Structural Optimization via 3D Printing Technology Using NPR Materials

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Abstract 3D printing technology is now the trendiest term in engineering in general and advanced structural design engineering in particular. Finding structures with optimum geometry and materials that fit the technologies above is difficult. This study presents an approach to creating a hybrid structure by combining Rhino Grasshopper and Karamba3D to replace the hybrid structure reinforced with hard particles presented in Ref. (Tee in Jom 72:1105–1117, 2020 [3]). The proposed hybrid structure is improved from the honeycomb structure by the Galapagos optimization algorithm, one of Rhino Grasshopper's optimization plugins. It considers the properties of materials with a Negative Poisson Ratio (NPR). These material properties were established based on the formulas presented in Sect. 3 using the Karamba3D parametric design tool. The tensile stress–strain curve demonstrates the optimal hybrid structure efficiency compared with the sample without the reinforcement and the two samples with the reinforced hard grain with different printing orientations in 3D printing technology. This demonstration was established using ABAQUS finite element software with the Arruda-Boyce material model for polymer materials.

Keywords 3D printing · Negative Poisson ratio materials · Galapagos algorithm · Karamba3d · Rhino grasshopper · Structural optimization

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1 Introduction

Additive manufacturing (AM), often known as 3D printing, enables lighter, stronger components and systems in industrial production. Communications, photography, architecture, and engineering have undergone digital revolutions. AM improves digital flexibility and efficiency in industrial operations.

AM adds material to an item. Creating an item by hand sometimes requires milling, machining, carving, sculpting, or other material removal methods.

Polymer-based composites are one of the most widely used and robust materials in 3D printing technology that Bekas et al. [1] have done with an overview of this material. The material determines 3D printing. Homogenization and local function multi-functionality is required for these materials. However, everyday objects have complicated forms and materials. Therefore, Toursangsaraki [2] demonstrated that developing a structure with various materials is efficient when subjected to loads with a significant weight reduction. The combination also alters AM manufacturing from multi-stage to single-process.

Furthermore, the work of Tee et al. [3] is interesting in using polymer-based composites. The rigid-rubbery polymeric material was used in PolyJet tensile testing. These tensile samples have two parts: VeroMagentaV polymer for rigidity and Agilus30 polymer for flexibility. His study examined these materials' mechanical characteristics and interactions utilizing 3D-printed composite stiff reinforcement particles.

Negative Poisson Ratio (NPR) is another Poisson ratio-related material property. Material and structure have this characteristic. The study by Lakes [4] demonstrated an overview of the advantages of materials and structures with NPR. NPR structures like honeycombs, diamond crystals, and Voronoi have parallels with nature. The characteristics of these structures are sustainability, considered in the field of engineering in general and the construction industry in particular, presented in the awe-inspiring study of Nazir et al. [5].

ABAQUS simulated a tensile test in this investigation. Based on the research [3]; the sample is made of two materials: rigid VeroMagentaV polymer and flexible Agilus30 polymer with a honeycomb structure. We optimize the honeycomb structure using NPR materials using Rhino Grasshopper's Galapagos algorithm plugin. Through stress–strain relationship curves, the post-optimized structure has better tensile strength than the study's constructions [3].

2 Effective Combination of Powerful Tools Rhino Grasshopper

Rhino precedes Grasshopper. This software's 3D rendering is unmatched. Rhino's Render image processing technologies help create clean, vibrant results. Rhino software is used by major companies for industrial design, pattern design, reliefs, footwear design, jewellery design, mechanical engineering (ships, cars, etc.), and more. McNeel also improves RhinoBIM solutions.

Rhino's Add-ons, like other major solutions, include Grasshopper. It provides a "clear history" of the model and improves rendering in 3DMax and Maya. Rhino created "Clear History" to tackle user difficulties in the model creation process, allowing updated modeling to backtrack. Grasshopper explains this.

Optimized add-ons, notably Galapagos, are Grasshopper's best feature. Rutten [6] created the first Rhino Grasshopper optimization algorithm [6]. Rhino plugins like LadyBug and HoneyBee for form blending, Pufferfish for multi-objective optimization, and Octopus for energy design are popular. Structural engineering analysis mentions Karamba3D.

3 Structural Optimization Process

As stated in the Introduction, this work builds on interesting concepts from studies [3] and [5], particularly [3]. The HoneyComb structure was used to optimize structural optimization with the Poisson ratio as a parameter. Pham et al. [7] and [8] examined the efficiency of this honeycomb construction. Auxetic honeycomb sandwich plates and nanoplates were studied for free vibration.

As illustrated in Fig. 1, this optimization approach only considers the flexible region of the tensile sample studied [3].

The structure's material is this study's biggest optimization issue. The Karamba3D plugin's settings changed the issue of the material's Negative Poisson Ratio. These parameters are calculated from the proposed formulas of Kováčik [9].

Poisson's ratio has been re-calculated to develop a new correlation between Poisson's ratio and the porosity in materials Eq. (1), showing the relationship among ϑ, E, and G.

$$\vartheta = \frac{E}{2G} - 1 \tag{1}$$

where E and G are defined based on the percolation model. E and G parameters have to consider the effect of porosity on parameters p and p_c according to Eqs. (2) and (3).

$$E = E_o\left(\frac{p_c - p}{p_c}\right)^{f_E} \text{ for } p \le p_c \tag{2}$$

$$G = G_o\left(\frac{p_c - p}{p_c}\right)^{f_G} \text{ for } p \le p_c \tag{3}$$

where E_o and G_o are respectively Young's modulus and shear modulus of the solid material, p_c is the percolation threshold with Young modulus and shear modulus

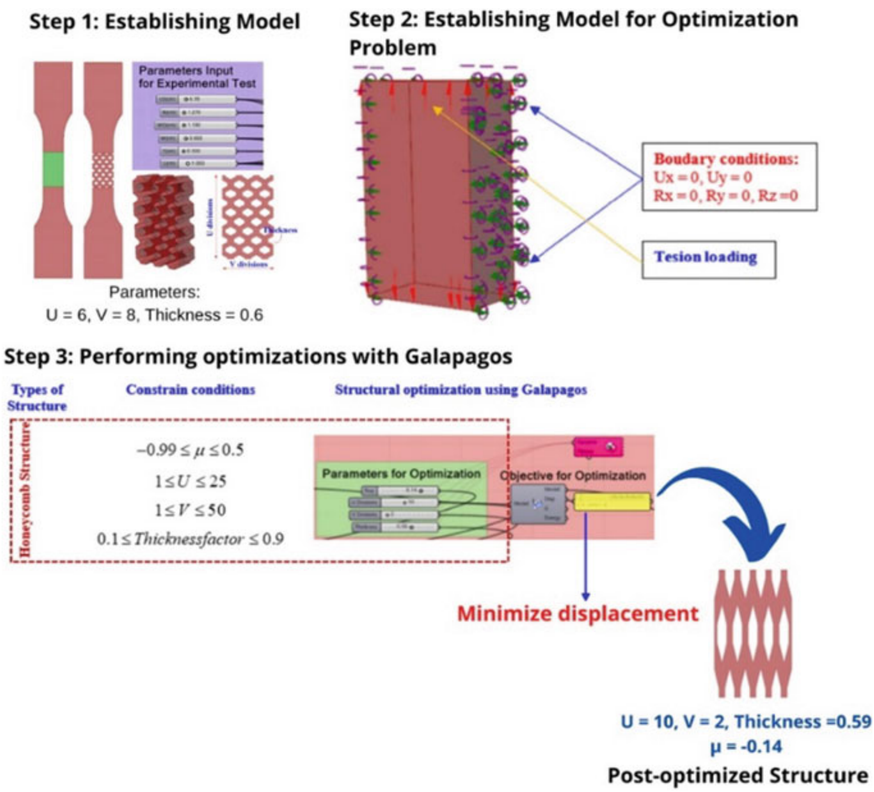

Fig. 1 Structural optimization process

being fixed at zeros, f_E and f_G are the characteristic exponents for the elastic and shear modulus of the porous material, respectively.

From Eqs. (1), (2), and (3), Poisson's ratio can be calculated as follows:

$$\nu = \frac{E_o}{2G_o}\left(\frac{p_c - p}{p_c}\right)^{f_E - f_G} - 1 \text{ with } p \le p_c \tag{4}$$

It can be noted that in Eq. (4), $\frac{E_o}{2G_o}$ is equal to $\nu_o + 1$, and Poisson's ratio can be rewritten as:

$$\nu = (\nu_o + 1)\left(\frac{p_c - p}{p_c}\right)^{f_v} - 1 \text{ with } p - p_c \le 0 \tag{5}$$

Where $f_v = f_E - f_G$. Equation (5) provides a new percolation model for Poisson's ratio. The porosity of porous material depends on homogeneous and isotropic characteristics.

Step 3 of Fig. 1 illustrates this paper's optimization challenge. This graphic shows how to use Galapagos. The slider's features enable it to constrain optimization difficulties. Minimize displacement (d) is the objective function. Tension load (F) causes this displacement:

$$Min(d) \text{ where } d \text{ is defined by } d = \sum_{i=1}^{j} D_i \tag{6}$$

where D_i is the displacement at the *ith* element. Moreover, j is the total number of structural elements. The displacement is given by:

$$D = \frac{F}{K'} \tag{7}$$

where F is the tension load, and K' is the bending stiffness of the structure calculated in Karamba3D.

4 Verification with FEM

The structure must be validated. We may use third-party technologies to verify the optimized design. This numerical verification analyzes using ABAQUS. Pre- and post-processing includes analysis.

Pre-processing builds models. This study imports a Rhino model into ABAQUS. Import *.igs or *.iges formatted models.

The next stage is defining the material, a vital portion of the simulation. The material Hybrid VMVmA30p is mentioned in the Introduction section [3]. It comprises a flexible polymer, Agilus30 (A30), and a rigid polymer, VeroMagentaV (VMV). Equation (8) Arruda et al. [10] shows that the Arruda-Boyce model explains the A30 material, which is ideal for hyperelastic materials.

$$\begin{aligned} U = &\mu\left\{\frac{1}{2}(\overline{I}_1 - 3) + \frac{1}{20\lambda_m^2}\left(\overline{I}_1^2 - 9\right) + \frac{11}{1050\lambda_m^4}\left(\overline{I}_1^3 - 27\right)\right. \\ &\left.+ \frac{19}{7000\lambda_m^6}\left(\overline{I}_1^4 - 81\right) + \frac{519}{673750\lambda_m^8}\left(\overline{I}_1^5 - 243\right)\right\} \\ &+ \frac{1}{D}\left(\frac{J_{el}^2 - 1}{2} - \ln J_{el}\right) \end{aligned} \tag{8}$$

The initial shear modulus (μ) and the locking stretch (λ_m) are the model coefficients added in ABAQUS. Typical values of μ and λ_m are presented in Fig. 2a from the study in [3]. The VMV material has an elastic–plastic mechanical characteristic. The elastic modulus (E_s) and yield strength (f_y) are the essential parameters, and

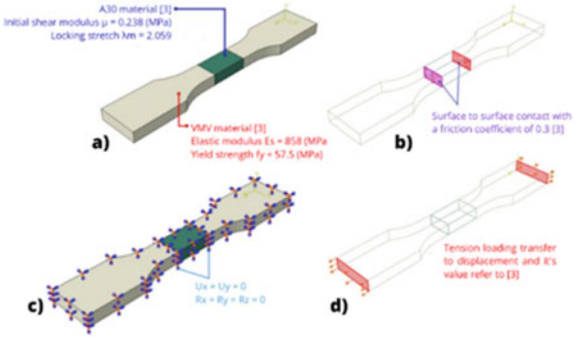

Fig. 2 The following material properties and conditions have been given to modeling: **a** Material properties, **b** Interaction conditions, **c** Boundary conditions, and **d** Tension loading

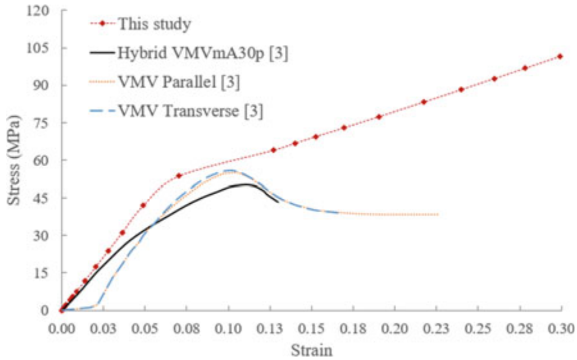

Fig. 3 The stress–strain curves obtained from the research [3] and the current work

their values are taken from the work in [3], as shown in Fig. 2a. The boundary and contact criteria are imposed in the next phase. It is necessary to define the interaction between the contact surfaces. The requirements are depicted in Fig. 2b, c. As illustrated in Fig. 3d, the hybrid construction is solely exposed to tension stress. The research [3] refers to typical load values. The elements utilized in the model for the end parts of the specimen are 8-node cubic C3D8R elements. The honeycomb structures were created by using C3D8H elements in the middle part. The stress–strain curves are obtained from the analytical findings in the post-processing stage. The following section contains a summary of all findings.

5 Results and Discussion

In Fig. 3, stress–strain curves of the optimized structure are compared to those of the Hybrid VMVmA30p specimen test, which was subjected to similar tensile loading [3]. The red dashed-line curve shows the optimized structure's significant influence in the middle part. The Arruda-Boyce model's flexible polymer material describes hybrid architectures' behavior.

6 Conclusion

This research shows how Rhino Grasshopper and Karamba3D can build stronger hybrid structures. Karamba3D contains a subroutine for negative Poisson's ratio porous materials. Better mechanical properties than the Honeycomb structure. Finite element analysis characterizes advanced constructions' stress–strain curves. The Arruda-Boyce model makes advanced structures behave like hyperelastic materials.

This study's behavior curves motivate polymer model development and further analysis and creation of novel hybrid structures with parameters. This simplifies structural characteristic data collection. Machine learning is one optimization model in data sciences.

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