Study on Topology Optimization Design for Additive Manufacturing

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ABSTRACT

Topology optimization is an advanced technique for structural optimization that aims to achieve an optimally efficient structure by redistribution materials while ensuring fulfillment of load-carrying, performance, and initial boundary. One of the obstacles in the process of optimizing structures for mechanical parts is that these optimized structures sometimes encounter difficulties during the manufacturing process. Additive Manufacturing (AM), also known as 3D printing technology, is a method of manufacturing machine parts through joining layers of material. AM opens up the possibility of fabricating complex structures, especially for structures that have been subjected to topology optimization techniques. This project aims to compare the initial shape of a box under static load and its shape after optimization. The subsequent produced models have reduced weights of 43%, 59%, 70%, 73%, and 77%, respectively, weighing 491.45 g, 357.42 g, 261.31 g, 235.56 g, and 203.87 g. All models are capable of supporting a 10 kg load, demonstrating the ability of the structure to meet technical specifications. The results show that combining structural optimization and additive manufacturing can take advantage of both approaches and show significant potential for modern manufacturing.

Keywords-additive manufacturing; 3D printing; topology optimization; optimization design

I. INTRODUCTION

Machine design, a crucial activity in the mechanical industry, aims to solve products' problems, meeting user requirements. Machine design engineering involves applying principles of physics to develop items, mechanisms, machines, and instruments. The process includes a mixture of various machine elements, including mechanical, electrical, and hydraulic components [1-4]. Mechanical design optimization includes determining the optimal combination of design variables and parameters to meet the performance requirements and constraints of a mechanical system [5-8]. Topology Optimization (TO) is an advanced technique for structural optimization that aims to achieve an optimally efficient structure by redistribution materials while ensuring fulfillment of load-carrying, performance, and initial boundary conditions [9-13]. Evaluation of Tree-Like Structures using TO as a design method was conducted in [9]. Authors in [10] used TO to present a continuum structure under geometric uncertainty [10]. Authors in [11] used topology technique for architectural design. Authors in [12] presented a self-adaptive material interpolation scheme to solve problems that may occur in topology design. TO techniques were used to optimally design a 4-degree-of-freedom robot arm in [13]. TO is an independent method of the initial configuration, that maximizes the efficiency of material distribution and structure within a specified 3D design space, following a set of predefined rules established by the designer. The objective is to enhance the performance of a component by utilizing mathematical modeling and optimization techniques to account for various factors such as external forces, load conditions, boundary conditions, constraints, and material properties within the specified design limits. One of the obstacles in the process of optimizing structures for mechanical sometimes encounters difficulties during the manufacturing process. In many cases, manufacturing these structures maybe impossible, or it can be time- consuming and expensive. Additive Manufacturing (AM), also known as 3D printing technology, is a method of manufacturing machine parts through joining layers of material. AM opens up the possibility of fabricating complex structures, especially for structures that have been subjected to topology optimization techniques. [14-17]. Due to the above advantages, 3D printing technology becomes an ideal tool to combine with structural optimization methods [18-25]. 3D printing technology can produce most complex shapes without much difficulty. Optimizing the part structure can improve the performance and quality of 3D printed products. The goal is to reduce the amount of initial plastic material for the 3D printing process while still ensuring the product's ability to work and optimize the structure to create flexible and diverse products, suitable for many different applications in the industrial and technical fields. The article employed the topology approach to enhance the structure, starting from the initial problem. Next, Computer-Aided Design (CAD) was used to refine the structure, ensuring that the product can be produced using 3D printing, a topic that has been rarely discussed in previous research. After the fabrication was completed successfully, the structure was tested to demonstrate the efficiency of the design process. The article focuses on the research and integration of optimizing mechanical structures into 3D printing technology to take full advantage of their potential, and at the same time have the prospect of wide application in modern production.

II. MATERIALS AND METHODS

Structural optimization can be classified into three types: size, shape, and topology optimization. Dimensional optimization involves identifying the most efficient design by adjusting dimensional variables like the cross-sectional dimensions of the truss and frame, or the thickness of the panels. Shape optimization is primarily conducted on continuous structures by adjusting predefined boundaries to attain the most efficient design. TO for discrete structures, like trusses and frames, aims to connect efficiently the material structure of the components. TO of continuous structures involves identifying the most efficient designs by selecting the optimal location and shape within the design domain. All TO methods in this study can be applied for shape optimization by removing excess material once it is confirmed that the area is not impacted by the force. In the fields of engineering and design, TO focuses on enhancing the structure or form of a product or system by utilizing its topographical features. The objective of TO is to modify a product's structure to faithfully represent its topographic or surface characteristics. This may require optimizing the surface shape, height, or other terrain characteristics to achieve optimal performance. This method is commonly used in research and product development, particularly in designing technical products, construction structures, and applications related to energy and environment. It optimizes the product's interaction with the terrain, enhancing performance and load-carrying capacity in specific terrain conditions. TO is primarily utilized to design high-performance, lightweight structures that meet design requirements by reducing material volume, making necessary modifications. Its diverse applications have been documented, particularly in the development of automotive, aircraft, and aerospace components, which frequently have weight restrictions.

A. Optimizing the Design of Machine Element under Static Load

The process of performing numerical simulations is carried out using Solid Works Software. The assumption implies that a cube-shaped part is under a distributed load of 100N, as depicted in Figure 1. The load-bearing part is made of ABS plastic. Calculate the 100 N force applied to the part at the force application plane. ABS material properties are described in Table I.

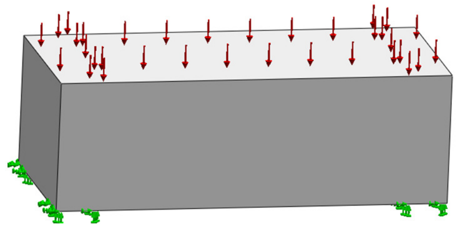

Fig. 1. Model with related boundary conditions.

TABLE I. ABS MATERIAL PROPERTIES

Parameter	**Value**	**Unit**
Young modulus	2.10^9	N/m^2
Shear modulus	$3,189.10^8$	N/m^2
Poisson's ratio	0.397	N/A
Density	1020	Kg/m^3
Tensile strength	3.10^7	N/m^2

Assume there is 1 kg of plastic initially. The box's required cross-sectional area is determined using the specified formula.

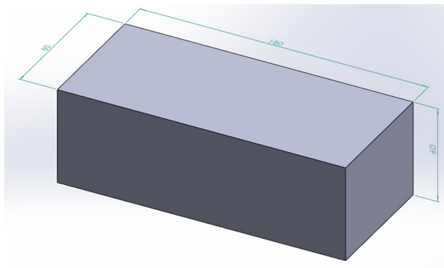

Fig. 2. Initial structure of a rectangular block.

With the above conditions, choose a preliminary initial size of a box with dimensions of 180×80×60, corresponding to the length, width, and height in mm as described in Figure 3. This product is tested on software again to ensure working conditions.

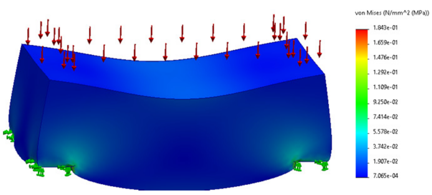

Fig. 3. Simulation result of Von Mises stress distribution in the block.

Simulation results from Figure 5 show that the maximum value of stress is 1.84 MPa and the minimum is 0.0007 MPa. The maximum stress appearing on the part is much smaller than the allowable stress of the material (30 MPa). Displacement is the movement of an object caused by an external force as shown in Figure 4. The simulation results from Figure 6 indicate that the maximum displacement value is 1,714e-3 mm, while the minimum displacement value is around 0 mm. The model's displacement level is very small, accurately reflecting reality.

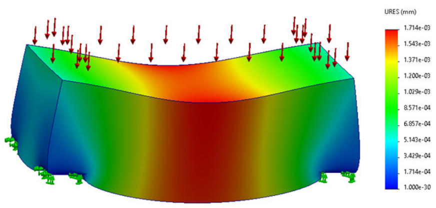

Fig. 4. Simulation result of displacement from finite element software.

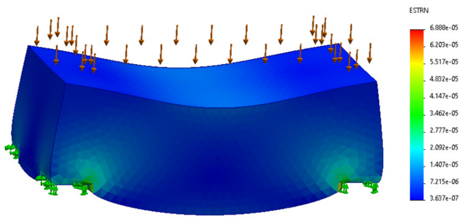

Fig. 5. Simulation result of strain from finite element software.

Strain is the change in size and shape of an object when it is affected by an external force. From the simulation results in Figure 7, the largest strain appearing on the model is 6,888e-5, the smallest strain is 3.637e-7. Strain appears at fixed positions of the model and is within the allowable level.

III. RESULTS AND DISCUSSION

The objective is to reduce the initial amount of plastic, with weight being the primary focus for optimization. The weight contributes to 43%, 59%, 70%, 73%, and 77% of the total design. The design's optimal structure aims to minimize weight, as depicted in Figures 6-10.

The initial optimal structure is typically complex, making it inconvenient for manufacturing and challenging for 3D printing. Hence, the structure needed to be modified to enhance manufacturability and aesthetics. High pressure zones are reinforced with extra materials to enhance strength. Following the structural optimization phase, the subsequent step involves refining the design to streamline the fabrication process. This process thoroughly analyzes the proposed optimal structure to modify design elements that are facing challenges during manufacturing. The following figures illustrate the optimal structure in its ultimate state. The modified model is subsequently evaluated using identical loads and boundary conditions as the initial design. Figures 11 to 15 represent the structure and weight for each individual model after refining the initial model in order to simplify manufacturing and enhance quality.

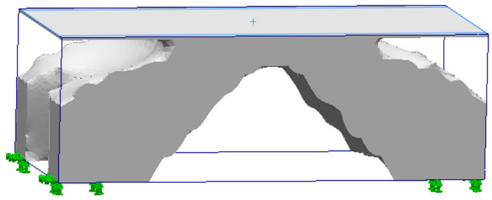

Fig. 6. The structure reduces weight by 43%.

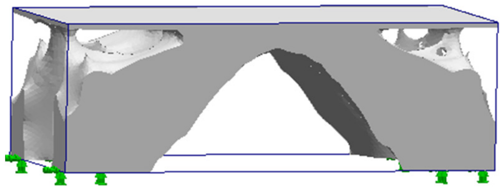

Fig. 7. The structure reduces weight by 59%.

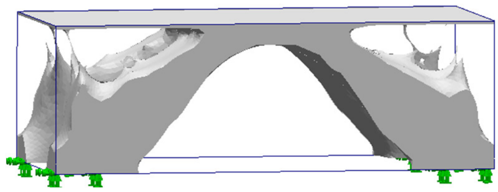

Fig. 8. The structure reduces weight by 70%.

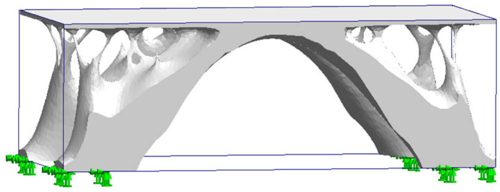

Fig. 9. The structure reduces weight by 73%.

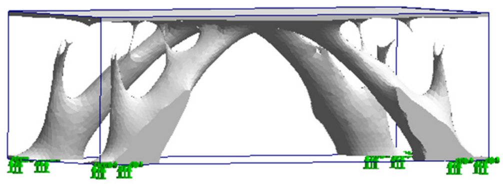

Fig. 10. The structure reduces weight by 77%.

Figures 11-15 illustrate the progression of prototypes from the original model to subsequent models that have reduced weights of 43%, 59%, 70%, 73%, and 77%, respectively weighing 491.45 g, 357.42 g, 261.31 g, 235.56 g, and 203.87 g.

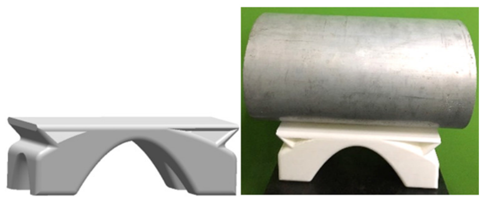

Fig. 11. The completed prototype received a 43% decrease in weight.

Fig. 12. The completed prototype received a 59% decrease in weight.

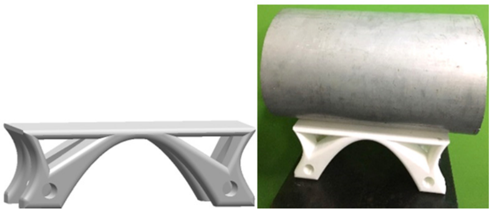

Fig. 13. The completed model received a 70% decrease in weight.

Fig. 14. The completed model received a 73% decrease in weight.

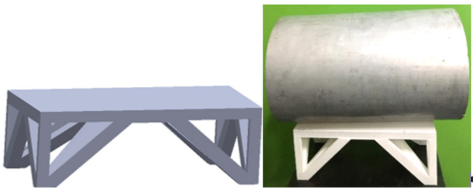

Fig. 15. The completed model received a 77% decrease in weight.

All models are capable of supporting a 10 kg load, demonstrating the ability of the structure to meet technical specifications.

After analyzing the proposed optimization models, it is crucial to compare the topology optimization results. An optimization analysis was conducted to confirm the stability of the structure. After finite element software solving, the maximum stress in the certain location of part will be shown. The factor of safety is the ratio of the maximum stress exerted on a component to the failure stress of the material. Table II summarizes the comparison of the redesigned models based on weight, allowable working stress, and safety factor.

TABLE II. COMPARING DI FFERENT OF PROTOTYPE DESIGNS

Mass (gram)	Maximum stress (MPa)	Factor of safety
491.45	1.574	19
357.42	2.66	11.28
261.31	3.047	9.84
235.56	7.253	4.14
203.87	5.864	5.11

The parts are fabricated using Fused Deposition Modeling (FDM) technology, where plastic is utilized as the printing material. The print head temperature is set at 180 ^{O}C, and each layer of the print has a height of 0.2 mm. The new designs have been proven to maintain identical loading conditions to the original design based on the experimental. Working with a 10 kg load, various plastic materials will exhibit unique designs, stresses, and safety factors for each model. Optimization combined with 3D printing is an effective method for creating varied structures while maintaining the initial specifications. The article's findings demonstrate an efficient optimization strategy for addressing specific issues with the aim of conserving and enhancing resource utilization.

IV. CONCLUSION

The article presents the most efficient approach to design, which integrates the use of 3D printing technology. Topology optimization may produce a variety of innovative structures that are difficult to fabricate using traditional manufacturing methods. 3D printing is an advanced manufacturing method that constructs designed components by adding materials layer by layer, allowing the fabrication of complex prototypes. This project aims to compare the initial shape of a box under static load and its shape after it has been optimized. There are five new designs proposed, reducing the volume by 43%, 59%, 70%, 73%, and 77% compared to the original weighing 491.45 g, 357.42 g, 261.31 g, 235.56 g, and 203.87 g, respectively. All models are capable of supporting a 10 kg load, demonstrating the ability of the structure to meet technical specifications. The results show that combining structural optimization and additive manufacturing may capitalize on the advantages of both methods and represents significant potential for modern manufacturing.

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