COMPUTATIONAL DESIGN FOR ADDITIVE MANUFACTURING OF A DOUBLY CURVED GYROID LATTICE WALL

A Research on a Computational Design for Additive Manufacturing Workflow

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Abstract. Additive Manufacturing (AM) for large format building components is becoming popular. AM has allowed architects and engineers to rethink the process of manufacturing building components through lightweighting strategies associated with the processes of AM. AM allows just-in-time production of components which reduces the need for large storage space and minimizes the carbon footprint of the supply chain by bringing the production closer to the actual construction site. However, the feasibility and efficiency of large format fused filament fabrication (FFF) for large building components are still unclear. This paper presents a Computational Design for Additive Manufacturing (CDfAM) workflow of a doubly curved gyroid lattice wall as part of the research on the technological affordance of large format planar FFF for a doubly curved gyroid lattice wall and the feasibility of 3D printing without support structures.

Keywords. Design for Additive Manufacturing, Fused Filament Fabrication, Large-Scale Additive Manufacturing, Computational Design, Lightweighting

1. Introduction

Large format Additive Manufacturing (AM) for building components is gaining traction in the architecture, engineering and construction (AEC) Sector. AM allows just-in-time production of components which reduces the need for large storage space and minimizes the carbon footprint of the supply chain by bringing the production closer to the actual construction site. Design for Additive Manufacturing's (DfAM) lightweighting strategies allow building components to be designed and manufactured with minimal material and little wastage. With AM, you can design components that are lighter and higher-performing. DfAM provides design freedom for designers to design and manufacture components with complex shapes which traditional manufacturing methods like Computerized Numerical Control milling machines are unable to produce, especially for components with complex internal surfaces. DfAM

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utilizes the lightweighting strategies such as a) parts consolidation, b) variable shelling, c) topological optimization, d) conformal ribbing and e) latticing. These five lightweighting strategies help to improve the design of a component such that it is lightweight without compromising its strength and in addition uses less material to manufacture the component. Using less material reduces the carbon footprint of the produced component.

Traditional manufacturing of a functional product usually consists of assembling different parts together using fixing methods like welding, bolting or riveting. The first lightweighting strategy, parts consolidation, merges multiple parts without any fixing and without compromise in its functionality. The second lightweighting strategy, variable shelling, uses Finite Element Method (FEM) structural analysis results to drive the creation of variable thickness of the external skin of a product. Materials are removed where stresses are lower and further reduce the weight of the product while maintaining the geometry of the external shape. The third lightweighting strategy, topological optimization, is a mathematical method that optimises a material composition within a given volume for a given set of loads, boundary conditions and constraints with the goal of maximising the performance of the component. A design region will have loads and restraints applied to it and the material in the design region will be gradually carved away until design constraints and objectives are met. The resultant optimised form is usually organic, hence additive manufacturing is usually the most appropriate manufacturing method used to manufacture the component. The fourth lightweighting strategy, conformal ribbing, enables walls for a component to be thin and light while improving its resistance to buckling through the creation of ridged grids on the thin surface of a component. The fifth lightweighting strategy, latticing, reduces the weight of a component through the use of lattice structures to replace a solid mass. Lattice structure also may imbue extra strength to the component through its geometic configuration. There are three common types of lattice structures, a) surface lattice, b) strut lattice and c) planar based lattice. Surface lattice is a "lattice that is generated from trigonometric equations. Modifying the equation controls the shape, size and density of the 3D structure" (Gen3D, 2022). Strut lattice is a "lattice that consists of a series of rod-like forms that are connected in different orientations to form the different unit cells of the lattice" (Gen3D, 2022). Planar based lattice is a "lattice created as a periodic pattern in a 2D plane and then extruded in a single direction to create the 3D structure" (Gen3D, 2022).

For building components like walls, a large format additive manufacturing process that utilizes robotic spatial fused filament fabrication (FFF) is able to print lightweight walls with a conformal strut lattice. However, planar FFF printing is the most widely used technology for 3D printing (Naboni et al., 2019) but is not ideal for printing thin lightweight strut lattice. Planar FFF printing is more suitable for printing surface lattice or planar lattice incremental fused planar layers. In addition, Planar FFF can be quickly implemented with a gantry type 3-axis 3D printer and does not need a complex 6-axis robotic AM system. If building components can be printed with the planar FFF method, it will be more accessible to small and medium enterprises (SMEs), allowing quicker and easier adoption of large format additive manufacturing by SMEs in the AEC sector. Hence this paper looks at the feasibility and efficiency of large format FFF for additive manufacturing of building components.

2. Research Methodology

The research uses a Computational Design for Additive Manufacturing (CDfAM) workflow of a doubly curved gyroid lattice wall as part of a research to study the feasibility and efficiency of large format planar FFF for large format architectural components. Gyroid lattice is selected over strut lattice because gyroid is better at ensuring privacy and also able to screen off noise effectively. A sample of a gyroid unit cell is shown in Figure 1. The comparison of surface lattice with strut lattice is not part of this paper. Readers may refer to Du Plessis (2018), Bernhard et al. (2021) and Wang et al. (2022) for a comparison of different lattices used in additive manufacturing. The CDfAM workflow shown in Figure 2 consists of three steps, a) computational design of a doubly curved wall, b) populating a gyroid lattice and c) additive manufacturing of doubly curved gyroid lattice wall. The research looks at two questions: a) what is the technological affordance of using 3D modelling software to generate a conformal gyroid lattice for a doubly curved wall? and b) is it possible to use a large format FFF printer to print a doubly curved gyroid lattice wall without support structures in order to reduce the manufacturing time and material used?

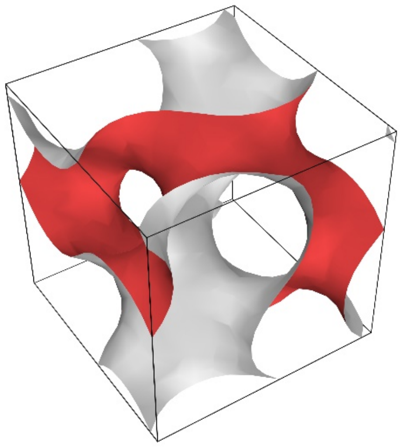

Figure 1. Gyroid unit cell

To look at the technological affordance of generating a conformal gyroid lattice, large number of gyroid unit cells will be generated incrementally until it becomes intractable to generate more gyroid unit cells. Grasshopper, a parametric modelling tool that plugs into the 3D modelling software, Rhinoceros, will be used to generate the gyroid lattice.

Second, the research looks at the feasibility of using a large format planar FFF printer to print the doubly curved gyroid lattice wall without support structures to reduce the 3D printing time. FFF for surfaces with inclination more than 60o would typically require support structures or else the layers will collapse before it solidifies. For a gyroid lattice wall with thousands gyroid unit cells, 3D printing it with support structures will increase the printing duration close to 2 times and the use of polymer filaments.

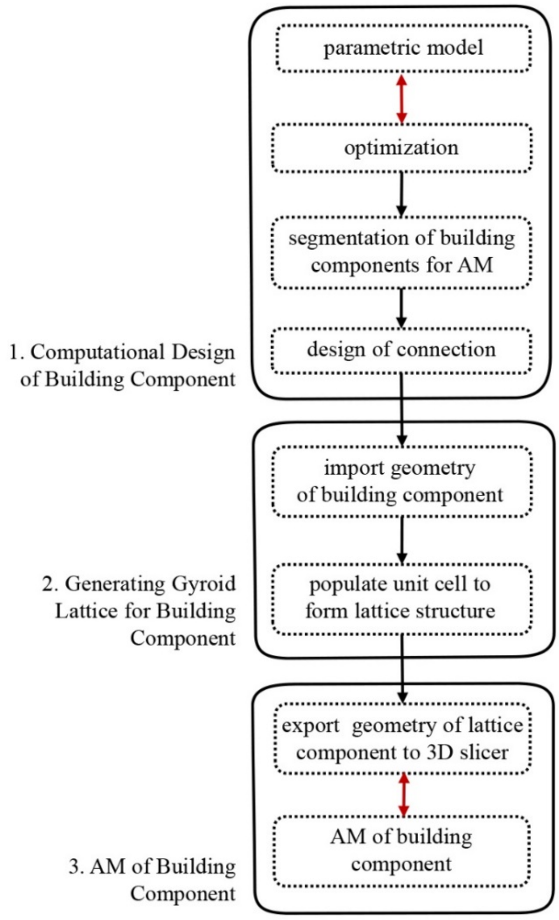

Figure 2. Diagram of CDfAM workflow

3. Computational Design for Additive Manufacturing

This section will describe in more detail the processes and issues encountered during three steps of the Computational Design for Additive Manufacturing (CDfAM) wokflow. The three steps are, a) computational design of a doubly curved wall, b) populating gyroid lattice and c) additive manufacturing of doubly curved gyroid lattice wall.

3.1. COMPUTATIONAL DESIGN OF A DOUBLY CURVED WALL

A 50mm thick doubly curved wall with overall length of 6m and a height of 3m is parametrically modelled with Grasshopper. The self-supporting doubly curved wall design is structurally optimized with Karamba3D, a parametric structural engineering plugin to Grasshopper. The parametric model of the doubly curved wall is shown in Figure 3. The parametric model is created with 3 interpolated curves. Seven vertices on the lower two interpolated curves are controlled parametrically along the y-axis.

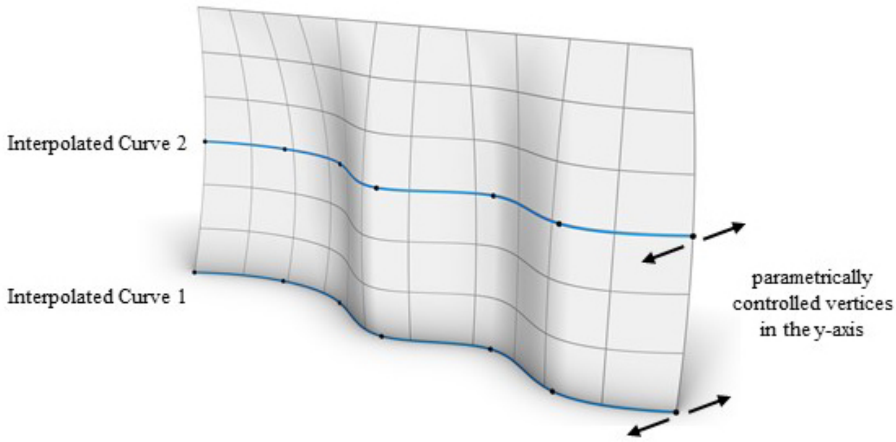

Figure 3. Parametric model of doubly curved wall

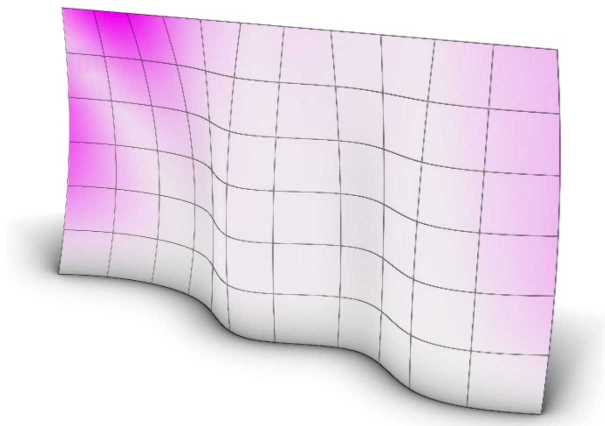

Figure 4. Optimized design of doubly curved wall

The design phenotype is defined by the parametrically controlled loft surface formed by the three interpolated curves. The design for the doubly curved wall is structurally optimised using the optimisation plugin, Galapagos. The design is optimised by minimising its maximum displacement. The optimisation was done with a small population of 10 and ran for 10 generations which was shown to be effective for design exploration (Caldas and Norford, 2002). Figure 4 shows the optimised design from the optimization with a maximum displacement of 2mm.

3.2. GENERATING THE GYROID LATTICE

The first research question looked at the technological affordance of using 3D modelling software to generate conformal gyroid lattice on a doubly curved wall. The generation of a large number of gyroids over a large surface area can become computationally intractable and cause the 3D modelling software to stall.

To generate the gyroid lattice for the doubly curved wall, the Millipede plugin to Grasshopper is used. The Millipede plugin has features to create isosurface meshes like a gyroid from volumetric scalar fields. Millipede was tested to see how fast it is able to populate a gyroid lattice and what the maximum number of gyroid unit cells Millipede can populated before it becomes intractable. The result from testing the limit of Millipede to generate gyroid lattice by incremental numbers of unit cells is shown in Table 1. Millipede is unable to generate 27,000 or more gyroid unit cells. Grasshopper stalls because of an overly large number of faces in the mesh model of the gyroid lattice. A single gyroid unit cell of 50mm3 has 881 mesh faces which means there 23,787,000 mesh faces for a gyroid lattice of 27,000 gyroid unit cells. However it is not an issue for the design of the doubly curved wall of overall length of 6m and height of 3m. The doubly curved wall only requires 3,200 gyroid unit cells.

To populate the gyroid unit cells on a doubly curved wall with Millipede, the doubly curved wall had to be subdivided into individual three-dimensional cells. The Pufferfish plugin is used to create the wall of subdivided cells from the surface of the doubly curved wall shown in Figure 5. A gyroid unit cell is then mapped into the subdivided cells to form the doubly curved wall of gyroid lattice shown in Figure 6 such that the edges of all gyroid unit cells match the edges of the adjacent gyroid unit cells to form a continuous surface that conforms to the volume of the doubly curved wall.

Number of gyroid unit cells (Unit Size: 50 x 50 x 50mm)	Time taken to generate gyroid unit cells (Millipede)
1,000 (10 x 10 x 10)	13.6
8,000 (20 x 20 x 20)	620.8
27,000 (30 x 30 x 30)	could not generate

Table 1. Comparison of generating gyroid unit cells with Millipede

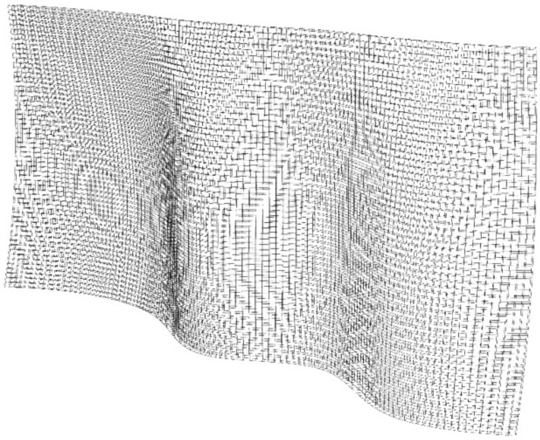

Figure 5. Subdivided cells for mapping a gyroid unit cell

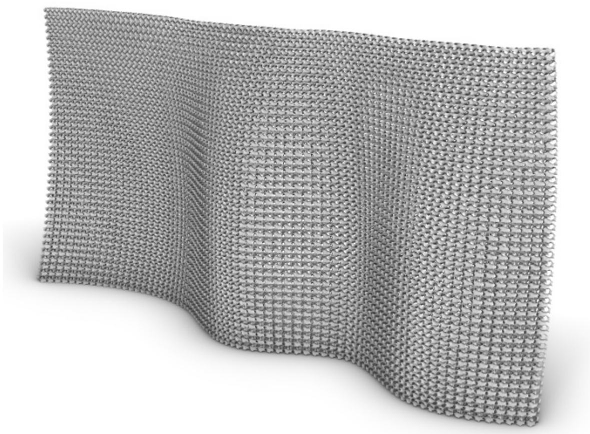

Figure 6. Doubly curved gyroid lattice wall

3.3. ADDITIVE MANUFACTURING

The second research question looks the feasibility of using a large format planar FFF printer to print the doubly curved gyroid lattice wall without support structures to reduce the 3D printing time and material for 3D printing. Unlike standard desktop FFF printers large format FFF printers will have its printing issues amplified due to a large number of controllable process parameters for FFF (Ali et al., 2022). To manufacture the doubly curved gyroid lattice wall, the wall has to be divided into segments that can fit the build volume of the large format 3D printer shown in Figure 3. For the purpose of this paper a 1:1 part sample of 50mm by 450mm by 450mm is test printed. The digital model of the part sample was exported as a 3MF file and imported into a 3D slicing software. A 3D slicing software converts the 3D model into multiple 2D layers through the 3D model which is become the toolpaths for the 3D printer to deposit the thermoplastic material to form layers of materials. The 3D slicing software generates the g-code which is a series of instructions controlling the FFF printer.

The large format 3D slicer, Blade, was used to create the g-code. Two prototypes were manufactured using high temperature biopolymer filament. The first prototype, Prototype 1, shown in Figure 7 was printed with the intent to reduce the amount of supports for the gyroid lattice wall sample. Supports are typical needed for components that have an overhang of 60º or more. However, the overuse of supports will increase the total manufacturing time. Hence, for Prototype 1, we only printed supports from the baseplate upwards to the first overhanging layer of the component.

Prototype 1 took 65hrs to print. Its overall geometry is discernible however it has collapsed strands of extrude filaments at the free edges that did not fuse well, along the two vertical sides of Prototype 1 shown in Figure 7. In addition, we observed that for bridges where two overhangs with angles more than 60o meet, the layers were printed well without any collapse.

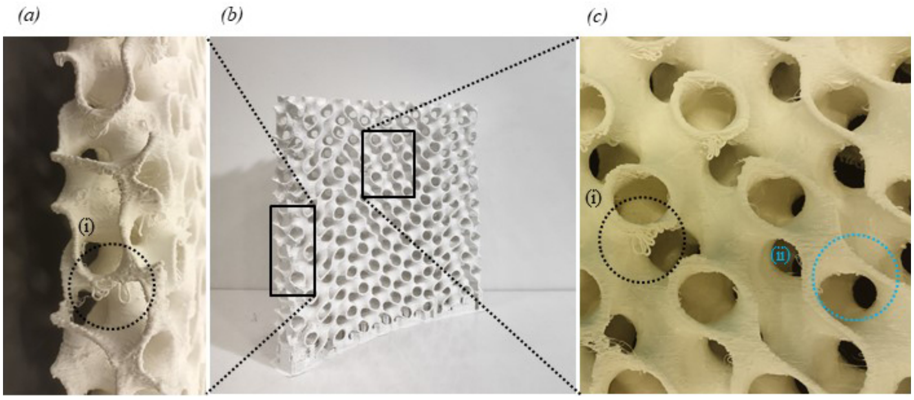

Figure 7. Prototype 1 - (a) collapsed overhang with strands; b) view of printed sample with supports up to the first row of overhangs; (c) a collapsed overhang (i) and a bridge that was fused well without any collapsed strands (ii).

To address the collapsed free edges along the vertical sides of the 1:1 part wall sample, a second sample, Prototype 2, is printed. Prototype 2 shown in Figure 8 is printed with a tree support to see if the supports can help circumvent the problem of the collapsed strands observed at the overhanging free edges of Prototype 1. Prototype 2 took 78hrs. The tree support did help in supporting the overhangs on the vertical edges of Prototype 2. However, the supports were difficult to remove cleanly from the surface of the 3D print shown in in the last image of Figure 8. Prototype 2 also shows collapsed strands in localised area along the front and back of Prototype 2. Full standard supports were considered but were not implemented because the estimated print time was 132hrs and the removal of numerous supports was considered not practical.

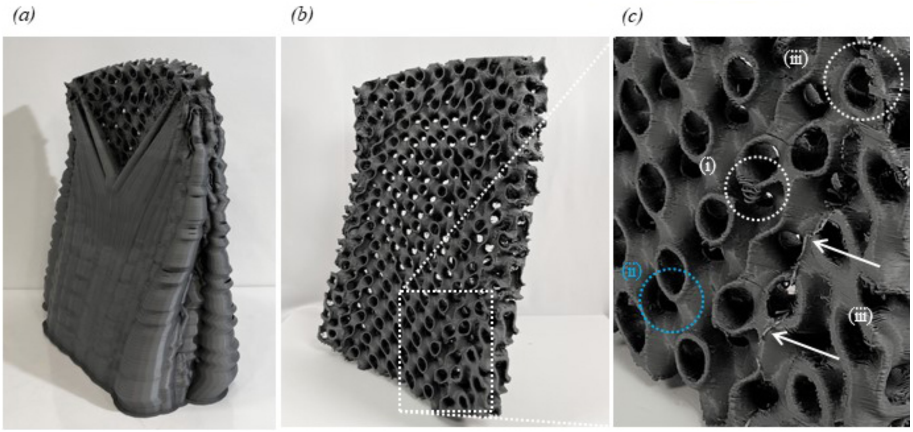

Figure 8. Prototype 2 - (a) with a tree support; (b) tree support removed to reveal gyroid lattice; (c) collapsed overhang (i), overhang less than 5mm which fused well without any collapsed strands (ii) and, marks left by tree supports (iii)

4. Conclusion and Limitations

The research in this paper started with two questions: a) what is the technological affordance of using 3D modelling software to generate a conformal gyroid lattice for a doubly curved wall?, and b) is it possible to use a large format FFF printer to print a doubly curved gyroid lattice wall without support structures in order to reduce the manufacturing time and material used?

For the first research question, the research found that the Millipede plugin becomes intractable when it generates approximately 27,000 gyroid unit cells. However, the software test is limited to 3 samples and dependant on the computer that was used. Further study with more sample sizes has to be done in order to give a more accurate characterization. In addition, the limitation in generating gyroid lattice is dependent on the size of the building component and the size of the gyroid unit cell used. Although the research in this paper is constraint to the design of a doubly curved wall, the CDfAM workflow provides a framework for us to test other architectural components for large format FFF.

For the second research question, large format FFF is not a plug and play system which guarantees a perfect print every time especially for complex surface structures like a gyroid lattice. Printing without support structures in order to reduce the manufacturing time and material used poses a challenge for printing complex surface structures with overhanging edges. The two prototypes revealed that free edges with an overhang of 5mm or more are likely to collapse. Bridges formed by two overhanging edges that meet are unlikely to collapse. To prevent the free edges of a gyroid lattice from collapsing, first, one needs to be mindful to ensure that all free edges have overhangs less than 5mm during the design of the gyroid lattice. Second, since the prototypes are printed using standard default settings, more test prints and a more detailed parametric analysis of both the gyroid lattice and the printer settings have to be looked at. Accurate settings for large format FFF can be looked into with a wider range of parametric analysis through a design of experiments to help calibrate both the design and the printer.

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