Biomimetic Generative Morphologies for 3D-Printing

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Abstract

The recent development of computational form-finding and additive manufacturing (AM) has broadened the opportunity for extensive exploration into the design of highly-efficient structural systems. The research presented in this paper investigates the potential to which topology optimisation and AM can be used to extend the boundaries of the design of high-performance construction systems. The main objective of this research is developing computational design to digital fabrication workflow for the construction of robotically controlled 3d-printed building assemblies. The topology optimised structure was developed using a novel topology optimisation workflow. This process builds up material only in areas of high stress based on biomimetic principles found in nature, maximising structural performance while minimising weight. The inherent qualities of AM, such as its ability to create complex geometries with high levels of accuracy and construction automation, make it an ideally suited method to produce these prototypes. This paper includes the development of generative design methodologies for AM workflows. By implementing these robotically controlled AM processes at multiple scales, this work can have wide-reaching applications in the construction industry. This paper presents the overall research methodology with an emphasis on computational design, structural analysis, evaluation, and the fabrication of scale models prototypes..

Keywords: optimisation, topology optimisation, additive manufacturing, 3d-printing, robotic fabrication, construction automation, form-finding, generative design, sustainability, high-performance design.

Figure 1: 3d-printed model of topologically optimised U-House prototype.

1 Introduction

Topology optimisation is a computational form-finding method for determining the best possible forms based on optimal material distribution within a discretised design space with a specific set of boundary conditions, including loads, supports, and other design constraints. Through an iterative process, the algorithm refines material distribution within the model volume boundary to meet a specific set of performance goals to maximise the performance of the structural system by increasing stiffness while reducing the weight by reserving material only in areas of high stress. These goals follow similar biomimetic principles found in nature for animals, birds, and plants where optimal strength-to-weight ratios are significant to ensure the efficient use of limited material resources (Bendsoe and Sigmund 2013) (**fig. 2**). There are various topology optimisation algorithms including Evolutionary Structural optimisation (ESO), Bi-directional Evolutionary Structural optimisation (BESO), and Solid Isotropic Microstructure with Penalization (SIMP). The work presented in this paper focuses on BESO and generative design methods (Rozvany 2009; Aremu et al. 2010).

Topology optimisation has transformed major mechanical engineering industries, including automotive and aerospace, which can typically achieve 20-40% weight savings (Cavazzuti et al. 2011; Zhu et al. 2016). On the other hand, traditional construction practices have seen little of the technological revolution that has transformed these fields and there still lacks substantive change to the construction framing of houses in decades. Despite the efforts to implement topology optimisation in large scale construction applications, full scale built examples are rare. This is partially due to a) the lack of a workflow to prepare complex topologically optimised 3d models for fabrication, b) the limitation of the current large scale AM methods c) the limitation of novel materials such as biodegradable reinforced polymers that are sustainable and more suitable for AM methods.

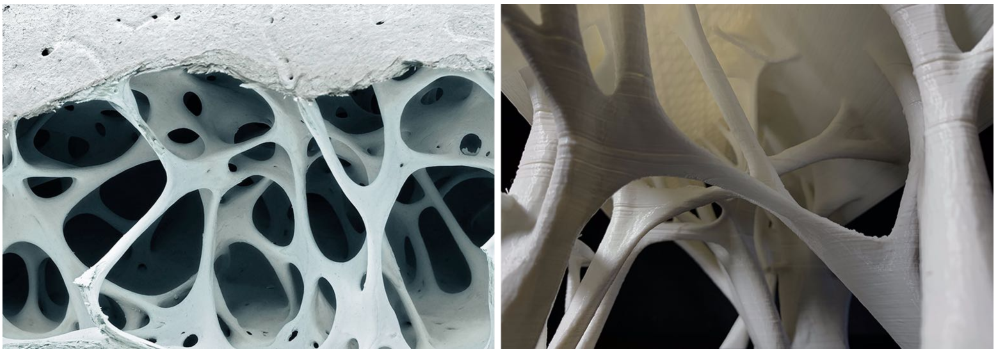

Figure 2: Biomimetic principles of topology optimisation: (a) Bird bone tissue. Coloured scanning electron micrograph (SEM) of a starling's skull. The internal bone structure is optimised to provides support and strength while maintaining minimal weight. [Photo credit: Steve Geschmeissner / Science Photo Library], (b) detail of the topologically optimised U-House 3d-printed model.

Current construction relies on subtractive methods that produce significant material waste, which, in turn, has a significant impact on the environment. Additive manufacturing (AM), also known as 3d-printing, offers innovative, safer, cost-effective, and environmentally sustainable alternatives to conventional construction. AM has the potential to eliminate construction waste, and when paired with the biomimetic design principle such as topology optimisation, AM can be easily adapted to create the complex geometric forms required for higher structural efficiency.

Furthermore, biodegradable and recycled composite material can be used in 3d-printing for sustainable building material alternatives to wood, masonry, concrete, and steel. However, AM and topology optimisation of components have been limited to small scale applications and has not been fully implemented in the construction industry. Addressing these possibilities, this paper presents an overview of a novel design to fabrication process of topologically optimised framing structures composed entirely of biodegradable composites to serve as a future alternative to the current conventional wood structural framing used in building construction.

2 Background

The advancement of robotic fabrication and material science has pushed the boundaries of AM. Currently, the four major large scale 3d-printing polymer-based systems are: Mesh Mould, Scaffold AM, 3d Curve Printing, and the Big Area Additive Manufacturing (BAAM) (Yin et al. 2018). Each of these systems has its strengths and limitations. The Mesh Mould system was developed in 2013 at the Swiss Federal Institute of Technology in Zurich (ETH). Mesh Mould uses a polymer lattice that is extruded with a robotic arm as an armature for a concrete formwork (Hack et al. 2013, 2015). The Mesh Mould method has great potential for on-site fabrication. Nevertheless, it was only tested as a prototype and has not yet been implemented into full-scale application.

Scaffold AM was introduced in 2015 by Branch Technology, and similar to Mesh Mould, Scaffold AM uses a robotically controlled extruder to create a network of thermoplastic polymer lattice structure as a scaffold for cementitious materials. Both Mesh Mould and Scaffold AM were designed with the intention of using less material. However, they are currently limited to non-load bearing construction applications.

3d Curve Printing was developed at the Institute for Advanced Architecture in Catalonia (IAAC), Spain (Jokic et al. 2014). 3d Curve Printing uses Plastic that solidifies instantly and an extruder that is attached to a robotic arm allowing it to print smooth or irregular surfaces without the need for additional support structures.

The Big Area Additive Manufacturing (BAAM) was developed as a collaborative effort by Cincinnati Inc. in Ohio and Oak Ridge National Laboratory (ORNL) in Tennessee. The BAAM system extrudes melted fiber reinforced polymer composites on a robotically-controlled heated platform (Love and Duty 2015). Polymer-based 3d printing in the architectural application was first tested at a full-scale wall assembly using the BAAM System in the Additive Manufacturing Integrated Energy research project (Biswas et al. 2016; Guerguis et al. 2017).

The research presented in this paper contributes to these efforts by developing a novel workflow for robotically controlled additive-manufacturing processes using a Kuka robotic arm with polymer-based pellet feed Fused Deposition Modeling (FDM) end effector extruder.

3 Computational design and form finding

The computational design and form finding workflow for this research was developed with the objective of designing a load-bearing structural framing for a house prototype, the U-House. The U-House is a 120 square meter model with a standard gabled roof that consists of two roof sections sloping in opposite directions where the horizontal highest edges meet to form the roof ridge (**fig. 1**). The computational design procedure is broken down into four steps which are described in detail in following sections: 1) 2d topology optimisation using stiffness-based Bi-directional Evolutionary Structural optimisation (BESO); 2) 3d topology optimisation using generative design; 3) finite element analysis (FEM) to evaluate the design performance of generative design iterations; 4) post-processing of mesh model and G-Code generation for 3d-printing (**fig. 3**).

The preliminary workflows described above were an essential step in the design process. The formal design guidelines derived from interpretations of the topology optimisation form-finding, finite element analysis of the generative design outcome. Different mesh post-processing approaches were tested to prepare the model for 3d-printing.

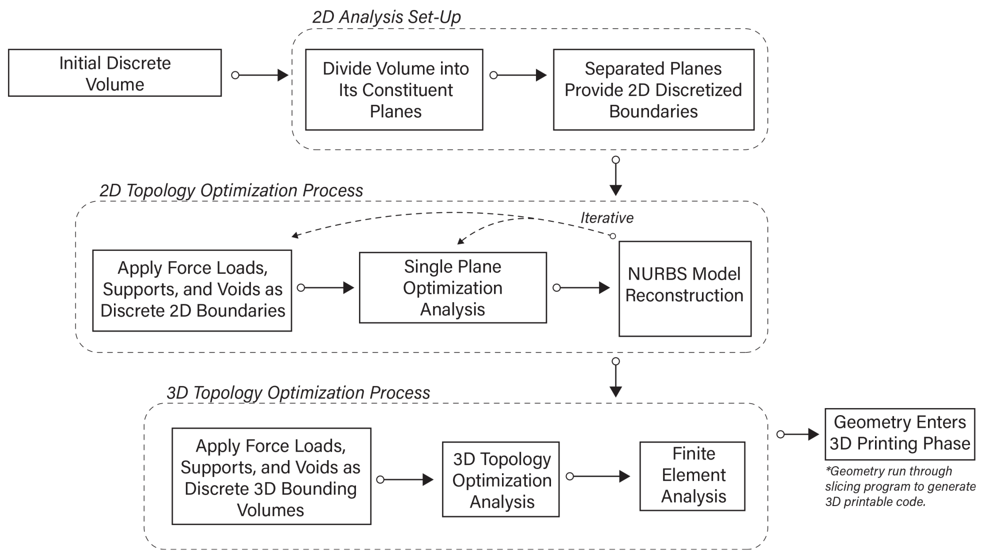

Figure 3: Workflow diagram of computational form finding, topology optimisation and 3d-printing.

3.1 Two dimensional topology optimisation

The 2d optimisation process provides an efficient method for understanding the possibilities of topology optimisation outcome of a given discretised volume in relation to specifically defined force load and support combinations. The 2d topology optimisation algorithm was generated using Millipede plug-in for McNeel Rhinoceros and Grasshopper (Michalatos and Payne 2014). Since these 2d studies can be generated quickly and with relatively low computing power, compared to 3d optimisation, they allow for a high degree of iteration in the design process. The outcome of the optimisation process depends strongly on the choice of load cases and support locations. The speed of iteration of this step helped the research team to rapidly make changes to the design space for various loads, boundary conditions, and constraints. To illustrate this aspect, we investigated the influence of varying load scenarios on each surface of the U-House model with the goal of maximising stiffness while reducing weight through optimal material distribution.

At first, a basic volume of the structure was created, then it was broken into individual surfaces. Façades and roof sections were defined as discretised boundaries for optimisation. Specific load cases were defined based on each surface location within the structure. The topology optimisation iterative steps could be repeated to refine the outcome until all the design criteria have been satisfied (**fig. 4** and **5**).

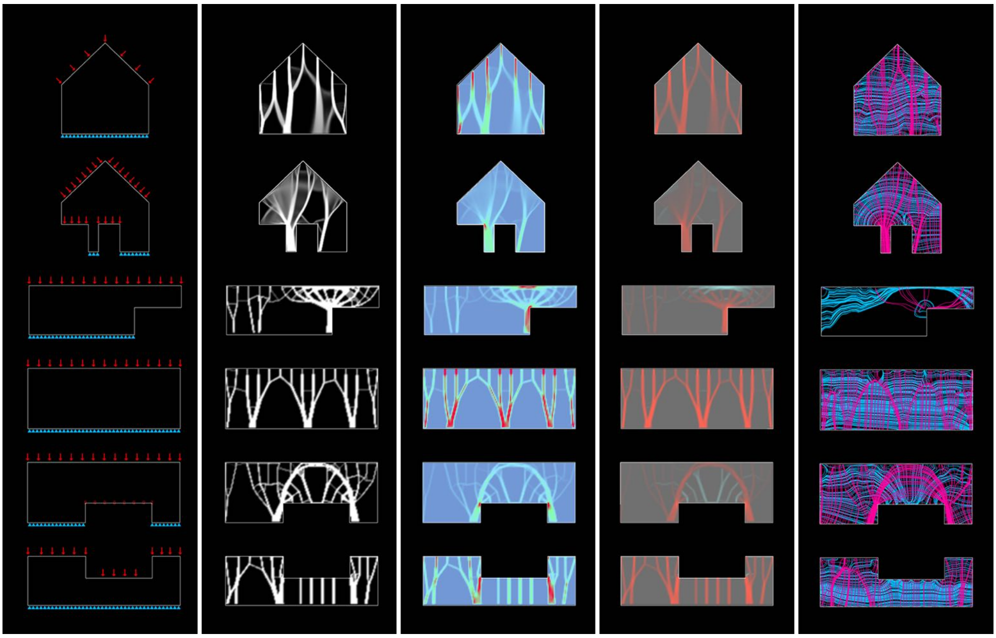

Figure 4: 2D topology optimisation of the unrolled surfaces of the U-House: (a) façades and roof boundary conditions with defined loads, voids, and supports, (b) Stiffness Factor, (c) Von Mises stress, (c) principal Stress, (e) principal stress lines.

Several workflows were investigated to interpret the 2d topology optimisation results to a 3d model while maintaining the initial design goals and the performance criteria. Initially, the team developed a hybrid process based on the results from the 2d topology optimisation as reference for the reconstruction of a 3 x 1.25 m wall panel by creating a low polygon mesh for a free form surface using T-spline a Non-Uniform B-Spline (NURBS) surfaces modeling plugin for McNeel Rhinoceros with control grids permit T-junctions (Sederberg et al. 2003). This workflow allows for geometrically continuous construction of (NURBS) surfaces of any complex topology. This method is suitable for initial testing of topology optimisation results, requires no post-editing and produces a mesh of sufficient fidelity for direct 3d-printing. However, this method requires additional manual modelling, which could present a challenge for larger and more complex models (**fig. 6**).

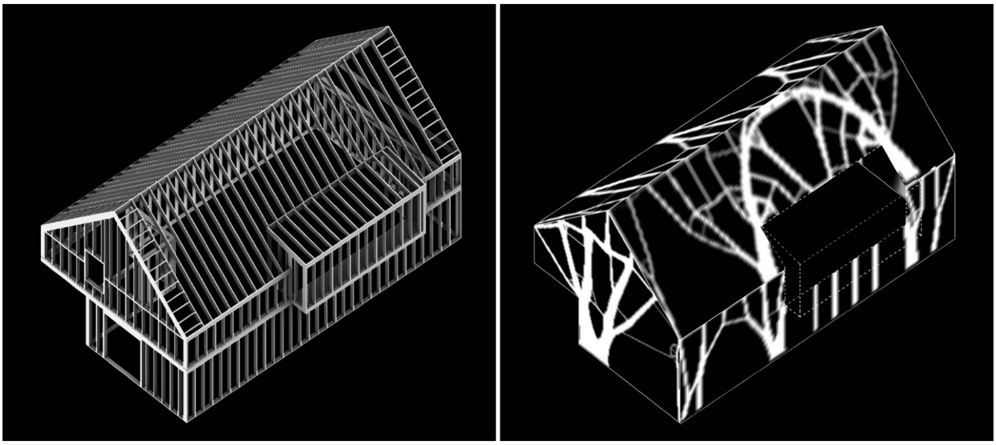

Figure 5: Traditional wood framing in comparison to the topologically optimised model: (a) standard wood framing of the U-House 400 mm on center, (b) assembled topologically optimised planar surfaces of the U-House model.

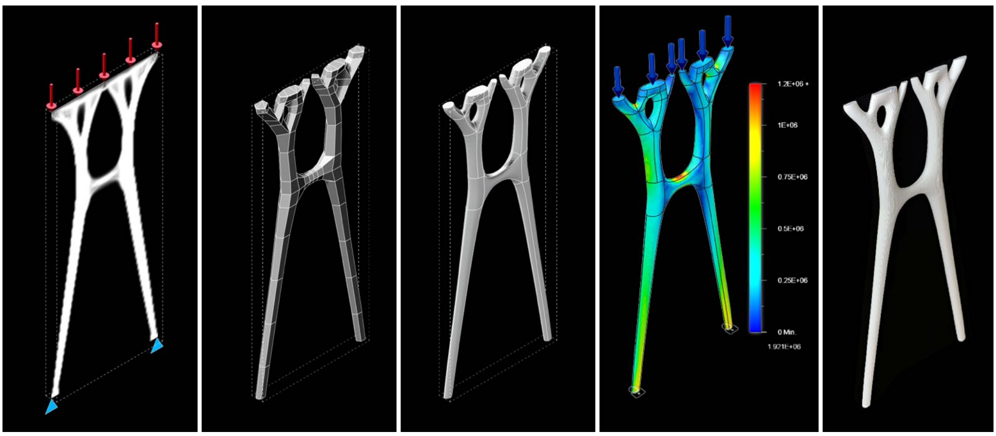

Figure 6: Reconstruction of the 2d topology optimisation: (a) initial stiffness mesh representing material distribution of the topologically optimised panel, (b) T-spline low-polygon mesh, (c) smooth NURBS surface, (d) finite element stress analysis (e) 3d-printed model.

Additional finite element stress analysis of the topologically optimised models was performed to validate the performance of the 3d model and to evaluate the initial design criteria. The result was a 33% material reduction with higher stiffness compared to the standard wood framing wall panel of the same size.

3.2 Three dimensional topology optimisation and generative design

Three dimensional topology optimisation or shape optimisation is generated based on paths between fixed constraint and the load applied on the volume boundary, including preserved regions, voids, and obstacle geometry in 3d space. The process of topology optimisation minimises the compliance of the elastic structure subject to constraints on the available material while maximising stiffness. The iterative algorithm uses a numerical method for determining optimal material distribution. In this implementation, the elasticity equations are solved using finite element, and sparse direct solver. The design field is resented by a multi-resolution finite element mesh volume, and the design update is performed using gradient-based criteria. The output mesh of shape optimisation often requires model reconstruction, post mesh editing and smoothing algorithm for the generation of parts that are ready for 3d-printing.

Similarly, generative design process starts with the definition of a boundary volume, load cases and constraints including initial, preserved and obstacle geometries in Fusion 360 which is a cloud based modelling and computational simulation software developed by Autodesk. Generative design takes into consideration stress distribution through an iterative process. Each iteration evaluates areas of high and low stress within the defined volume boundary. In low-stress areas, the algorithm gradually removes material and correspondingly in high-stress areas preserves material while avoiding obstacle parts. The process goes through different iterations until all the design criteria with a specified targeted factor of safety have been fulfilled (**fig. 7**).

Generative design iterative processes of 3d topology optimisation generate editable T-spline geometry and take into consideration constraints influenced by manufacturing methods such as 3-axis milling or additive manufacturing. It can solve complex design problems such as consolidating parts, minimising mass while maximising stiffness compared to all solid part of similar design. Next, each iteration was compared and evaluated to meet the design objectives. The result of the finite element topologically optimised mesh was converged and converted into a smooth T-spline surface, which either can be saved as Stereolithography (STL) file and printed directly or can be exported as T-Spline surface for further editing. One of the significant advantages of the generative design workflow is that the final model requires virtually no post-processing and is ready for slicing and g-code generation for 3d printing. The algorithm generated 45 iterations reducing the overall volume of the topologically optimised model to 4.98 cubic meters compared to 8.73 cubic meters of standard wood framing, achieving a total of approximately 43% material reduction (**fig. 8**).

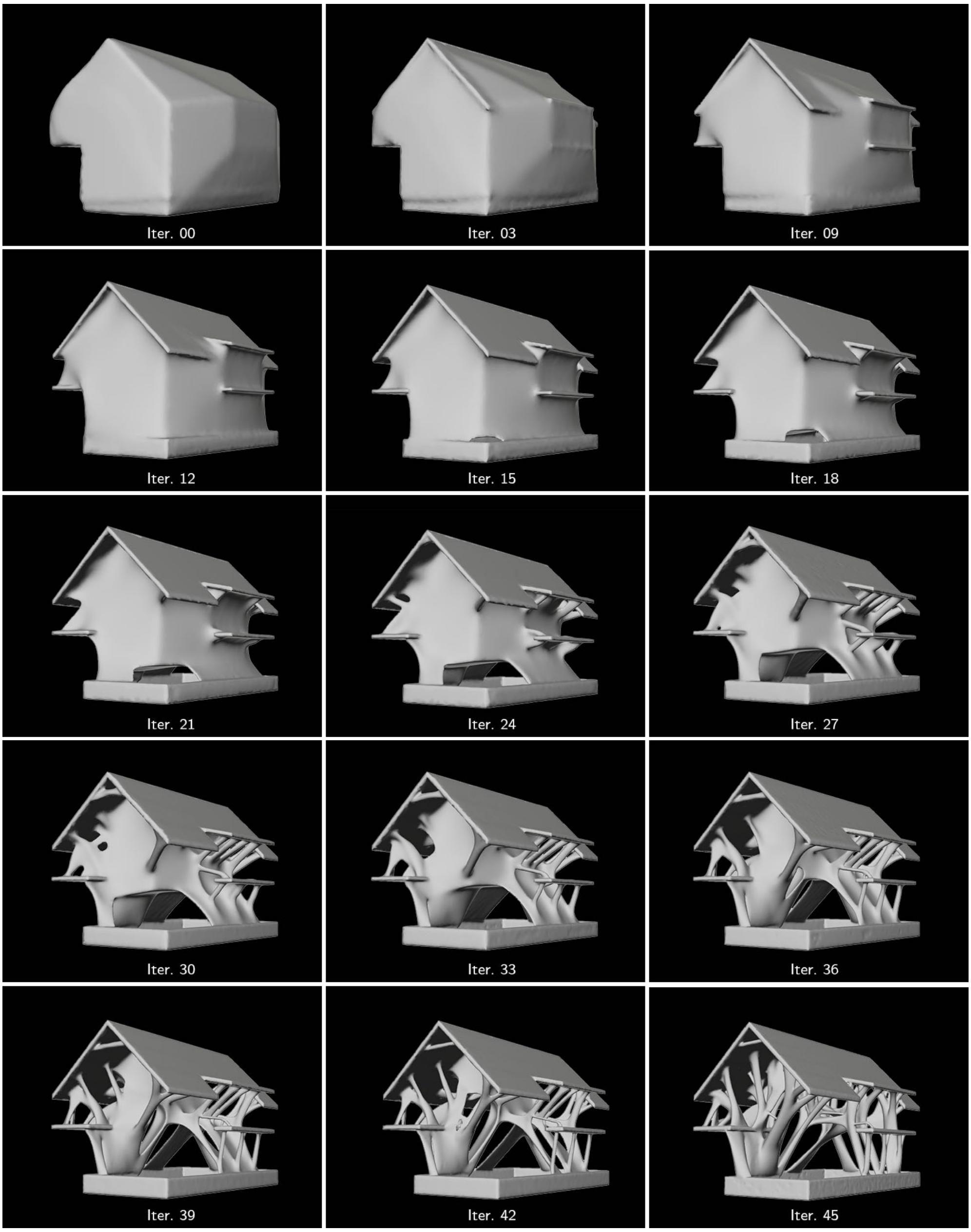

Figure 7: 3d topology optimisation: permutations of the U-House generative design for additive manufacturing fabrication method constraints.

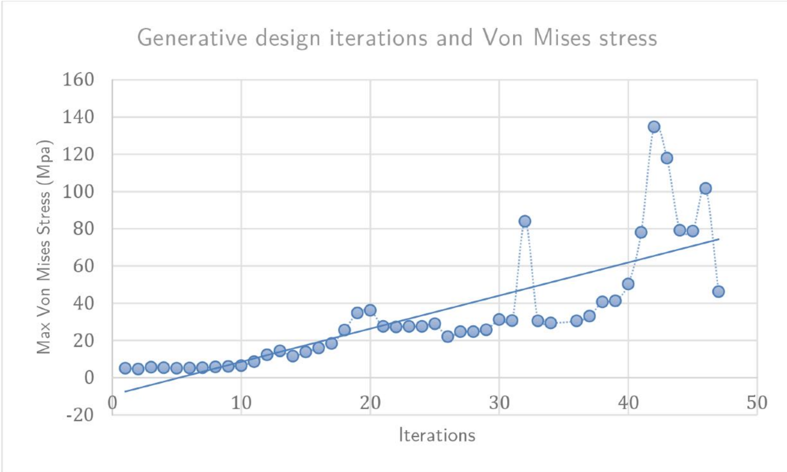

Figure 8: Iterations of the U-House generative design and Von Mises stress.

It is remarkable to see how the optimised geometries (**fig. 7** and **9**) resemble the organic forms of the natural bone structure of the starling's skull shown in **fig. 2a**. This is not a coincidence. As Wolff's law states that animal bone varies in densities based on loads applied on it (Wolff 2012), computational form-finding morphologies of topology optimisation follow the same principles that drives the weight reduction of the bird skeletal structure. Both structures need to be stiff towards applied surface pressure to resist longitudinal bending, therefore resulting in a similar distribution of the internal structural elements.

3.3 3d-printing of scale model prototype

Scale models were used to investigate the 3d-printing direction and the orientation of the models on the build plate with minimal or no support material. Preliminary 3d-printed tests of the branching of the tubular forms of the 3d topologically optimised model resulted in a self-supported geometry that does not require additional support material and can be a method to test and simulate common large-scale 3d-printing issues, such as built plate adhesion, layers delamination and overhanging parts support (**fig. 9**).

The use of large scale 3d-printed structure enables to further the understanding of the capabilities and limitations of polymer-based 3d-printing in an architectural application. The research approaches in this paper have provided new insight into the efficiency of the topologically optimised 3d-printed building structure. The use of 3d-printing scale models allows for the fabrication of high-performance topologically optimised structures at a high level of detail, accuracy, and precision. Additionally, the potential application of biodegradable reinforced polymers can provide the structural strength necessary for large-scale applications.

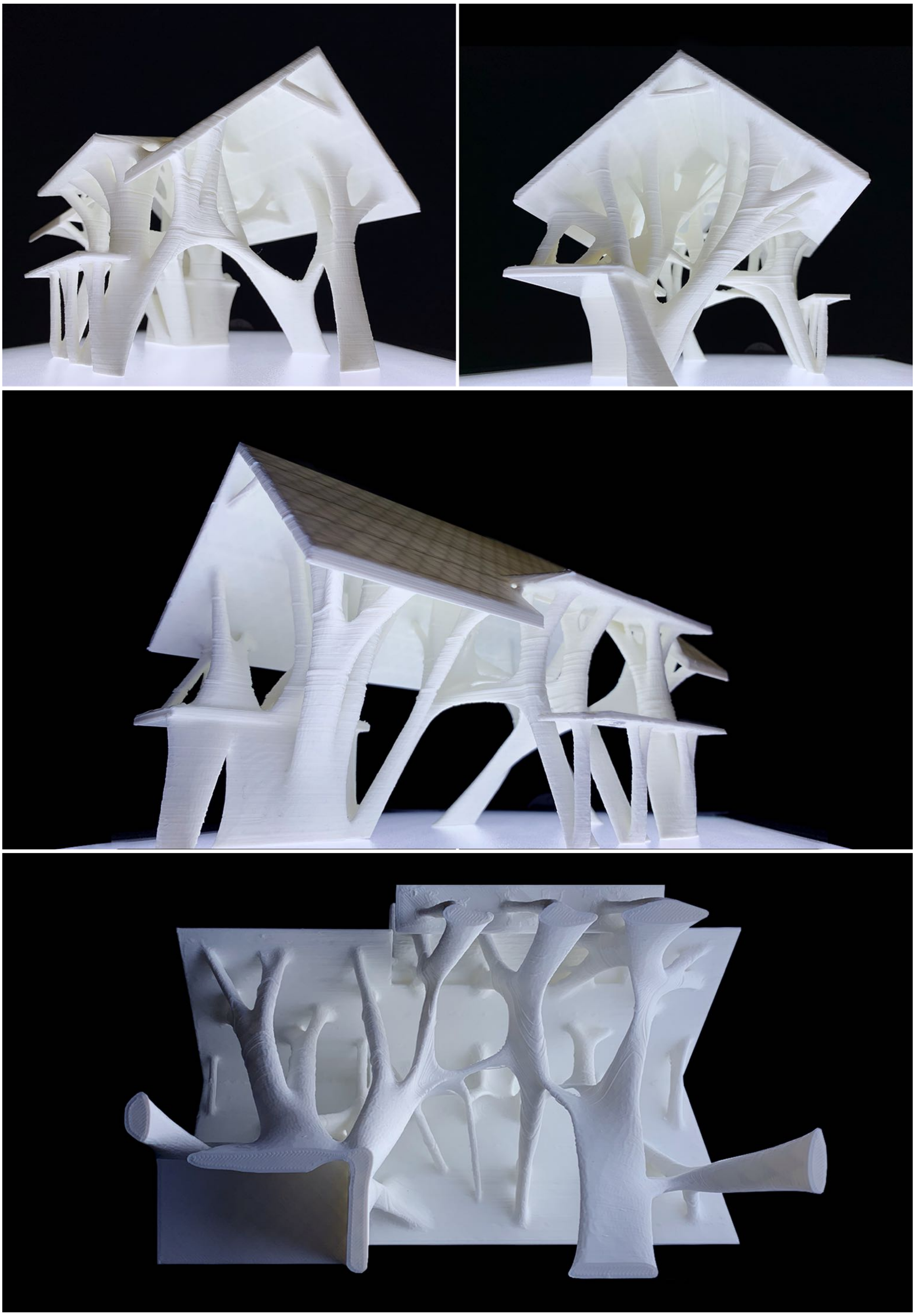

Figure 9: 3d printed model of the topologically optimised U-House structure.

4 Conclusion

With the two successful workflows described, this paper can conclude that 3d-printing can sufficiently produce high fidelity architectural components of geometric complexity directly through topology optimisation. Additionally, this paper showed new directions for the use of topology optimisation and generative design workflows, more accurate interpretations of the topology optimisation results were achieved. 3d-printing technology, combined with a customised digital workflow for the design development and production, has been successfully used to efficiently build a topologically optimised scale model prototype with optimal structural performance.

The paper only showed the successful, first results of the developed workflow of the design of high-performance topologically optimised structural frame with novel forms. This can be considered as a first validation of the approach. More significantly, the finite element analysis of the model (**fig. 6d**) showed a higher performance of topology optimisation results as compared to standard wood framing models.

In applications of robotically controlled additive manufacturing for full-scale building components for an entire house, further research must address the following challenges:

Component-based design: The framing structure would need to be divided and assembled from multiple prefabricated panels taking into consideration the location of each panel when defining boundary conditions and different load cases. Additionally, connection design between each panel will also play a significant role in ensuring the integrity of the overall structure.

Integrative systems: This paper highlights the significant potential of using 3d-printing to fabricate large-scale parts with an optimal structural performance for specific material reduction targets. Nonetheless, to harness the full potential of AM, other integrative design approaches should be considered to incorporate other systems such as mechanical electrical and plumbing systems within the printed parts.

Alternative construction material: the structural optimisation form-finding is one key aspect of the research. However, further exploration of novel materials is required for higher performance and lightweight, sustainable building material alternatives. The ‘materials by design’ approach and the utilisation of the material across length scale nano-to-macro enable highly complex designs with optimal structural strength/stiffness and manufacturability in complex forms. The authors consider this research as the first step toward a novel, fully integrated approach to construction driven by the material economy and have the potential to transform the current construction practices.

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