EXPLORATION OF COMPUTATIONAL DESIGN AND ROBOTIC FABRICATION WITH WIRE-ARC ADDITIVE MANUFACTURING TECHNIQUES

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Abstract. This paper discussed the exploration of computational design and robotic fabrication with Wire-Arc Additive Manufacturing techniques in a robotic metal printing workshop in Digital Futures 2018. Based on the previous research on structural-performance based design and robotic fabrication, this year's workshop mainly focused on the Wire-Arc Additive Manufacturing techniques and its possible outcomes. A prototype chair was tested for preparation. And the final target of the workshop was to build a bridge about 11m across the river. Through this metal printed bridge project, several computational optimization methods were applied to fulfill the final design. And Wire-Arc Additive Manufacturing techniques with robotic fabrication were carried out during the fabrication process.

Keywords. Computational design; robotic fabrication; wire-arc additive manufacturing techniques.

1. Introduction

In the Digital Futures 2017 workshop, it was aimed to propose a method to find an optimal solution for a robotic printed modified plastic (MP) pedestrian bridge from both architects and engineers aspects. And the first 3D printed modified plastic pedestrian bridge in China was built up (Figure 1)(YUAN et al., 2018). But as the plastic material has its structural and stability weakness compared to steel and concrete. The authors started to think of using metal material in 2018. And Wire-Arc Additive Manufacturing techniques have aroused wide attention in the architecture community when world's first robotic 3D printed steel bridge was announced by MX3D in October 2015 and scheduled to be finished in 2018, which aimed to 3D print an 8m stainless steel bridge with Wire-Arc Additive Manufacturing techniques (Joosten, 2015). It was decided to test the Wire-Arc Additive Manufacturing techniques to build up a bridge on the same site as last year. A prototype chair was tested for preparation at first. And the final outcome of this workshop was a robotic printed metal bridge about 11m across the river. (Figure 2)

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 1, 143-152.

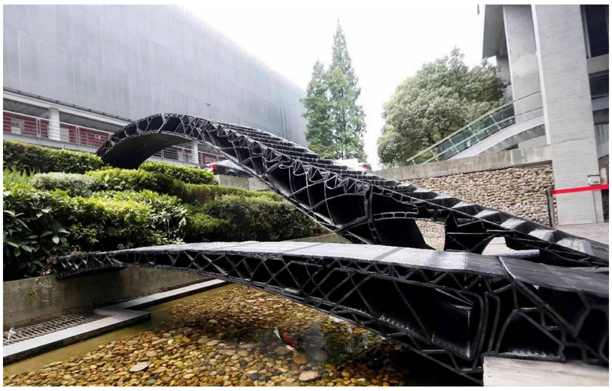

Figure 1. first 3D printed modified plastic pedestrian bridge in China.

Compared to other 3D additive manufacturing techniques like plastic printing, due to the material used in Wire-Arc Additive Manufacturing techniques is metal, the structural performance of its final printed element has a huge step forward. This progress in structural performance due to material properties has led to widespread attention. This research took the 3d printed metal bridge workshop in Digital FUTURES 2018 as an instance to explore computational design and robotic fabrication with Wire-Arc Additive Manufacturing techniques and its future possibilities.

Figure 2. 3d printed metal bridge.

2. Wire-Arc Additive Manufacturing Techniques

Additive Manufacturing technology is based on the principle of discrete-stacking, driven by three-dimensional data of parts, and the rapid prototyping technology of solid parts is made by layer-by-layer accumulation of materials (Wohlers and Gornet, 2014). Metal additive manufacturing techniques can be divided into three categories according to the type of heat source: laser, electron beam and arc. In the past 20 years, studies have be carried out on the powder-based metal additive manufacturing technology using laser and electron beam as heat sources. (Murr et al., 2012) By continuously melting or sintering metal powder, complex structural parts can be printed layer by layer. Due to raw materials and heat source characteristics, metal powder-based laser and electron beam additive manufacturing techniques exhibit certain limitations when forming large-sized complex structures.

The low-cost, high-efficiency Wire-Arc Additive Manufacturing technology, which was developed based on surfacing technology, has attracted the attention of some scholars. Wire-Arc Additive Manufacturing technology uses arc as the energy beam and manufactures solid metal parts using layer-by-layer welding. The formed parts are composed of all welds. The open forming environment has no restrictions on the size of the formed parts. This makes 3D printed metal architecture assemblies within reasonable budget possible. (Williams et al., 2016)

3. Prototype Chair and Structure Tests

As research team first got in touch with Wire-Arc Additive Manufacturing techniques, before the final bridge was designed, research team planned to test a chair to get some experience in digital design and robotic fabrication using Wire-Arc Additive Manufacturing techniques.

Figure 3. printed metal chair.

Through some basic tests, it was found that the structural strength of the elements using Wire-Arc Additive Manufacturing techniques is higher, while the printing speed is far less than plastic printing. And if the final bridge is printed layer by layer, it will not be finished in time. Therefore, it was decided that the final bridge body would be formed by printed metal rods. The authors completed a prototype chair(Figure 3) consists of rods and verified its feasibility. Moreover, many tension and bending tests were carried out(Figure 4), which gave us the data needed in future analysis. From the structure test, a printed metal rod with a diameter of 9mm can take a maximum tensile load of 14KN and 36MPa bending resistance (Figure 5).

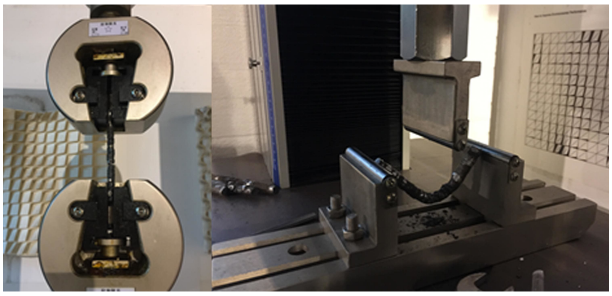

Figure 4. structure tests.

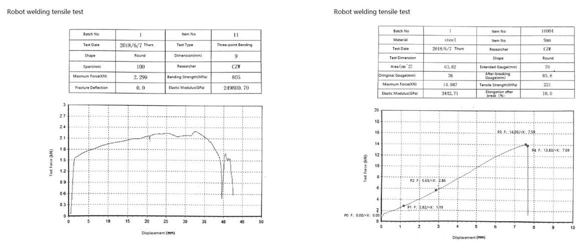

Figure 5. Structure Test Data.

It is easy to find that the bending resistance is relatively small in printed steel bars. It is because the spot welding method leaves some air bubbles (Figure 6) in the rod during the printing process. Thus, the printing structure is not that dense, and even large defects may occur locally. A secondary support system in the final design of the bridge was introduced based on structural tests to ensure its safety.

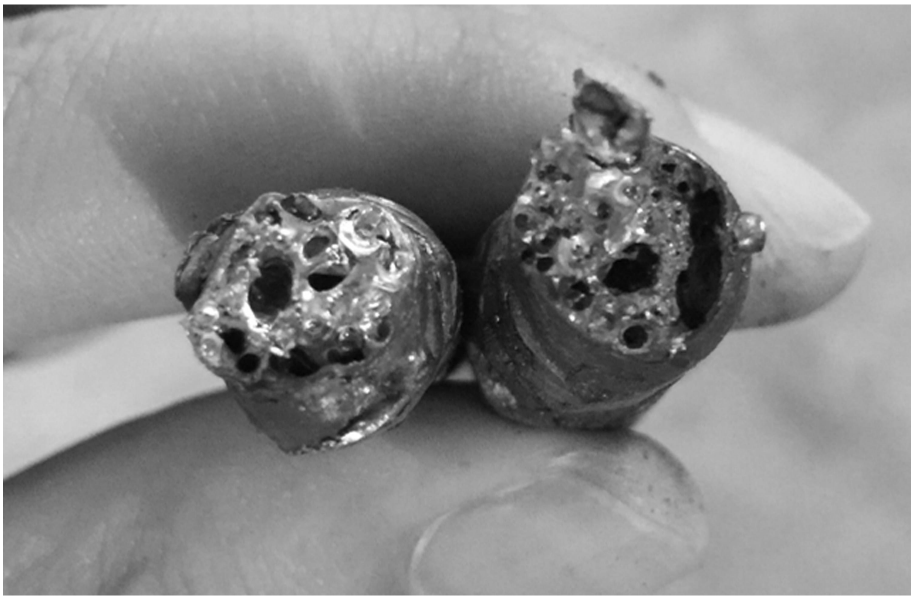

Figure 6. air bubble defects in the rods.

4. Computational Design and Digital Fabrication of Printed Metal Bridge

Due to limited time for fabrication, both time and structural and visual beauty and utility factors were considered during the computational design process. And based on the knowledge from the prototype chair, the concept of the bridge design came from the idea of combining the traditional arch bridge shape with the spatial grid (Figure 7). And finally, a bridge structure composed of spatial rods with stairs for people to walk on and a secondary support system to ensure its safety was determined.

During the form-finding process, a variety of methods were adopted. First, based on the simulation results in kangaroo, a suitable span-rise ratio was determined. And a reasonable design domain was obtained. Secondly, Bi-directional Evolutionary Structural Optimization (BESO) was applied to get an overall shape of the bridge within the design domain derived from step 1. As the evolution continues, the shape of the bridge becomes thinner at the center of the bridge (Figure 8).

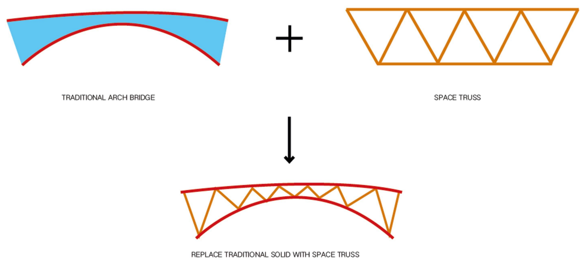

Figure 7. design concept.

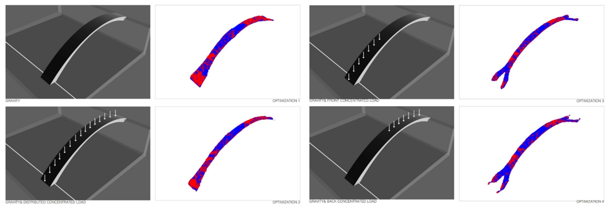

Figure 8. BESO Optimization.

After completing the initial BESO optimization and form-finding process, some control lines were needed to be identified for further design exploration. In the third step, the position of the control edge lines of the bridge on the top plane was determined according to the trend of the principal stress line. Because the final bridge needed to consist of steps for people to walk through safely. In the fourth step of the design, the control lines of the bridge steps in the section were determined. In this way, people can walk relatively flat on the bridge. With the given design domain after BESO and the design control line obtained from the third and fourth steps, the design space was divided into an array of points. And rod elements were generated from a single point to another point that was within the pre-set maximum length between two points. Because the printing time of the bridge was strictly controlled by the workshop deadline, the total length of the rods was needed to be reduced while the strength of the bridge had to be ensured. To do that, the authors used an optimization method that could be called ESO Element Reduction on step 5. Instead of changing the form of solid structure, the authors used only rod elements for iteration this time. Each time when step button was pressed, the rod model was tested through a FEA analysis, it would sort all the rods in the model in the sequence of structure behavior. The more useless and inefficient rods would be deleted by the program in each step. The authors did the optimization iteration until the rod model could be printed out by 3 robotics in time (Figure 9).

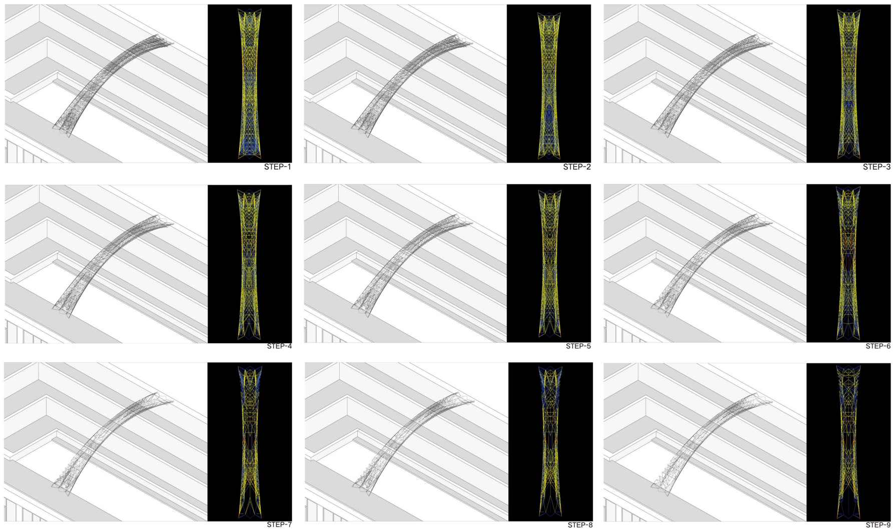

Figure 9. ESO element reduction.

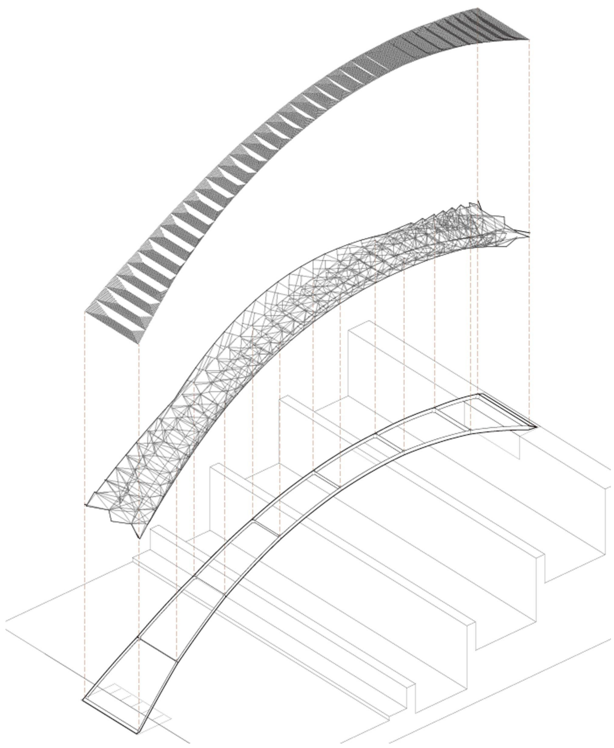

Figure 10. final design decomposition diagram.

At step 6, some necessary elements were added for the requirement of general bridge design like a ramp on the top of the bridge on account of safety reasons. In step 7, due to the previous chair test and structural test, it is decided to add a secondary spatial frame to ensure 100% safety of the structure. At the same time, this secondary structure system was also the working reference for the follow-up robotic metal printing process. This secondary support system was going to be pre-built and the final metal rods are wire-arc welded on the steel frame to obtain the final metal structure.

For the final design (Figure 10), it has a self-weight of 584 kg, 292kg for printed truss system, and 292kg for the steel frames and stairs. Adding on the extra steel plate for supports on both ends, the total weight is 998kg. The final design result was imported into the structural calculation software for structural verification under three working conditions (Figure 11). After the structural behaviors were ensured, the final fabrication process began.

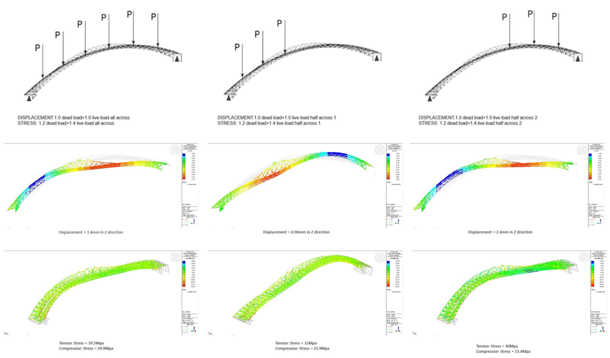

Figure 11. Structure Analysis.

Wire-Arc Additive Manufacturing techniques were used to print the metal rod bridge. Construction segmentation was determined based on the division of the secondary spatial frame system. And then lines of each segment were sent to grasshopper. A series of grasshopper definitions defined three robots' motion paths, arc welding switches and cooling time commands. The program finally exported SRC file, allowing three robots to start the fabrication of the bridge structure simultaneously.

For the fabrication process, the entire bridge was divided into 7 parts. And for each part, there is one frame in the secondary support system to act as the robotic position reference. And the robotic perform wire-arc additive manufacturing techniques to complete every single part of the bridge (Figure 12). And rods between two connecting spatial frame were manually weld. Finally, three robots completed a total of 579.5m metal rod printing, which took a total of 15 days. The bridge was assembled into 3 sections in the factory and then transferred to site. And the final assembly was finished in one day.

Figure 12. wire-arc additive manufacturing process.

5. Conclusion

Through this 3D printed metal bridge project using Wire-Arc Additive Manufacturing techniques, the authors verified its feasibility and potential with computational design and robotic fabrication technology. Of course, there are certain deficiencies. Firstly, due to its print speed limitation, the layer by layer printing method will lead to a longer fabrication period, while spatial rods printing method will cause more restriction to the design. There is also a certain contradiction in the necessity of using wire-arc additive manufacturing techniques rather than standard members in spatial rods method. Secondly, the accumulative error caused by the layer height in the real world and layer height set in the program will lead to fabrication failure. More research on the distance feedback system of Wire-Arc Additive Manufacturing is needed to be enhanced in the future. In the end, through this project, the authors hold the view that it would be great possibilities in using Wire-Arc Additive Manufacturing techniques in computational design and robotic fabrication workflow in the future.

Acknowledgement

This research is funded by the National Natural Science Foundation of China (Grant No.51578378), the Special Funds for State Key R&D Program during the 13th Five-year Plan Period of China (Grant No.2016YFC0702104), the Sino-German Center Research Program (Grant No.GZ1162), and Science and Technology Commission of Shanghai Municipality (Grant No.16dz1206502, GrantNo.16dz2250500,GrantNo.17dz1203405,GrantNo.18dz1205604).

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