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Algorithmic Design for 3D Printing at Building Scale

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ABSTRACT: *This paper addresses the use of algorithmic design paired with additive manufacturing and their potential impact on architectural design and fabrication of a full-sized building, as demonstrated with the AMIE project. AMIE (Additive Manufacturing and Integrated Energy) was collaboration to 3d print a building and vehicle. Both the car and building were designed to generate, store and share energy in an effort to reduce or eliminate reliability on the power grid. This paper is intended to outline our methodology in successfully designing for these innovative strategies, with a focus on the use of computational design tools as a catalyst for design optimization, integrated project delivery, rapid prototyping and fabrication of building elements using additive manufacturing.*

KEYWORDS – *AMIE, ADDITIVE MANUFACTURING, 3D PRINTING, ABS, BAAM*

Fig. (1): Rendering of AMIE enclosure concept design and PUV (Printed Utility Vehicle)

1 INTRODUCTION

The AMIE (Additively Manufactured Integrated Energy) demonstration project was the result of a broad collaboration between members of national labs, design industry and academia. It was these partnerships that ultimately made AMIE possible, given the wide range of expertise and resources required to realize a project with this magnitude.

The AMIE demonstration project, shown in Fig. 1, utilizes additive manufacturing to connect a natural-gas-powered hybrid electric vehicle to a high-performance building enclosure designed to produce, consume, and store renewable energy. All components of the demonstration were designed, tested, built, and assembled in nine months. Components of the building and vehicle were additively manufactured (3D printed). The vehicle's natural gas engine provides complementary power to the building. The photovoltaic panels on the building's roof harvest solar energy that can be stored and shared with the vehicle. The vehicle performs the same function for the home. This symbiotic concept enhances the resiliency of the residential grid, decreasing peak demand and allows a home to leave the grid entirely when needed.

The use of additive manufacturing or 3D printing at full scale in architecture application is still at a very nascent stage. While there are other efforts to explore these areas of rapid prototyping of building construction using traditional materials like concrete, the work presented in the paper focuses on printing using ABS material similar to desktop 3D printers with one major limitation. The system used during this research doesn't allow for printing overhang parts since BAAM (Big Area Additive Manufacturing) does not use additional support material that would allow for this. The rest of the paper focuses on the advanced modeling techniques, geometry optimization used during the design of the enclosure and the assembly process of AMIE.

2 WHY ALGORITHMIC MODELING?

Algorithmic modeling provides designers with new ways to experiment with their models at various design stages. Some key features of algorithmic or script-based modeling include the ability to generate forms parametrically, obtaining forms of great complexity from simple shapes, rapidly adapting major changes in the model, and creating multiple iterations of the design to quickly be tested and 3D-printed. Together, these features render algorithmic modeling an ideal design technique for additive manufacturing and rapid prototyping.

3 ENCLOSURE DESIGN AND ASSEMBLY

AMIE is a single-room building unit that was designed to showcase the capabilities of additive manufacturing and its application in high performance buildings. The design integrates low cost vacuum insulated panels that are sandwiched between two layers of a 3D printed shell. The structure was 3D printed using the Big Area Additive Manufacturing (BAAM) technology (Holshouser et al., 2013). BAAM technology enables rapid production of sturdy, lightweight composite parts that are 5 times stronger than wood.

The building exterior shell was designed as a series of 10 rings. The width of each ring is 2ft which is driven by the maximum size of the vacuum insulated panels. Also by keeping the ring width relatively small reduced the weight of each ring for the final assembly. The overall dimension of the enclosure is L 10.9m (36ft) x W 3.6m (12ft) x H 4.2m (14ft). AMIE design team tried to utilize the capabilities of the BAAM by creating a 3D printed panel system that incorporate all the elements of a wall sandwich including structure, insulation, air and moisture barriers, and exterior and interior cladding into one vertically integrated building shell. This approach allowed for efficient use of the material. The BAAM system also allowed for easily printing doubly curved surfaces without the need of a custom mold for each unique ring not only for aesthetics, but also the curved surfaces reduce localized stresses on the exterior (Fig. 2).

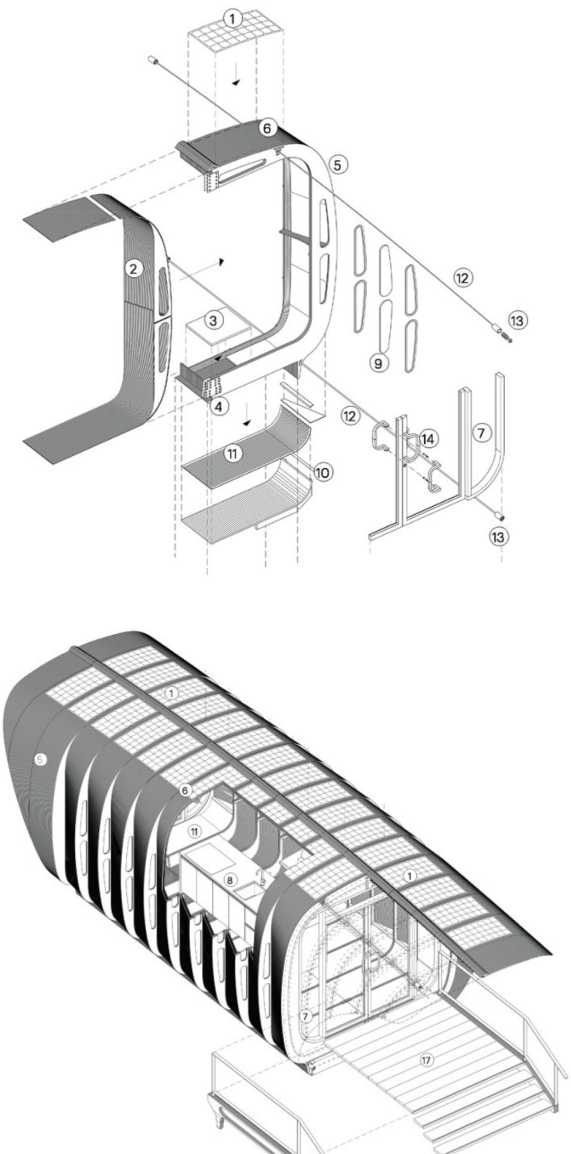


Fig. (2): Top: Master ring components.
Bottom: Assembly diagram

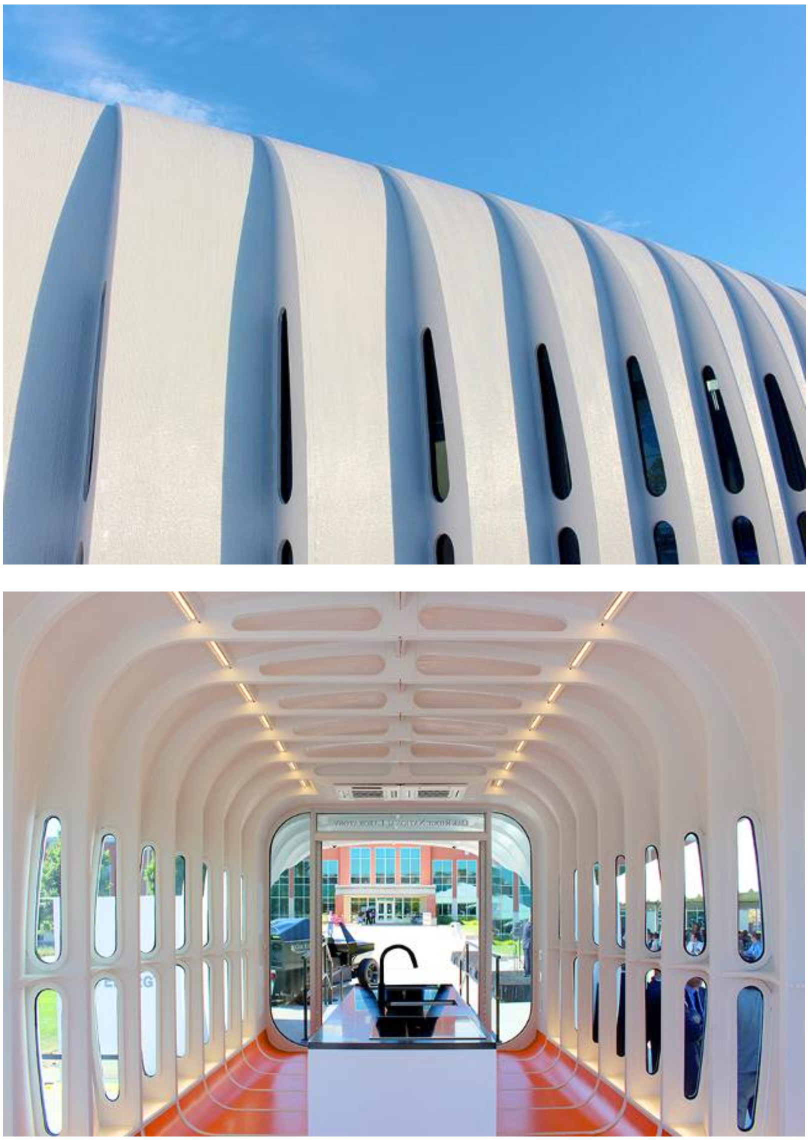


Fig. (3): Top: Joined rings from exterior; Bottom: Rings from interior.

The printing was done a half ring at a time in C-shapes which were then combined to form the full-ring and joined with a steel plate. 80 percent of the enclosure was 3D printed with carbon fiber-reinforced acrylonitrile butadiene styrene (ABS) plastic composite material using the BAAM system.

The printed half-rings were designed to standardize non 3D printed component such as the glazing. While each ring is unique as the result of the overall doubly curved surface that the main geometry was created from the, tear drop opening on the gills are all exactly the same size. At the same time, despite the small size of each side window, when combined together it floods the interior with natural indirect light. This also allowed the majority of the exterior wall to remain opaque and insulated, achieving a total overall window/wall ratio of under 20%. The angled opening gills created visual phenomena in the interior where the user experiences the space differently based on the point of entry (Fig.3).

During the design process two major constraints of the BAAM printer were considered. The first was the structural weakness of the printed parts in the z-direction. In the method of printing used, layers of ABS were deposited in the plane of the printing bed, the x-y plane. Subsequent layers were printed directly on top of this, building the form in the z-direction through layers of print. As consecutive layers of ABS were built up, as seen in Fig. 4 and 5, the structural characteristics of the printed form proved to be stronger in the x-y plane than in the stacked z direction. This was due to the partial cooling of the material between each printed layer after it was initially deposited. To capitalize on this inherent x-y strength, the team printed the structural rings on their side, parallel with the x-y plane of the print bed, thus leveraging the strength of the x-y direction once the ring was tipped up and used to distribute loading and lateral forces in the final building. Additionally, to prevent any separation of the layers in the z-direction, the structural team used a post-tensioned steel rod running the full length of the building to keep the rings and the 3D printed layers in constant compression (Fig. 9).

The second constraint was that the BAAM system does not include any secondary support material deposition for the part. This doesn't allow printing any overhang parts or undercut in the model. The team experimented with different build up angles that can allow the extruder to print partial overhang pieces especially at the joint rim between each ring. Later the team realized that if any traveling angle made by the extruder are greater than 40 degrees, the print layers start to sag and result in a failed print. This constraint dictated the angle of elements such as the exterior shell detail (Fig. 4).

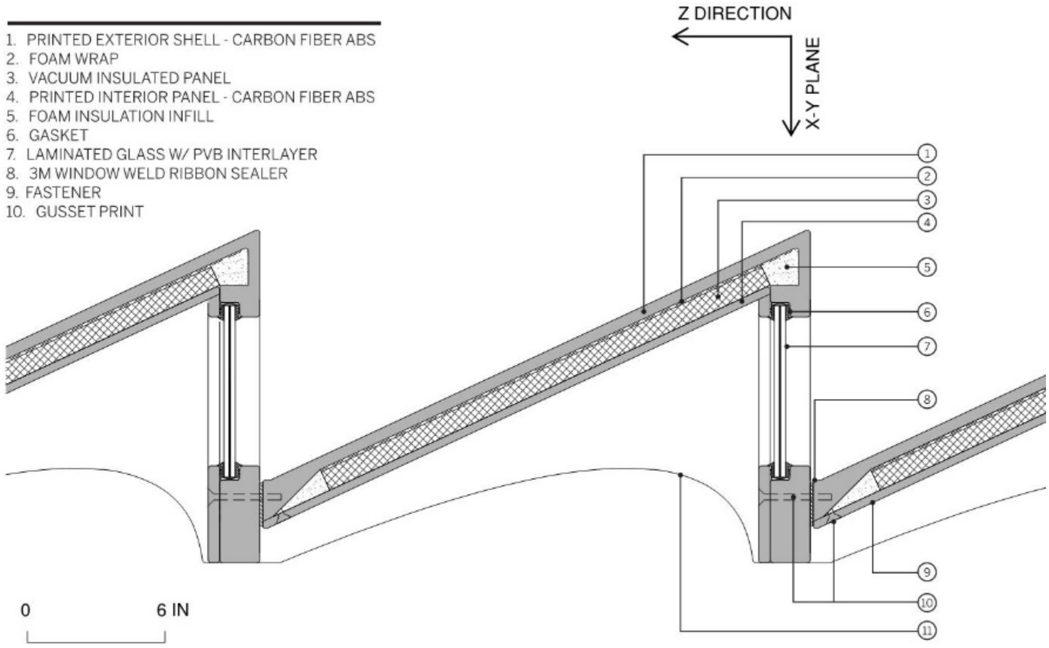


Fig. (4): Plan detail of ring connection and glazing.

The use of rapid prototyping and the direct design to print approach enabled flexibility/power in design by removing constraints of traditional methods. The total weight of the printed enclosure is approximately 13,500 lbs. At a rate of 60 lb/hr, the total print time was estimated to be four weeks: 13,500 lbs. * 60 lb/hr = 225+ hrs., not including machine setup time, etc. Fig. 5 shows the printing of the ABS rings and Fig. 6 shows the process of exterior rings assembly.

Fig. (5): Left: Printing ABS layers; Right: Printing one of the AMIE rings on the BAAM.

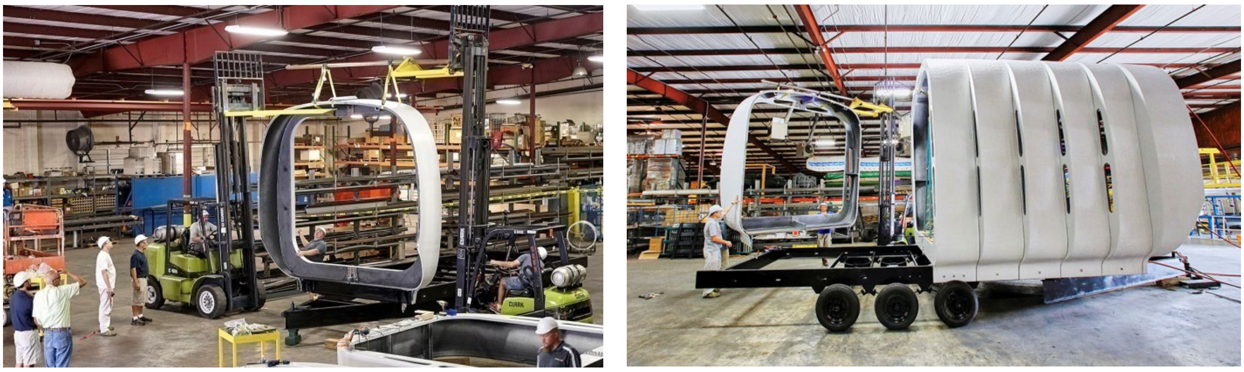


Fig. (6): The assembly of the AMIE enclosure.

3.1 THE NECESSITY FOR A HIGHLY DETAILED MODEL

Traditional modeling techniques do not allow incorporation of all the details in the master model. For example, the details of an extruded aluminum section of a curtain wall panel frame are often drafted in the detail views only since they are mainly used for reference, not for fabrication. The manufacturers then have to create their own version of the shop drawings of the model for the fabrication of the actual parts. However, in AMIE every single detail required for the final assembly was included in the design of the model since the master ring model combines all the elements of a standard wall sandwich into a single part. This eliminates the need for assembly of smaller parts. The algorithmic definition was designed to break down the model into smaller sections allowing maximum flexibility of the model throughout the design process.

This part-to-whole connection allows for easy referencing of smaller sections to the entire model. This approach also made it possible to include all the necessary connections needed for the final assembly. Such subdivision of the hierarchy of the definition allowed for achieving this while maintaining a significantly small file size of the model that can be easily tracked down for any errors that may occur in the definition (Fig. 7).

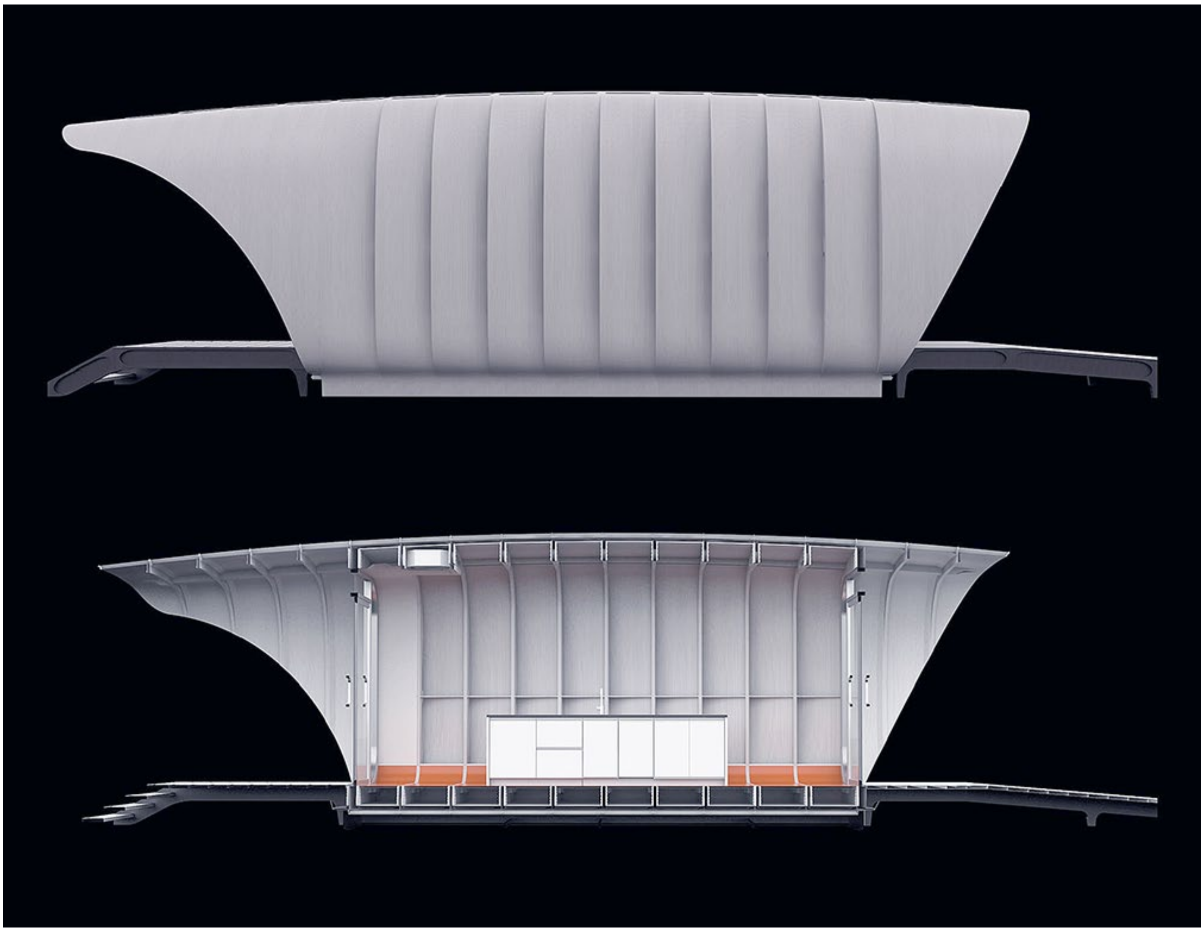


Fig. (7): Top: Rendered elevation of the 3D model. Bottom: Rendered section of the model including all the details needed for the final assembly.

3.2 A WATERTIGHT MODEL

One of the main goals of the research was to use the final design to test the 3D-printing capabilities of the BAAM. Therefore, the design team set up the model in such a way that ensured a constant check for naked and non-manifold edges. This also ensured that the model was "watertight" throughout every stage of the design process and ready for immediate 3D-printing at any point (Fig. 8).

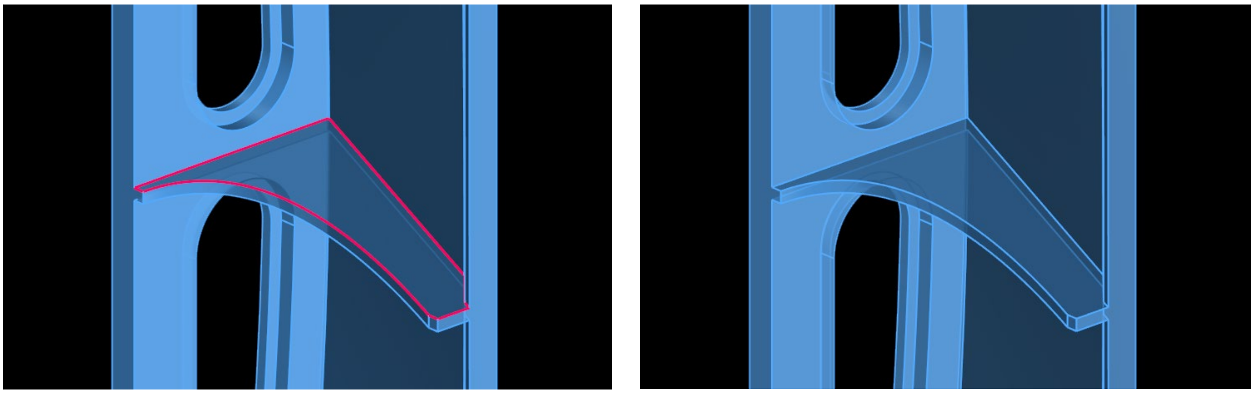


Fig. (8): Left: The model is constantly highlighting naked edges. Right: Same model after being repaired

3.3 Non 3D Printed Parts Meets Maximum Flexibility of Model Alteration

Since the BAAM system allows for printing at high level of accuracy, the research team decided to utilize this capability to incorporate all the detail of the hook ups, sockets, shrouds and sleeves, and to receive any non 3D printed parts such as glazing, light fixtures, tension rod, doors, and the HVAC system.

Since at early stages of the design none of the final products were yet specified, the algorithmic definition was designed to include a place holder for each known part with maximum flexibility to add any new elements as required to the model throughout the design process. For instance, the structure team addressed the weakness of the print in the Z direction by introducing a pre-tensioned rod that runs through the whole structure connecting both ends. A special sleeve was added to the model at the four corners of each ring. Additionally, a custom pocket was added to each end of the canopies to host the rod disk spring. All brackets for ceiling light fixtures, HVAC covers, doors and window frames were also dealt with in the same fashion (Fig. 9).

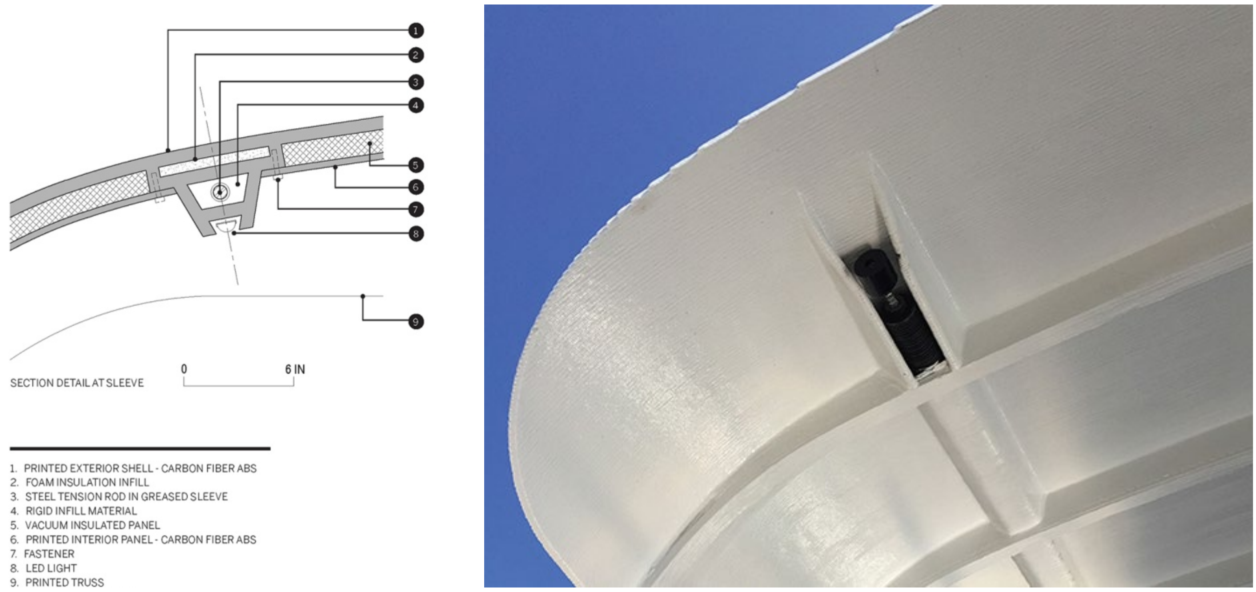


Fig. (9): Left: Detail of the pre-tensioned rod sleeve and light fixture socket; Right: 3D printed canopy with incorporated rod sleeve and disk spring pocket.

3.4 Rapid Model Adaptation for Major Design Changes

Initially, the design team chose to use reinforced fiberglass ABS for its durability during the initial tests and for its natural white finish, eliminating the need to paint the final print. However, after the first full C ring was printed, a major layer delamination problem occurred, and the research team started to question the structural integrity of the material for that scale. More tests were done and it became apparent that ABS reinforced with 30% carbon fiber (black) is a better choice, resulting in much more durable printed sections and no layer delamination occurrence when printed at full size scale.

This adjustment of the starting material also resulted in a change in the bead size due to changes in nozzle size of the extruder from 0.30” to 0.35”. This required that every offset increment in the model had to match the extruded thickness of the material from the 3D printer to prevent gaps and holes from appearing. While the larger bead widths would eliminate the holes given coarser resolution settings, the team would have ended up with a gap between beads, limiting structural performance.

Overall, 16 different models with various offset increments (0.35, 0.36, 0.37 and 0.38) and different mesh density/quality for each one (50%, 60% and 75%) were tested using tool path simulator software. A total of 48 models were tested to determine which increment translated the best and to find the balance between speed, resolution and the quality of the final print (Fig. 10). It was also determined that a two-bead thickness for the warped wall shell offered the best thickness to strength ratio. Increasing mesh quality to the finest level of mesh resolution resulted in eliminating all the gaps in the prints, but it significantly increased the printing time. So the team endeavored to find a balance between mesh quality and printing time.

Next, the team updated all the offset dimensions in the model based on the new tested increment. This mesh optimization resulted in reducing the printing time from 15 hours per C-section (half-ring) to 8 hours per section (a 48% reduction in production time). The team also tested different mesh translators to best control mesh density distribution. With traditional modeling techniques this task would be virtually impossible, requiring a complete rebuild of the model every time one of these changes was made.

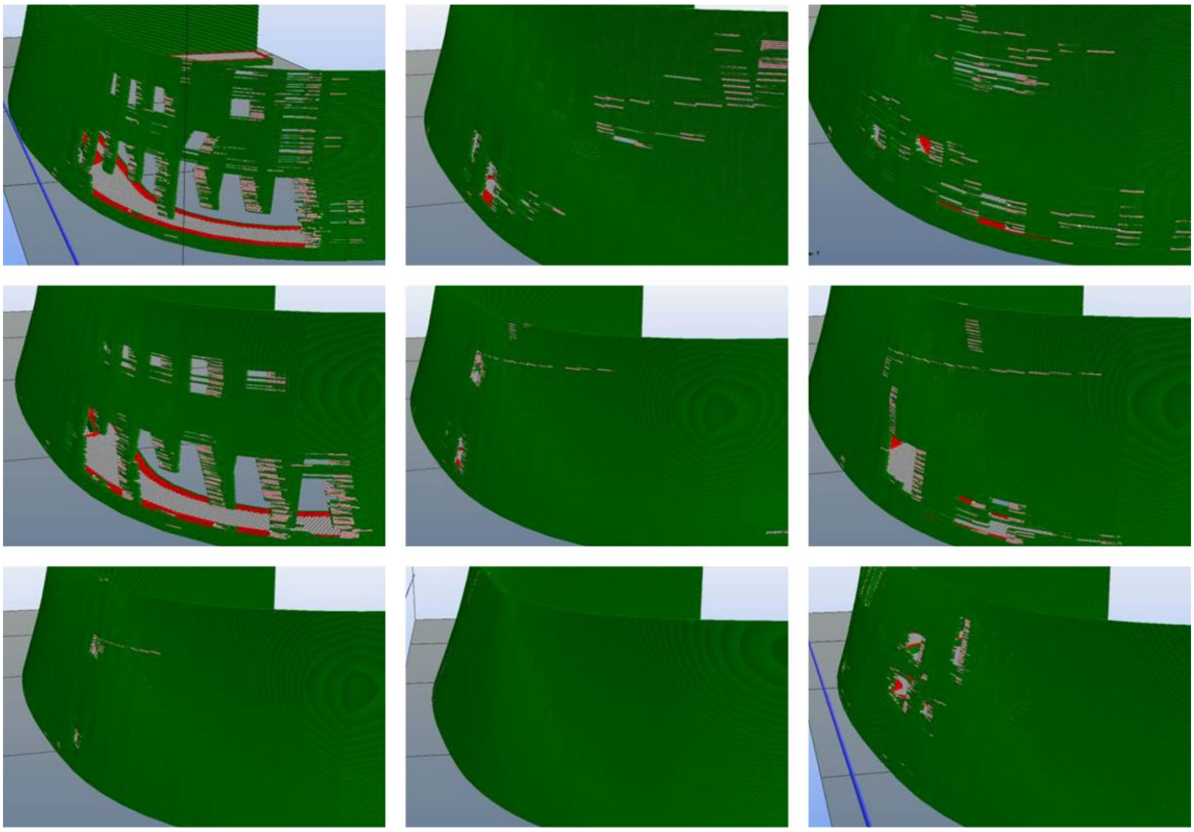


Fig. (10): Testing of the various bead sizes and mesh density using the tool path simulator.

3.5 Interior Surface Optimization for MAI Panels

One of the key components that needed to be tested during the research project was a new type of vacuum-insulated panel that is only 1 inch thick with the potential R-value of 35 hr-ft2-F/Btu. For comparison, current building insulation materials can only achieve an R-value of 6 or less within 1 inch. The vacuum-insulated panels have a very thin, fragile shell that, once punctured, loses almost 90% of its insulation value. These panels have very limited flexibility in terms of bending beyond a certain angle, and a custom form has to be modeled to create panels that are either warped or exceed a bending angle of 20 degrees. The team used a script that was originally developed to optimize doubly-curved surfaces or undevelopable surfaces to reduce the number of hot bent glass panels. The interior surface of the ring was optimized in the same way to reduce the number of custom-bent panels while maximizing the number of standard flat panels (Fig. 11).

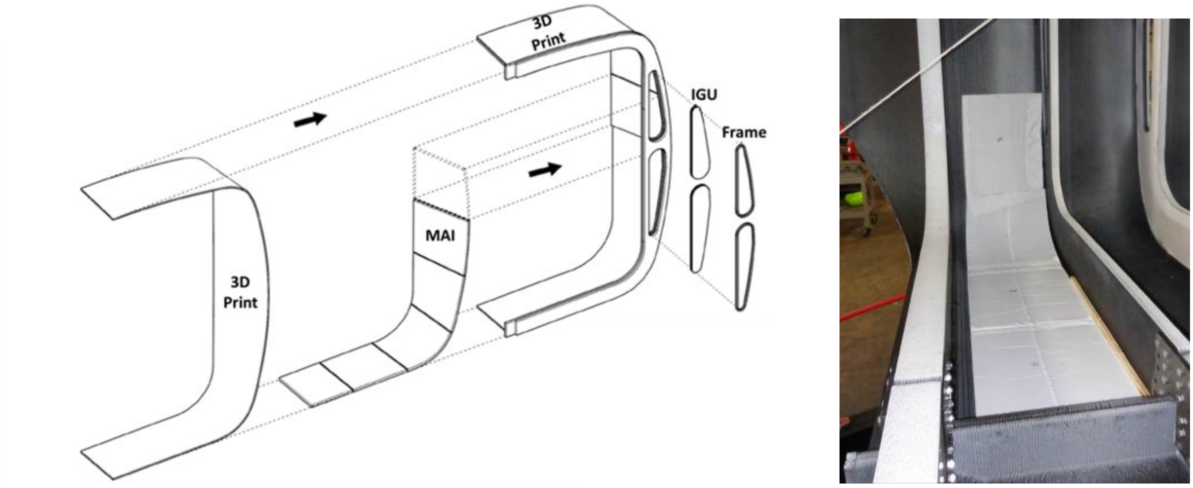
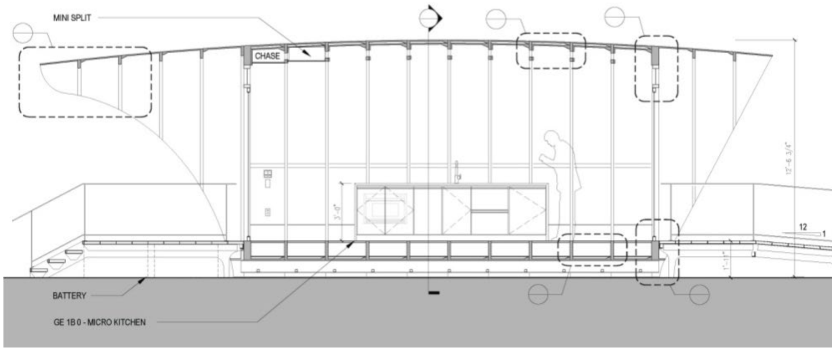


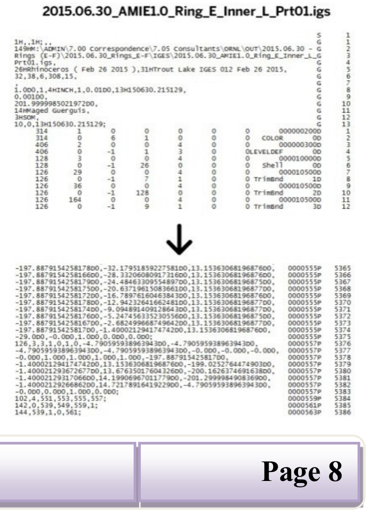
Fig. (11): Left: MAI incorporated in AMIE design. Right: MAI inserted into the 3D printed rings during assembly.

4 Project Delivery

During the production of AMIE, an alternative process of building was demonstrated. Traditionally, architects design a building and provide drawings to the contractor. The contactor then prepares shop drawings for fabrication to be reviewed by the architect. The original design intent can be affected by multiple layers of drawings, reviews and communication exchanges.

However, with AMIE the designers worked very closely with the researchers and the team responsible for the final assembly of the parts. Rather than issuing the typical 2D representational drawings, the AMIE deliverable was the actual 3D digital model shared directly with the printing team as an IGES data file (Fig. 12).





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144,539,1,0,561;                                                 0000563P   5386
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Fig. (12): Construction document versus IGES data file.

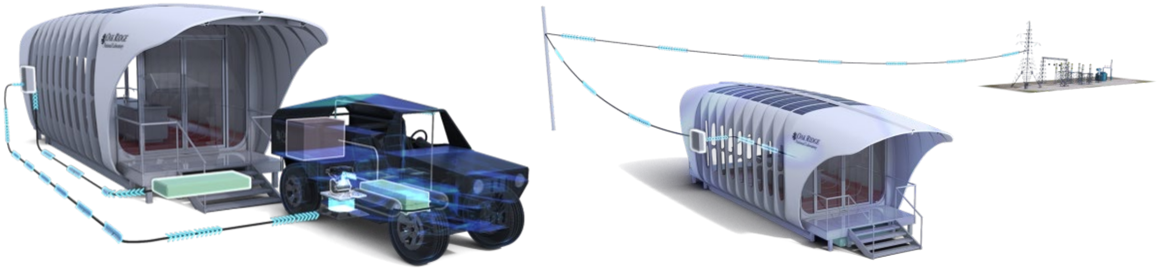
The data was processed and fed directly into BAAM. The built result was a physical manifestation of the actual design model. Any errors in the 3D printed part could be immediately reported to the design team for revision and alteration. Using this delivery method, problems were quickly reviewed and resolved with input from all members of the team, greatly reducing the project timeline and eliminating chances for the design to get “lost in translation”. This new delivery method using physibles on the other hand puts more responsibility on designers, since it extends their role in the blurry lines between design and fabrication.

5 The Integrated Energy System

AMIE features the world’s first level 2 (6.6 kW) bi-directional wireless power transfer system. The transfer system allows driver to charge the vehicle wirelessly when parked over the charging pad. The smart control system is designed to decide which way the wireless power transfer should send energy and the origin of the energy (e.g., solar, wind, battery storage, the grid). This method offers a convenient and safer alternative to plugging the electric vehicles into wall outlets.

Vehicle supplying energy to building

Building supplying energy to vehicle.



Energy directed to storage array

Grid connection option

Fig. (13): Building control and power management strategies directing electrical energy flow.

6 Conclusion and Future Work

AMIE (Fig. 14) is the world’s first and largest 3D printed polymer building that can share power with a vehicle. This research was completed in a period of nine months, AMIE is an examination of new ways and technologies to design and build energy efficient buildings that can also efficiently integrate with the grid and vehicles. In addition, AMIE’s design explores the potential for 3D printed systems of building components to combine all of the wall elements such as structure, insulation, air and moisture barriers, and exterior cladding into one vertically integrated building shell eliminating the need of assembly of smaller parts while significantly reducing the wall thickness and achieving insulation value.

The design, engineering and science generated in AMIE also provide momentum for other examinations of how large-scale additive manufacturing can be used in buildings. The high geometric control of additive manufacturing paired with algorithmic modeling allows precise openings for fenestration, sockets, and other details to be included in the model rather than being added later as separate elements, greatly reducing waste in construction. With industry partners, the AMIE team will continue to investigate this and other opportunities to leverage the success of AMIE to achieve energy efficient building technologies solutions.

Fig. (14): AMIE final assembled enclosure

Nomenclature

AMIE	=	Additive Manufacturing Integrated Energy
BAAM	=	Big Area Additive Manufacturing
MAI	=	Modified Atmosphere Insulation

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