FORM FINDING FOR 3D PRINTED PEDESTRIAN BRIDGES

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Abstract. Due to the highly interrelation between architecture and engineering involved in the early design stage of 3D printing, form-finding is the critical step in the large-scale 3D printing projects. This paper focused on the research of form-finding applied in large-scale 3D printed structures, specifically, in the design of two pedestrian bridges. A three-step form finding approach was introduced in this paper. Multiple numerical methods were involved in the approach to find an optimal solution for both aesthetics and structural design for two 3D printed pedestrian bridges. The application of the three steps of form-finding, which take consideration of material properties, site limitations, applied loads etc., to the design of the large-scale 3D printed bridges were discussed in details in this paper. The approach of form-finding in an early designing stage disused in this paper helps to understand the combination of architecture and structure engineering.

Keywords. Form Finding; 3D Printing; Structural Performance; Material Performance; Topology Optimization.

1. Introduction

Additive manufacturing (AM) or 3D printing technology has influenced the environment around us continuously since the first printed solid model by Hideo Kodama (1981). After the rapid development of 3D printing technology of the last thirty years, many modern industries have decided to replace traditional manufacturing with robotic manufacturing, for example, building industry. For a long time, architects and engineers have been seeking a solution for 3D printing in the application to large scale structures. This paper uses 3D printed bridges as the research objects, and addresses the solution on how to find the optimal structure form that suitable for robotic 3D printing process.

The research on 3D printed bridge has made some remarkable progress in the last few years, and steel and concrete have been used as 3D printing materials in large scale projects. The world’s first robotic 3D printed steel bridge was announced by MX3D in October 2015, and scheduled to be finished in June 2018, and this project aims to 3D print an 8m stainless steel bridge with gas metal arc welding based additive manufacturing (Joosten, 2015). Although 3D printed
steel structure has a strong structural performance, the high printing cost and slow printing speed limits its application to regular additive manufacturing projects.

Concrete is a more common material used in 3D printing projects on large scale structure. In December 2016, the first 3D printed concrete pedestrian bridge was completed in Spain, and the bridge was made entirely of concrete with measuring of 12 meters in length and 1.75 meters in width (Julia, 2016). Another 3D printed concrete bridge designed by BAM Infra was completed in Netherlands in October 2017, the bridge was printed in pieces from a concrete mixture, reinforced with steel cable, before being assembled and erected on-site (Irving, 2017). Both projects claimed that their material usage has been reduced in a large amount, and the construction speed has been increased sharply by using 3D printing technology.

Due to highly interrelation between architecture and engineering involved in the early design stage, form finding is the critical step in large scale 3D printing projects. However, in the previous large-scale projects, the bridge forms have not been optimized for additive manufacturing process. This paper aims to propose a method on finding an optimal solution from both architects and engineers aspects. The method was used in designing the 3D printed modified plastic (MP) pedestrian bridges at Tongji University in Shanghai, China during the Digital Future 2017 Workshop (Figure 1).

![China’s 1st 3D printed MP pedestrian bridges.](image)

2. Three-Step Form Finding Approach

The three-step form finding approach includes three numerical methods, which are used to conduct the form finding for 3D printed bridge, as well as other large-scale 3D printed structures. All steps involved in the form finding process should take consideration the material properties, site layout, fabrication process, construction period, and transportation. Three main principles used in this approach include catenary equation, topology optimization theory and finite element modeling. The three-step form finding approach benefits 3D printing projects with less material cost, shorter fabrication period, lighter structure weight, and lower carbon emissions.
2.1. MINIMIZING BENDING FORCE INSIDE STRUCTURE

The first step of the three-step form finding approach is to prevent the bending failure within the structure under load applied. As the structure performance greatly depending on material selection, material properties give a well understanding on how the material going to behave under different conditions. The detailed material properties of MP were shown in Table 1.

Table 1. Material Properties of Modified Plastic (MP).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Official Name</td>
<td>Modified plastic</td>
</tr>
<tr>
<td>Derived From</td>
<td>Recycled plastic</td>
</tr>
<tr>
<td>Degradable</td>
<td>No</td>
</tr>
<tr>
<td>Melting Point</td>
<td>294°C (591.8°F)</td>
</tr>
<tr>
<td>Rupture Tensile Strength</td>
<td>57.8 MPa (8300 psi)</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>55.3 MPa (8000 psi)</td>
</tr>
<tr>
<td>Resistant Temperature</td>
<td>To 50°C</td>
</tr>
<tr>
<td>Indoor / Outdoor</td>
<td>Indoor</td>
</tr>
<tr>
<td>Solubility in Water</td>
<td>Water soluble</td>
</tr>
<tr>
<td>Dimension of Block</td>
<td>0.001 in (0.025 mm)</td>
</tr>
<tr>
<td>Glass Transition</td>
<td>70°C (158°F)</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>37.6 MPa (5500 psi)</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>2150 psi (7460 kPa)</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>3.3 GPa (479.2 kN/m²)</td>
</tr>
<tr>
<td>Elasticity</td>
<td>298°C</td>
</tr>
</tbody>
</table>

Material properties table shown that the MP has Young’s Modulus of 3.3GPa, with tensile strength of 57.8MPa and flexural strength of 55.3MPa. The resistant temperature indicates the 3D printed MP bridge can stand outside in a normal environment theoretically.

The fabrication process for 3D printed bridge was by using fused deposition modeling (FDM) method, it varies the structural performance compare to traditional uniform material structure.

Fig 2&3 indicate different fabrication process may influence the load transfer inside the block, if the block was made by FDM process, the tensile resistance in X direction has poor performance compare to uniform material block. The FDM block and uniform block will have the similar performance only at the situation of axial load transfer within the structure without bending force.
To ensure axial load dominant the overall structure, the principle of catenary equation was used to find the form. A catenary curve forms due to its own weight or under a uniform load, and can be described by the formula $y=(1/a)\cosh(ax)$ (Fig.4) (Becker, 2014).

If a catenary arch with $a=0.2$, with uniform load, $w$, and span, $L$, the reactions at any point along the arch at some distance $x$ from the left support can be calculated by the formula:

$$f_x = \frac{wL}{5.52} \quad \text{and} \quad f_y = \frac{wL}{2} - wx$$

(1)

the following diagram shown the reaction vectors at increments of L/20 (Figure 5) (Becker, 2014).

By analysis with the reactions of catenary structure, no bending moment occurs at neither supports, loads applied can transfer through the catenary curve as axial force and therefore produce a sustainable structure.

Two reversed catenary-like curves were determined as the bridge’s upper and lower counter line to ensure no other unnecessary loads transfer within the bridge besides axial load. A software named Kangaroo was be able to simulate the catenary curves by apply a tension or compression force. By consideration of site layout (Figure 6) and measuring necessary dimensions, input the boundary conditions from the site by using the locations of end points and the value of applied loads (Figure 7).
By adjusting the value of applied force and other necessary input parameters, several numerical results were generated (Figure 8).

Considering the bridge slope required by the local building code and the relationship between the bridge geometry and surrounding environment, an optimal result was selected as the initial design of the bridges (Figure 9).

The structure form generated at this step is able to transfer the applied load as axial loads and therefore minimize the possibility of bending moment. This is a sustainable structure laid as the foundation for the following two other optimization methods.

2.2. MATERIAL REDUCTION BASED ON STRUCTURAL TOPOLOGICAL OPTIMIZATION

The purpose of this step is to reduce the inefficient material as much as possible, and generate the lightest structure with meet requirement of structure stiffness. Which like the purpose of topology optimization, finding the optimal lay-out of a structure within a specified region (Bendsøe, 2004). Hence, structural topological optimization method was used in the project to achieve this goal.

The solid isotropic material with penalization (SIMP) method found by Mlejnek can find the optimal solution for continuum structure. An application runs in Rhino3D software environment can calculate the optimal solution based
on SIMP method, as well as genetic algorithm (GA) to improve the calculation speed.

Three key elements of structural topological optimization are object function, design variable, and boundary condition. In this case, the object function we used in SIMP method is to minimize the structure weight, design variable refers the limitation of structure stiffness, boundary condition indicates the load region, load applied, object region, supports type, and etc. (Figure 10).

After a series of iterations, achieved a clear result shown the result of SIMP method. Black area indicates the location of inefficient material in the structure, as white area indicates where stiffness need to take prioritized consideration in design process (Figure 11).

All calculation was made on the assumptions of uniform load applied on the upper bridge surface, fixed supports on both sides, and isotropic material. The change of support type could bring significant difference in results (Figure 12), left column set support type as fix support, and right column set support type as pin support.
The results with 50% material reduction and fixed support type was selected as the structure form in this step. It contributes the structure performance for the bridge design by reducing a large amount of the structure self-weights.

2.3. EXAMINING STRUCTURAL PERFORMANCE BY FINITE ELEMENT MODELING

To avoid local stress concentration occurs in the overall structure, a structural analysis based on finite element modeling was necessary to exam the structural performance. The percentage of material reduction used in previous step was purely empirical, and therefore a finite element analysis helps to check if the reduction percentage within a reasonable range.

It is recommended to have a structure analysis diagram for each varied material reduction percentage simultaneously as a monitor tool. As the structure tending lighter, the amount of vertical displacements was increasing, then the deformation of bridge sections under load applied need to be controlled under a safe range by evaluating the stress diagram of the bridges (Figure 13).

![Figure 13. Structural Performance under Different Material Reduction Percentage.](image)

In addition, the whole big bridge was divided into multiple smaller pieces for the convenience of transportation, and the structure analysis helps to locate an area that suitable for cutting and minimal effect on structure strength reduction (Figure 14).

![Figure 14. Cutting Area on Larger Bridge.](image)

The results from numerical simulation by FEM in Abaqus also suggest the smaller bridge can safely supports 5 people as concentrated load with displacement...
of 1cm, and the larger bridge only has 3.8mm displacement in Z direction under a uniform load of 3Kn/m² (Figure 15). The safety index of the bridges is between the range of 10 to 15.

3. Fabrication Process

After finishing the form finding processes, the optimal bridges’ cross-sections were used for robotic fabrication by programming the robot’s movement. Two bridges were fabricated by three 6-axis robots in the laboratory for a total of 360 hours and assembled on site (Figure 15&16).
4. Limitations

The optimal solutions from second and third step were found based on FEM, however, the results are approximate numbers due to FEM principles. Therefore, the optimized structure form by using this method can only be an approximate value.

No evidence showed structure under axial loads has same performance for both FDM processed structure and uniform material structure. And the structure performance could vary due to the optimization process was done under a two-dimensional environment, but the load was transfer inside a three-dimensional structure in reality.

Plastic, as a 3D printing material, has always been a challenge in outdoor projects, as the stability of the material is relative low than steel and concrete. During the extreme summer weather condition in Shanghai, the temperature on paved road could be 70°C, and the upper surface temperature on the bridges is about 60°C (Figure 18). The surface temperature is very closed to the MP glass transition temperature (deformation temperature) of 62°C, and causes some significant changes in material performance by long-time exposure in high environmental temperature. Many recent research have focused on improving polymer material properties for 3D printing, and stated the monomeric and polymeric materials, like MP, is much more appropriate in next industrial revolution than traditional building material. (Stansbury&Idacavage, 2016).

5. Conclusions

The three-step form-finding approach, a form-finding method for large-scale 3D printed objects, has been presented. The catenary curves were used to generate the geometry outlines of the bridges; Structural Topological Optimization was used to obtain a lighter structure, to conserve the 3D printing materials, and to increase the construction speed; Finite Element Analysis were used to conduct the pre-structure analyses to control the 3D printing material reduction within a reasonable range and to exam overall structure performance. Two large-scale 3D printed MP pedestrian bridges by the Tongji University in Shanghai, China, in July 2017, show that the three-step form-finding approach provides a reasonable method to find an optimal solution from both architects and structure engineers aspects. The three-step approach can be applied to all 3D printed structures.
Acknowledgement

This research is funded by National Natural Science Foundation of China (Grant No.51578378), National Key R&D Program of China (Grant No.2016YFC0702104), Sino-German Center (Grant No.GZ1162), and Shanghai Science and Technology Committee (Grant No.16dz1206502, Grant No.16dz2250500, Grant No.17dz1203405).

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