Title:
Form-Finding and Structural Shape Optimization of the Metal 3D-Printed Multi-Branch Node with Complex Geometry

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Introduction:
In the last few years, considerable attention has been paid to additive manufacturing (AM) technologies [1] to redesign and modify the industrial products with regard to its merits. At the initial stage of technology development, AM was mostly used as a building platform for prototyping, whereas its usage has been recently extended to industrial applications. Amid the different methods of AM technology, the development of metal AM, in particular, Powder Bed Fusion (PBF) and metal Binder Jetting (MBJ), facilitate the production of high-quality and complex parts in several sectors of industry such as aerospace, medical, architecture and civil engineering. Understanding the novel advantage of metal 3d-printing in the development of high-performance and functional parts for applications in the construction sector enables researchers to propose different design and form-finding methods for construction components.

One of the most commonly used civic buildings namely, space frames (SF's) are enumerated due to their wide applications for building the stations, pavilions, sport complexes, museums, etc. These structures are designed by using some algorithms like vMESH system [3] by which a tetrahedral three-dimensional mesh is generated from a given prismatic volume. The resultant randomly generated graph–shaped structures will give the dimensional information such as bar orientations and initial nodes topologies. Since the generated wireframe structure has random shape, the connecting nodes also have unique and irregular configuration as seen in Fig. 1. This research aims to propose two design methods for the SF's nodes that possess irregular shapes with complex geometry. These methods namely, the curve parameter method and the fatness parameter method, rely on the particular capabilities of CAD software to sketch the original part, parameterization of the geometry and finally structural shape optimization of the part. The former method takes longer time to be completed while the latter one is faster. In contrast to the NURBS models, these methods are acclaimed due to their less computational time, less complexity of the model and more scalability. The manufacturability of the final parts is also considered in metal AM framework and the performance of each part is analyzed by functional testing.
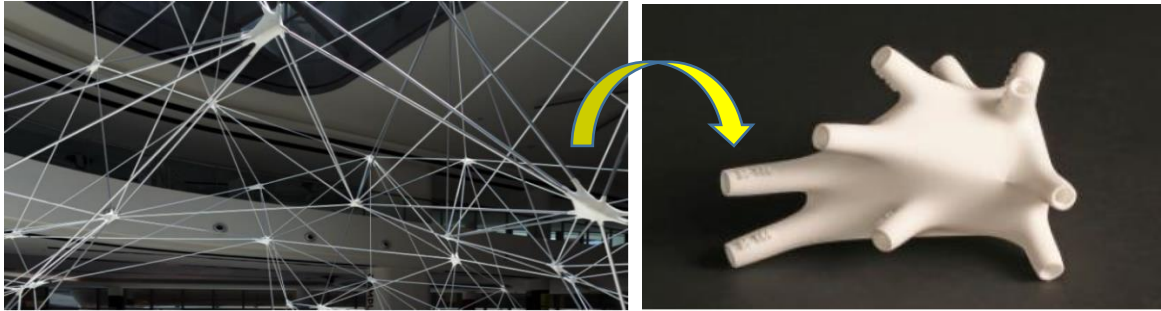
Fig. 1: From left to right. (a) SF Generated by vMESH System, (b) Close-up View of the Node with Unique Configuration.

Main Idea:
As discussed in the previous section, two methods namely, curve parameter method and fatness parameter method are used to design SF's nodes in this study. Resulting node designs are intended to be smooth and lightweight. A multi-branch node is sketched using the dimensional information of the blank space between the converging bars in a pre-designed SF and then parameterized by two different approaches to perform structural optimization.

Curve Parameter Method
In the first approach, i.e., curve parameter method, a multi-branch intersected cylinders is sketched manually using the dimensional information of the blank space between the converging bars in a pre-designed SF, which is created by vMESH system (see Fig. 2(a)). A spline curve is sketched between neighboring cylinders and then the distances between the control points of each spline curve to the intersection point are chosen as optimization parameters (see Fig. 2(b)). These distances between the control points and intersection point adjusts the concavity of the created surface between three spline curves as shown in Fig. 2(c) and finally the solid node is created, respectively as illustrated in Fig. 2(d). The number of parameters for this particular node is obtained 41, which are optimized by using genetic algorithm to obtain the minimum von Mises stress versus applied axial loads on each branch of the node.
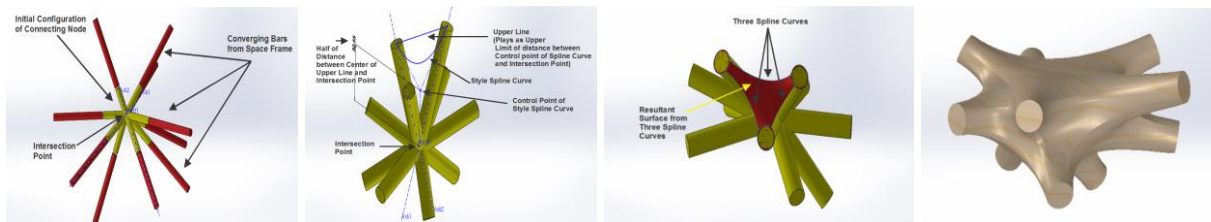

Fig. 2: From left to right. (a) Initial Configuration of the Node, (b) Spline Curve Control Point, (c) Filling Surface between Three Sketched Curves, (d) Solid Node Configuration before Structural Optimization.

This design procedure is completed in three steps. These steps, namely node sketching, parameterization and structural optimization, can be applied to all types of nodes which belongs to the class of node as used in vMesh structures and shown in Fig. 1(b). The optimization procedure is accomplished using a genetic algorithm to minimize the maximum von-Mises stress as the objective function subjected to the mass of the node as constraint function. The design method is implemented using three software packages, with LiveLink interfaces among them: SOLIDWORKS, MATLAB and COMSOL. The digital workflow between these software packages is shown in Fig. 3(a).
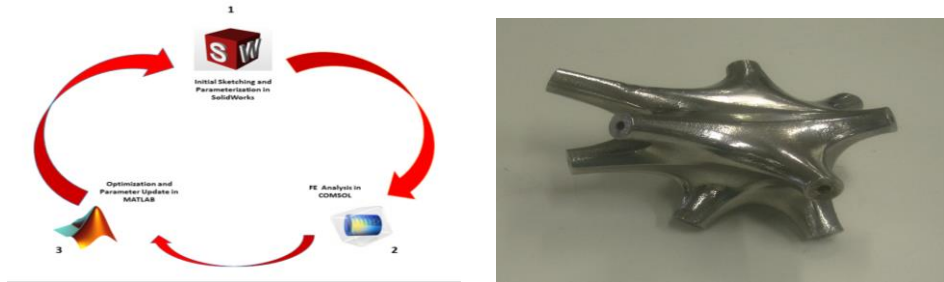
Fig. 3: From left to right. (a) Livelink Circle between Three Software for Structural Shape Optimization of the Node, (b) Optimized 3d-printed Node by using Curve Parameter Method.

Fatness Parameter Method
In other method, called fatness parameter method, which is a fast and automated approach, the fatness parameters of the center part of the node and the root radiuses of each branch are chosen as the main parameters of optimization as shown in Fig. 4(a), Fig. 4(b), Fig. 4(c), Fig. 4(d).
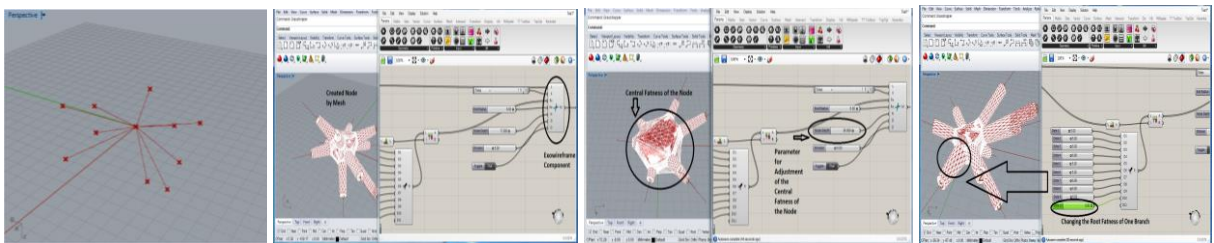

Fig. 4: From left to right. (a) Initial Points and Lines Based on the Dimensional Information, (b) Initial Mesh Creation of the Node by using Exo Wirefram Component at Grasshopper Software, (c) Control of Central Fatness of the Node by using one of the Parameters of Exo Wireframe Component, (d) Control of Root Fatness of each Node's Branch by using another Sets of Parameters at Exo Wireframe Component.

The number of parameters in this method for this particular node is obtained 11, which are optimized by using genetic algorithm. The optimization procedure is accomplished using a genetic algorithm to minimize the maximum von-Mises stress as the objective function subjected to the mass of the node as constraint function. This method is implemented using a different CAD environment in order to take advantage of its more systematic and quicker capabilities. Specifically, the following software are used: Rhinoceros (Rhino) for the design environment, Grasshopper for parametric design, Exo Wireframe for node geometric modeling, Karamba 3D for FEA, and Galapagos for optimization. The digital workflow is shown schematically in Fig. 5(a).

Fig. 5: From left to right. (a) Overview of Optimization Process, (b) Final Metal 3d-Printed Node by using Fatness Parameter Method.

Functional Testing and Comparison

In order to determine the mechanical properties of the printed nodes using EOS M280 [2] metal 3D-printer, a functional experiment is conducted. This experiment aims to measure and compare the amount of stiffness for two nodes along their build direction. To determine the approximate stiffness of the nodes along the build direction, 1% strain is applied to the same point on each node by using the point load gripper of an INSTRON tensile testing machine as shown in Fig. 5(a) and Fig. 5(b). The nodes are fixed to the platform and the experiment is carried out three times to ensure the repeatability of the test.
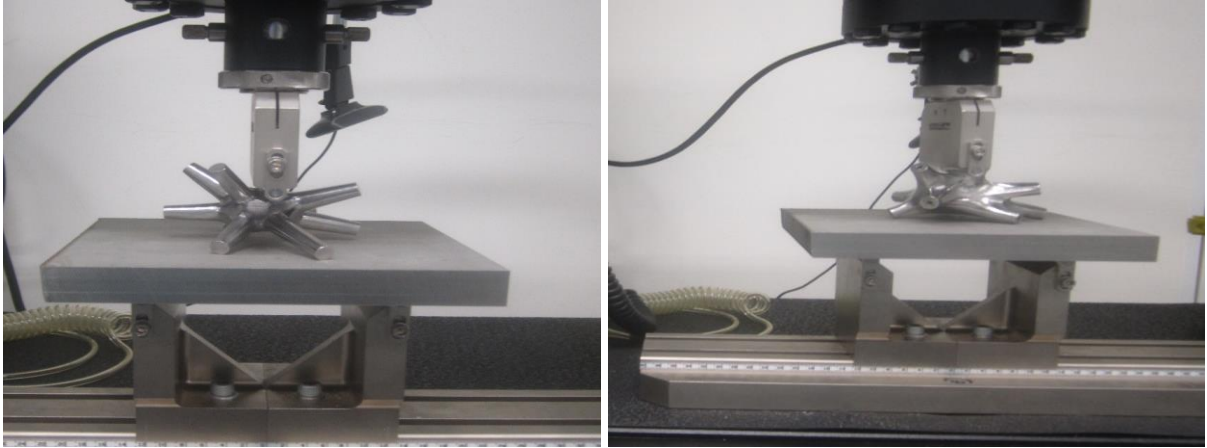

Fig. 5: From left to right. (a) Fatness Parameter Node under Point Load, (b) Curve Parameter Node under Point Load.

After applying the strain, the machine measures the output force (N) and the input extension (mm) and the corresponding force-extension curve is plotted as seen in Fig. 6.
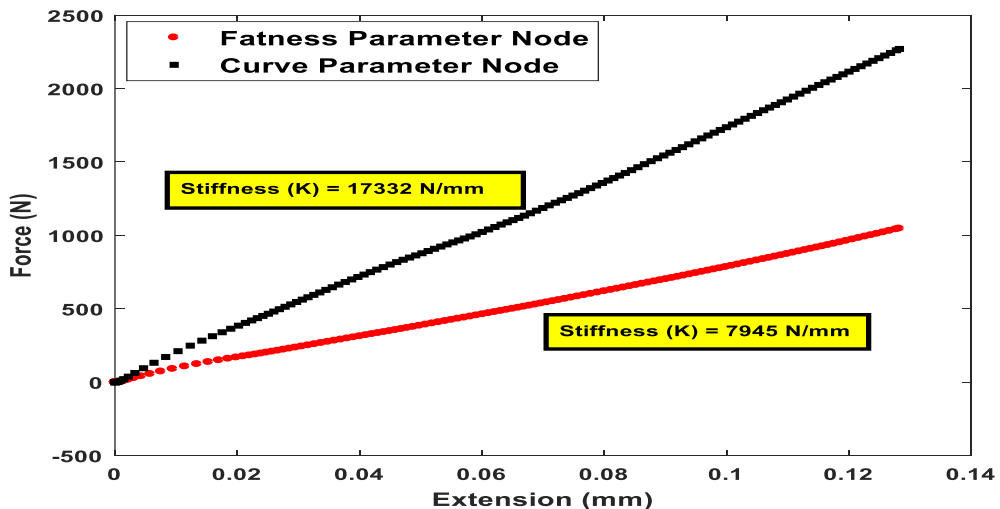

Fig. 6: Force-Extension properties of both nodes.

As expected, the curve parameter node reveals larger average stiffness of 17100 N/mm in comparison with the lower value of 7754 N/mm for the fatness parameter node due to the greater amount of material along the build direction. However, from the mass point of view, the average stiffness/weight ratio of 15508 N/kg.mm is obtained for the fatness parameter node against the 15600 N/kg.mm for the curve parameter node. Tab. 1 represents the comprehensive comparison in terms of advantages and disadvantages of the two nodes in this study. This table can be used as a reference for designers to have an economical and technical estimation in the overall design process.

Design Parameters	Approximate Sketch Time (hrs)	Output Format of the Sketch	Approximate Build Time (hrs)	Average Stiffness along Build Direction (N/mm)	Average Stiffness/Weight Ratio (N/kg.mm)
Fatness Parameter Node	≈0.15	Mesh (Converted to Solid using Secondary Software)	≈12	7754	15508
Curve Parameter Node	≈1	Solid	≈15	17100	15600

Tab. 1: Overall comparison between two nodes after manufacturing.

Overall comparison between the two nodes gives valuable information to improve the design procedure as well as making decisions for choosing the final configuration of the node. From the information given in Tab. 1, one can realize the only merits of curve parameter node are higher stiffness and easy accessibility to solid format, at the expense of weight, sketch and build times. In an effort to combat these imperfections, alternative methods of optimization such as topology optimization should be investigated in the future study.

Conclusion:
In this article, two variations of the form-finding methods for SF nodes were demonstrated in terms of structural optimization. Design procedure on the investigation of the structural properties of the nodes was carried out and the functional testing apparatus was described thoroughly. The experimental and modeling results show that each form-finding method has some advantages over each other. E.g., on the one hand, the node designed by fatness parameter method delivers lighter product with higher stiffness per unit of mass, while on the other hand, by using curve parameter method, the more accessibility to solid format of the CAD model and the higher stiffness will be resulted. At last, Apart from the advantages and disadvantages of each design method, this article introduced systematic approaches to design and development of such components with a wide range of configurations and complex geometries.

References:
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[3] Wachsmann, K.: The Turning Point of Building: Structure and Design, Reinhold Publication Corporation, 1961.