, relieving the thermal stresses. The base connection developed by ORNL and SOM is shown below in Figure 7.

The second modification is the end connections of the PT tendons. The thermal movements of AMIE would cause the pretension in the rods to be lost in service (go slack). If this were to happen, the benefit of the pre-compression in the Z direction would be lost. This challenge was overcome by providing a “spring box” on each end of the tension rod that would allow the tension to be held even under the design movements. This spring assembly is shown below in Figure 8.

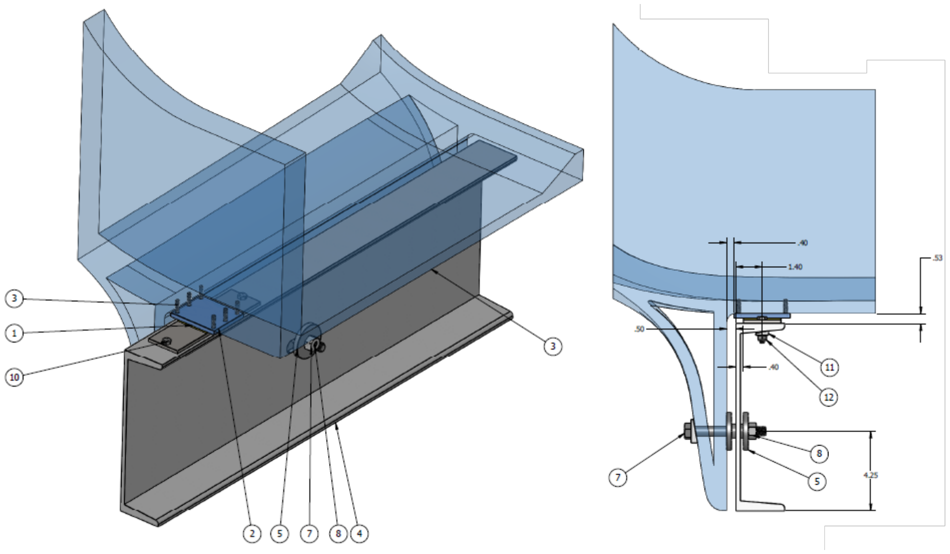

Figure 7: Slide Bearing Details

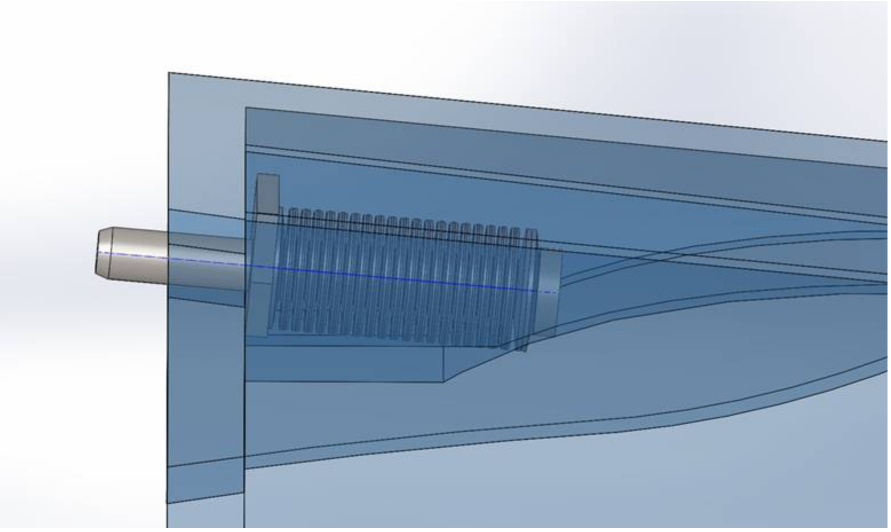

Figure 8: Tension Rod Spring Assembly

Testing and Verification Program

There is little information available for the design of an ABS structure at the building scale. Accordingly, engineering first principles had to be used in order to size the elements and connections. However, because this building will be occupied by the public, a more detailed verification was necessary. For this reason, SOM recommended that ORNL perform full scale destructive testing on the major components and connections of AMIE. This included the roof truss assembly, floor joist assembly, and chassis connections. Each of these tests showed that the capacity of the structure was 4 to 8 times stronger that what will be required in service. These factors of safety were considered to be appropriate given the unprecedented nature of the project:

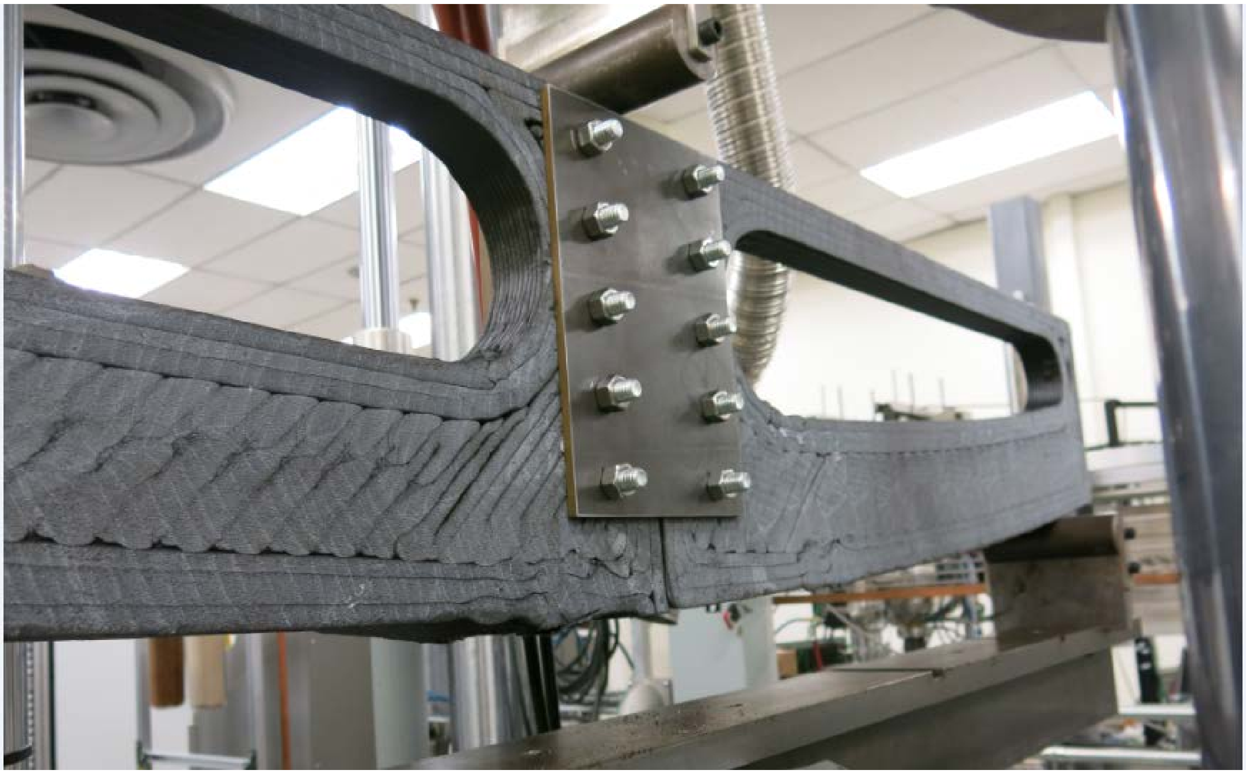

Figure 9: Successful Three Point Bending Test of Roof Assembly

Conclusions

Cutting edge materials and processes will create new challenges for designers in the future. This project shows how practical knowledge can be applied to a new material in order to develop credible building structures. The key to the success of this and other technologies moving forward is the development of solutions which work with the materials chosen, instead of forcing pre-conceived solutions on materials which may not be suitable for the application.