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REVERSE NATURES: DESIGN SYNTHESIS OF TEXTURE-BASED METAMATERIALS (TBMS)

Patel, Sayjel Vijay (1); Mignone, Paul John (1); Tam, Mark Kam-Ming (1,2); Rosen, David (1)
1: Singapore University of Technology and Design, Singapore; 2: Massachusetts Institute of Technology, United States of America

Abstract

We describe a new approach for generating micro-structures for 3-D printing called 'Texture-based Metamaterials'. Current micro-structure synthesis methods jump to install a performance goal from the outset. This is not useful in conceptual design when design goal are not yet well-defined. In order to fully realize 3-D printing design spaces, requires new exploratory methods. Using 3-D scans of natural textures as components, we can expand the catalog of 3-D printed microstructures. To do this, we introduce a new modelling procedure to generate new unit-cell geometries. Unit-cells can be repeated or combined with other structures to provide performance behavior at the macro-scale. To apply these structures in a design, we then simulate and characterize their mechanical behavior. Finally, we present a case study example to show the process and tool-chain.

Keywords: 3D printing, Design for Additive Manufacturing (DfAM), Computer Aided Design (CAD), Simulation

Contact:
Sayjel Patel
Singapore University of Technology and Design
SUTD Digital Manufacturing & Design Centre
Singapore
sayjel_patel@sutd.edu.sg

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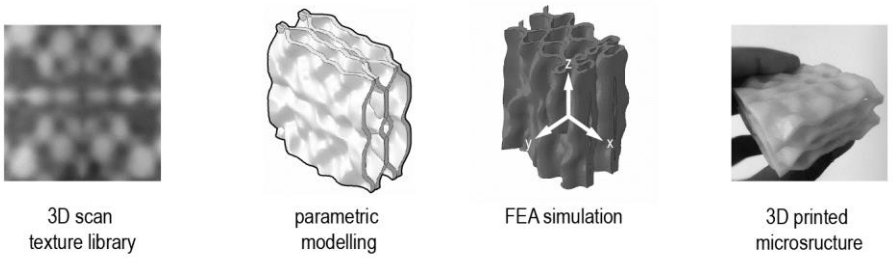
1 INTRODUCTION

Designers have long been inspired by the excellent engineering properties of cellular materials. Comprised of periodic microstructures, cellular materials optimize strength, and provide other functional benefits (Ashby, 1983). Previously, these structures were unfeasible to manufacture due to their geometric complexity and resolution. Since then, it has recently become possible to create architected cellular materials using additive manufacturing (AM).

Liberating designers from the limitations of ‘off-the-shelf’ materials, the manufacturing freedom of AM expands the range of designed behavior through microstructure (Rosen, 2007). Yet, this emerging digital playfield belies the goal-driven methods of recent micro-structure designs (Bickel et al., 2010; Schumacher et al., 2015; Ion et al., 2015). By installing well-defined performance targets from the outset, these approaches are convergent towards optimal solutions. However, most design problems are largely undetermined; especially during the initial stages of design (Dorst, 2004). As a result, there is a need for new conceptual approaches to address the growing design space of AM materials.

Addressing these issues, ‘Texture-Based Meta-materials’ (TBMs) introduces a new microstructure design process. Focusing on the design of microstructure unit-cells, TBMs are created through the procedural arraying and mirroring of 3-D scan textures. By using textures as design variables in unit-cell generation, the aim of TBMs is radically expand the solution space. Drawing from online databases of random or bio-inspired textures, TBMs allow a designer to quickly explore a broad range of microstructure designs during early-stage conceptual exploration (Figure 1).

This paper is organized in five parts: The first chapter includes a problem statement. The second chapter presents a theoretical frame for TBMs. The third chapter demonstrates the TBMs tool-chain. The fourth chapter implements the tool-chain to generate and analyse new unit-cell designs. The closing chapter considers directions for a paradigmatic shift in materials design exploration towards TBMs. Beyond the growing capabilities of manufacturing media to produce high-resolution structures, there is an explicit need for new exploratory methods to engage complexity at many design-scales. The experiments reviewed and the tools developed here are suggestive of a more general multiscale approach to design exploration and modelling.



3D scan texture library

parametric modelling

FEA simulation

3D printed microsructure

Figure 1. We propose a tool chain for sampling 3-D scan textures to promote the exploration of new microstructure designs

2 STATE OF THE ART AND PROBLEM DEFINITION

2.1 Metamaterials

A subset of designed cellular materials, ‘metamaterials’ are small structural assemblies that obtain their bulk properties from the shape and arrangement of unit-cell structures rather than from the material itself. Historically, metamaterials have been defined as manmade, macroscopic composites, having periodic structures developed to produce behaviors not found in nature. Schumacher et al (2016) relaxes the definition of metamaterials in the context of 3-D printing, to include material properties not available on 3-D printers. For instance, using geometry alone, several researchers (Ion et al., 2016; Lee et al., 2012; Nguyen et al., 2013) have been able to create designs with soft and hard regions by varying periodic unit-cells with different densities. Similarly, Bickel et al. (2010) describes a complete process to compose metamaterials to achieve specified deformation goals. This method starts with the design and optimization of single unit-cells. In turn, they are tiled to create a periodic structure. This strategy simplifies simulation by allowing for the computation of a single representative unit cell rather than the entire structure.

The range of unit-cell designs in these projects were limited by the support constraints of the 3-D printer—whereby, only structural cells with continuous void spaces were feasible. However, the recent development of new soluble support materials, robotic-enabled layer-based methods, and metal AM processes allow for the fabrication of a broader range of unit-cell designs supported by TBMs. By providing a process to generate new unit-cell designs, it is envisioned that TBMs can be extended to other meta-materials design processes.

2.2 Computational Material Generation and Characterization

For decades, the material science field has been interested in computational methods for generating materials. These methods have usually been developed to represent an actual material microstructure resulting from a fabrication process. If a computational microstructure can statistically represent an actual structure to a high-level of confidence, the need for experimental characterisation can be reduced, thus reducing research lead times and costs.

A well-established approach for computationally generating material structures is computational sphere packing. These techniques involve the arrangement of non-overlapping spheres (Torquato, 2000). The sphere packing methods have tended to emphasize microstructures produced from powder processing methods. Kriging is also another structural generation method, allowing users to quantify, predict and generate a structure using existing spatial data. This technique has also recently been used in the design and optimisation of metamaterials (Bradley, 2013).

Irrespective of the structure generation method, characterizing the structure's morphology (be it a material microstructure or a meta-material structure) using statistical means has two benefits. First, it enables a quantitative understanding of the microstructure–property relationship and the sensitivity of various descriptors of microstructure morphology, with respect to their impacts on the prediction of bulk properties. Second, based on the statistical descriptors, a structure can be reconstructed from a sample space to remove the need for repeating costly high-resolution imaging techniques (e.g., scanning or electron microscopy) whenever a digital microstructure is needed for analysis or model validation.

In this paper, instead of designing a material with target property and performance, we focus on property predictions of TMBs based on bio-inspired and random image datasets. Therefore, the core contribution is to link the TBMs microstructure morphology, its randomness, and material design variables to show that with the methods described herein, future multiscale material design efforts can successfully explore the design space.

2.3 Combinatorial Unit Stacking

Periodic cellular sandwich structures have been a key topic of active manufacturing research (Hadyn et al., 2003). Stacking of cold-formed sheet materials is an economic process for manufacturing cellular microstructures. Other research has investigated varying the organization, and stacking procedures to generate different unit-cell architectures (Mignone, 2015, 2017). This method produces new designs by combining microstructures from a library and simulating their deformation behaviour. This work has found that these methods offer shape-diversity, as well as enhanced performance. Akin to these approaches, TBMs create new unit-cell architectures by vertically arraying textured surfaces.

2.4 3-D Sampling

3-D Sampling (3-DS) is a design modelling strategy borrowed from music and computer graphics (Patel and Mueller, 2015). 3-DS introduces a systematic approach to re-compose 3-D scan data in new designs. Using 3-D scan data as input, these methods guide the exploration of design alternatives. By sampling 3-D scan data, designers can draw from first-hand knowledge to direct this process. While previous efforts focus on surface texturing, this paper extends previous 3-D sampling concepts to 3-D volume for the synthesis of new meta-materials.

2.5 Research question

The paper describes a TBMs tool-chain and design procedure, and assesses the suitability of TBMs metamaterial design exploration. This paper addresses three fundamental questions:

- How are TBMs generated?

- How are textures and the behaviour of the resultant TBMs related?
- When should a designer use TBMs?

3 METHODOLOGY

This section outlines a general method and tool-chain for TBMs.

3.1 Conceptual Overview

This goal of TBMs is to diversify the meta-material design space. Figure 2 outlines the design procedure for creating TBMs unit-cells: The first step is to normalize the image data contrast for comparison and consistency. The second step involves the use of a custom algorithm, developed by the authors, to generate unit-cell geometry using texture input and other parameters. The third step is to use image processing techniques to characterize the structure. The fourth step uses Finite Element Analysis (FEA) to test the unit-cell's deformation behaviour. The last step is to categorize the unit-cell design and its descriptions within a TBMs database. The scope of this paper focuses on step (2) and (4), while touching on the other steps. Future work will explore stages (3) and (5) in greater detail.

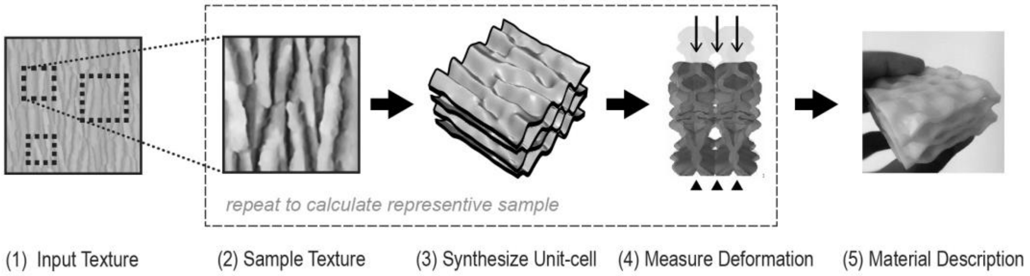


Figure 2. Overview of the design system

3.2 Tool-chain

This section describes a tool-chain for generating TBMs. To compare TBMs for design, an understanding of their mechanical behaviour is required. For this purpose, new computer-aided design and engineering analysis tool-chain is developed, which combines common engineering and architectural software packages (Figure 3).

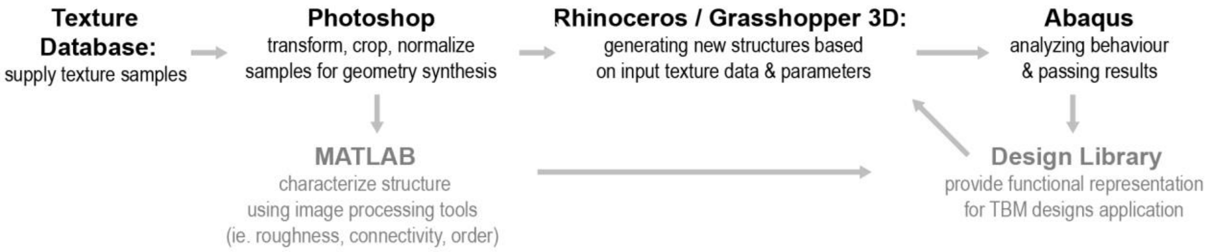


Figure 3. Software platforms used in tool-chain

3.2.1 Sampling: Texture Database

The first step selects ‘textures’ to seed unit-generation. In this work, 'texture' refers to grayscale bitmap images of textures generated by 3-D scanners, where pixel brightness correlates to surface height at a given point. Textures are continuous 'functional surfaces': this means there is one z-value per coordinate point, which eliminates the occurrence of overhang conditions. The geometric representation allows existing image processing methods to be applied in synthesis. Textures can be created using include 3-D scanners, smartphones, or image editing software. However, the examples shown in this paper are obtained from a royalty-free online repository (www.textures.com).

3.2.2 Initialization: Image Processing

The second step is to normalize textures for consistency. A process called "histogram equalization" is used to increase the contrast of the grayscale texture, by distributing intensities of the obtained image on the full range of the histogram (0-255 for 8-bit grayscale image). This step is necessary for consistency and comparison of texture samples, as grayscale images typically contain only a subset of the full grayscale spectrum. Cropping and scaling may also be used to adjust the feature size of a texture.

3.2.3 Synthesis: Grasshopper and Rhinoceros 3-D

The third step involves the synthesis a unit-cell geometry. A custom modelling tool was developed using Grasshopper 3-D, which is a visual programming language (VPL) plugin for the geometry modeller of Rhinoceros 3-D. Figures 4 and 5 summarize the process and parameters controlled: (1) A designer imports the texture into the parametric tool; (2) Using this data, the tool converts it into a NURBS surface; (3) Thickness is added to this surface to create a poly-surface; (4) The tool then arrays and mirrors the poly-surface vertically to create a stacked assembly; (5) Using a '*Boolean Union'* operation, the poly-surfaces are combined as 'water-tight' geometry; (6) The geometry is exported as a STEP file for further processing.

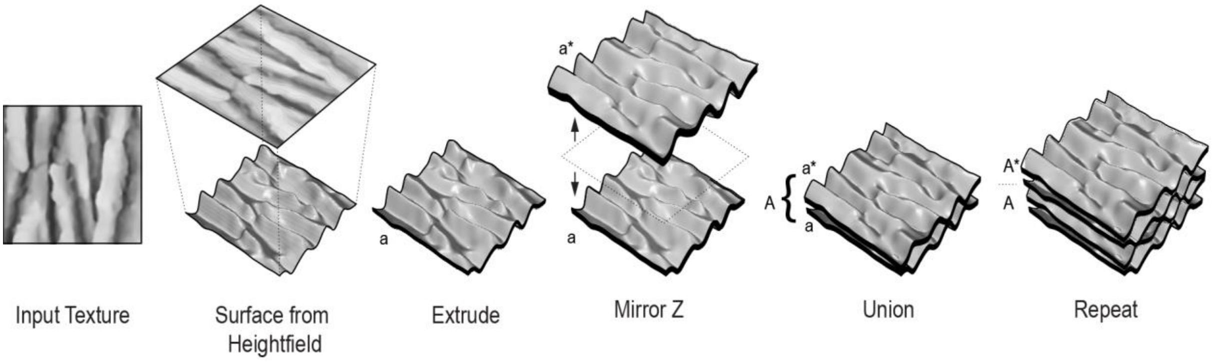


Figure 4. Geometric synthesis of unit-cell

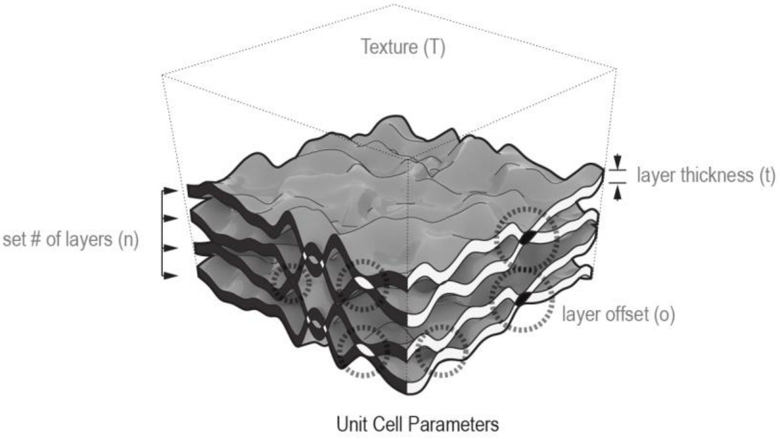


Figure 5. Summary of unit-cell design parameters

3.2.4 Simulate Behaviour: Abaqus

The fourth step is to simulate the TBM samples to describe their mechanical behaviour. The STEP files generated in the previous stage are imported into the Abaqus finite element analysis (FEA) program. Each TBM is tested in a common setup. The TBMs are mechanically compressed in their principal directions using two different simulation conditions. Firstly, an elastic simulation determines its effective elastic modulus (E_eff) and its ratio relative to the elastic modulus of the unit-cell's constituent material (E_s). This ratio is defined as 'E_eff/E_s'. Secondly, an elastic-perfectly plastic simulation is used to understand its structural performance (i.e., Force v Displacement). For each type of simulation, the structures are compressed in the principal Y and X directions to see the difference in mechanical behaviour. The simulations were loaded by displacement and were fixed in 3-D space with pinned boundary conditions (Figure 6).

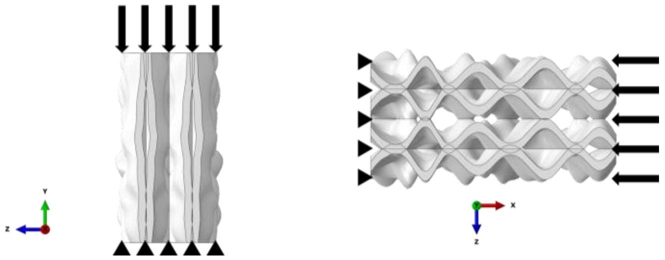


Figure 6. Loads and Boundary conditions of the bark structures in their (left) principal Y and (right) principal X directions

4 IMPLEMENTATION

This section describes simple case study to demonstrate how TBMs can be used to generate unit-cell design variations with unique mechanical behaviour.

4.1 Unit-cell generation

Seeking to demonstrate a high degree of design variation, three textures - two bio-inspired and one random texture are explored in this implementation (Figure 7). They were chosen because of perceived subjective and functional differences: (1) bark – networked, branched, directional; (2) sand – continuous, directional; (3) starfish –round features, non-directional. For consistency, histogram equalization and cropping is applied to each texture to normalize the surface area and feature quantity per unit-cell. Finally, a custom Grasshopper plugin component generates the overall form of the texture using the procedure described in Section 3.2.3 (Figure 6).

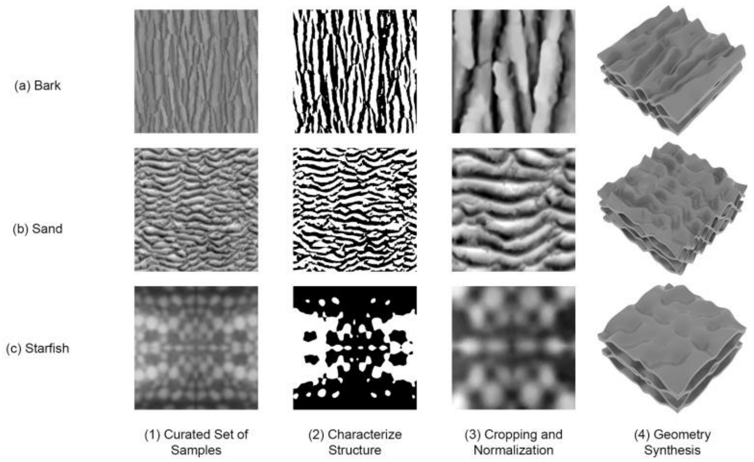


Figure 7. Texture Images used in Case Study: (a) Bark; sharp branched ridges, directional; (b) sand continues linear depressions; c) Starfish; discrete round pockets. Representations; (1) texture image retrieved from online library (2) threshold image to reveal structure topology (3) sample cropped and normalized for consistency, (4) geometry synthesis

4.2 Simulation

A metal-based additive manufacturing process was the assumed mode of production for the TBMs, which offers a realistic method to produce the TBMs. For simulation purposes, Aluminum was assumed as the constituent material of the TBMs. Performed in Abaqus, the analysis focuses on two key performance metrics: (1) E_eff/E_s, which is the ratio of the effective elastic modulus of the aluminum TBM structure relative to solid aluminum, and (2) Elastic-Plastic structural performance of the TBMs from its resultant force-displacement relationship. Structures are imported as a 3-D solid objects (STEP file) into Abaqus for finite element analysis. Each structure fills a boundary volume of 50mm x 50mm x 25mm. By adjusting the thickness, the volume of material for each structure is normalized to 20,000 cubic millimeters. In standardizing both the material and boundary volumes, the TMBs are fixed at a porosity value of approximately 68%. To investigate their linear and nonlinear structural behavior, the structures are assumed to be made of a 6000-series aluminum and given the following material properties: (1) Young Modulus–70,000 MPa; (2) Poisson's Ratio–0.33; (3) Yield Strength–276 MPa. Figures 8 – 10 summarize the results and demonstrate the properties of each unit-cell design in both X and Y-axis.

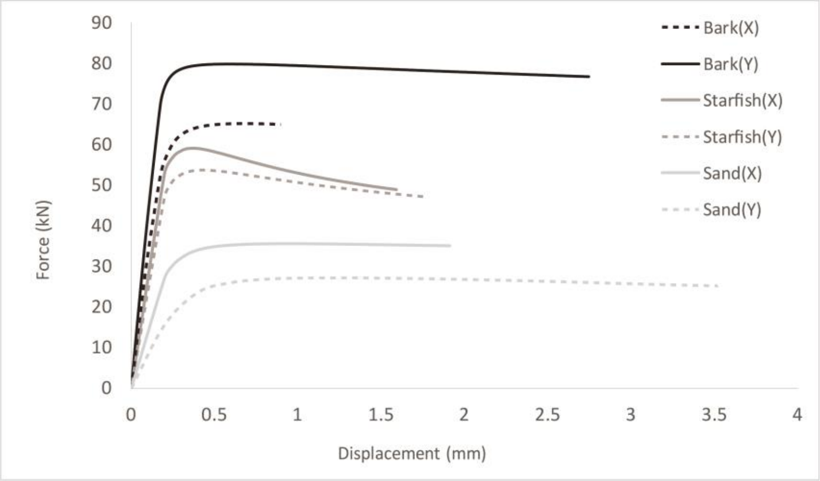


Figure 8. Force v. displacement behaviour observed in samples

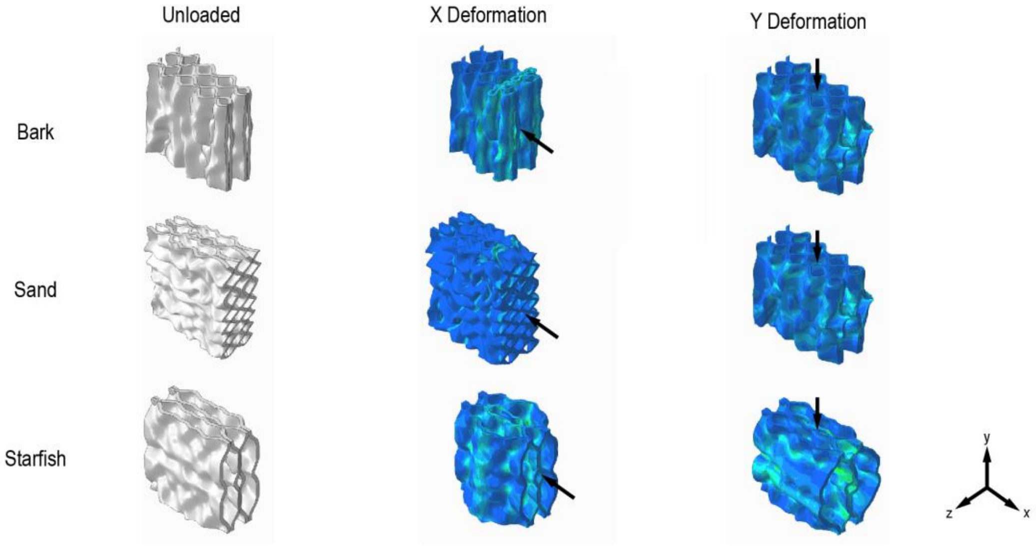


Figure 9. Deformation simulation visualized in Abaqus

4.3 Discussion and Results

4.3.1 Bark

The bark TBM (Figure 11) consists of a series of vertical ridges, which are traditionally in alignment with the tree height. This would imply that the compressive stiffness of bark in the vertical (i.e., Y-axis) direction would be greater than the horizontal direction (i.e., X-axis). Figure 10 confirms this anisotropic behaviour as E_eff/E_s results for the bark in the Y-direction are over 5.3 times greater than that reported in the X-direction. E_eff/E_s of the bark in the Y-direction was also found to be 0.24 – showing a significant reduction in stiffness when compared to solid aluminium. When analysing the nonlinear model (Figure 8), the bark model reaches a perfectly plastic state earlier when loaded in the Y direction.

4.3.2 Starfish

The starfish TBM (Figure 12) displayed a more uniform distribution of round features throughout the 3-D model– resulting in near-isotropic mechanical behaviour. This is reflected through the results presented in Figure 10, where the values of E_eff/E_s in both directions are within a 12.8% margin. This consistency is also displayed in their respective nonlinear force displacement behaviours in Figure 8.

4.3.3 Sand

The sand TBM (Figure 13) consists of a series of horizontal ridges that are traditionally in alignment with the direction of water-wave propagation, which is a natural and random process. While sand is a granular structure, its TBMs-derivative assumes a continuous solid representation. The analysis shows that the compressive elasticity of the sand model in the horizontal (i.e., X-axis) direction would be greater than the vertical direction (i.e., Y-axis). Figure 10 confirms this anisotropy as the E_eff/E_s results for the bark in the X-direction are over 2.1 times greater than that reported in the vertical (i.e., Y) direction. The degree of anisotropic behaviour is found not to be as extensive as in the bark model.

4.3.4 Results Overall

When evaluating the three structures at a fixed porosity of 68%, they produced E_eff/E_s values between 0.05 – 0.24. Since the material volume for each TBM was controlled simply by adjusting the surface thickness of textures, it can be assumed that the porosity and mechanical properties of TBMs may also be adjusted similarly. The degree of anisotropy in the mechanical properties of TMBs was found to vary significantly between the structures. The most anisotropic TBMs was found to be the bark model, which shows a 432.2% difference between X and Y E_eff/E_s results. The most isotropic was found to be the starfish model, with only a 12.8% difference between elastic property results. Depending on the application TMBs, the highly anisotropic structures could be exploited in applications where high material stiffness is desirable in one direction and, and more compliant behaviour is required in the other direction. This flexibility in controlling the properties in TBMs renders them highly useful for exploring a range of material and component designs.

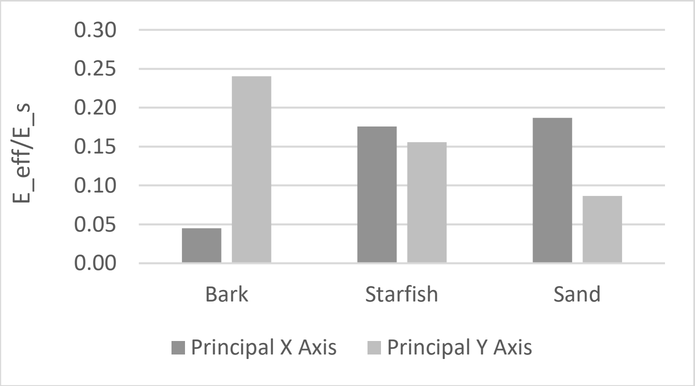


Figure 10. Elastic Modulus Ratio of TBMs in X and Y axis

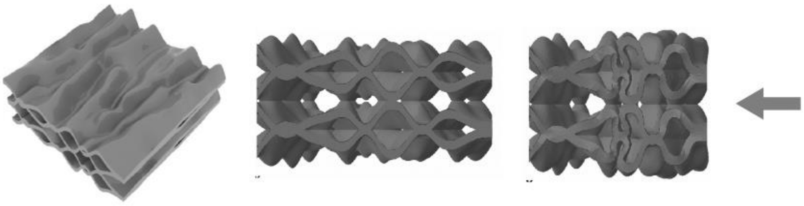


Figure 11. Bark deformation in X axis

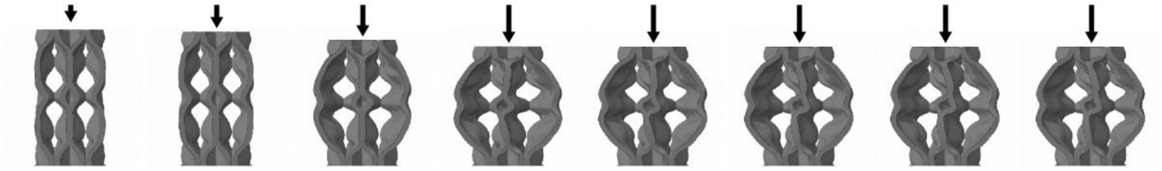


Figure 12. Starfish deformation in Y axis

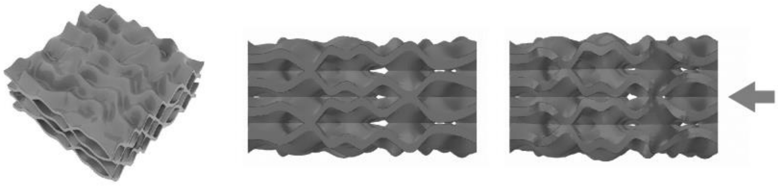


Figure 13. Sand deformation in X-axis

4.3.5 Texture Features vs. TBMs Properties

Initial results suggest a link between the features of texture image and the degree of anisotropy in mechanical properties of the resultant TBMs. Both the bio-inspired image datasets (i.e., bark and starfish) were revealed to exhibit both isotropic and anisotropic behaviour during mechanical simulation. For the bark model, this behaviour can be linked to image features that were long and aligned in a specific direction, which is analogous to a unidirectional fibre composite. Such composites tend to yield anisotropic behaviour under mechanical load. The isotropic behaviour in the starfish model can be linked to the round features distributed uniformly in a near-symmetrical manner. This is analogous to a particle reinforced composite material, which can produce isotropic mechanical behaviour. The random sand sample was also found to be anisotropic, however it was a product of a random and natural process.

5 CONCLUSION

5.1 Summary

The TBMs design procedure and tool-chain can be used to explore new regions of the AM design space. It is presumed TBMs are most useful in early design, where they can be used to identify good starting points that can be further developed using existing methods. This paper makes the following contributions: (1) A design procedure for generating microstructure-unit cells using 3-D scan textures; (2) A tool-chain for modelling and simulating the mechanical behavior of TBMs; (3) Initial results, demonstrating how the tool-chain can be used to create unit-cell variations with diverse properties.

TBMs demonstrate a simple modelling approach for designing unit-cells with a diverse range of properties at a specified porosity. This should be further explored by a sensitivity analysis of the mechanical properties at different porosity values. While we focus on the analysis of single unit-cells, future work could investigate the macroscopic behaviour of repeated unit cells. Future work should also focus on exploring other TBMs and comparing them to other surface generation methods (e.g., kriging), which can also give varying degrees of stiffness or compliance in specific directions. Beyond mechanical properties, the potential multi-functional benefits of TBMs surface geometries could be explored (ie. acoustics, aerodynamics, optical, tactile). Finally, future work will seek to apply TBMs to a full design example.

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