TOPOLOGY OPTIMIZATION IN ADDITIVE MANUFACTURING

Onyekachi Okorie, B.Eng. in Mechanical Engineering

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School of Engineering and Digital Sciences
Department of Mechanical & Aerospace Engineering
Nazarbayev University

53 Kabanbay Batyr Avenue,
Astana, Kazakhstan, 010000

Supervisor: Associate Professor Konstantinos Kostas
Co-supervisor: Assistant Professor Asma Perveen

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DECLARATION

I hereby, declare that this manuscript, entitled "*Topology Optimization in Additive Manufacturing*", is the result of my own work except for quotations and citations, which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or intentional institution.

Engr Senator O.

Name: Onyekachi Okorie

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Abstract

Right from its inception, additive manufacturing has consistently revolutionized the ways in which components are manufactured in various industries by making it possible to engineer more complex and custom-made products, which are otherwise difficult to achieve using traditional manufacturing approaches. Topology optimization when integrated into additive manufacturing provides unmatched possibilities for the manufacturing of lightweight, more intricate and customized products using less material at a relatively lower production cost and time, and in a more environmentally friendly and sustainable way. Despite these possibilities, there is still some lack of adequate scholarly articles in the subject of topology optimization in additive manufacturing for industrial applications.

This thesis aims at applying appropriate topology optimization methods for enhancing the design of functional components for aerospace and biomedical applications. These components will be produced via additive manufacturing, and we aspire to modify them in a way that leads to weight reduction without sacrificing their original mechanical properties. Density-based techniques and the level set method implemented in ANSYS WORKBENCH[1] were used to optimize the models whereas the Ultimaker S5[2] 3D printer was used for 3D printing. Finally, the LGTester[3] compression and tensile machine was used to test and compare the mechanical strength of the printed parts.

Overall, a 20% weight reduction was achieved with the optimized designs while maintaining the compression displacement of the initial components. This result indicates that topologically optimized components can significantly enhance the design of components, especially for the case of weight-sensitive industrial application.

Key Words:

Additive manufacturing, topology optimization, level set method.

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[1] https://www.ansys.com/products/ansys-workbench

[2] https://ultimaker.com/3d-printers/ultimaker-s5

[3] http://www.lgtester.com/English/index.php?m=content&c=index&a=lists&catid=16

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List of Abbreviations & Symbols

AM	Additive Manufacturing
TO	Topology Optimization
FDM	Fused Deposition Modeling
PLA	Polylactic Acid

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1. INTRODUCTION

1.1. Research Background

Over the years, the rapid growth and development in additive manufacturing has continued to revolutionize several industries, as AM is utilized for building both prototypes and for mass production, and finds usage in engineering, aerospace, automobile, military, dental, fashion, medical, jewellery, footwear, architecture, eyewear, construction, education, food, and many other areas [1]; With such advancements, designers and engineers are constantly being challenged into developing more efficient techniques for production of functional parts with less materials, time, energy and costs [2]. In order to realize the full possibilities which additive manufacturing offers, topology optimization has continued to gain attention as engineers and designers continue to research and develop new and efficient approaches for incorporating TO into AM, in order to produce such complex parts which are otherwise too intricate to manufacture traditionally. When topology optimization is incorporated into additive manufacturing for various industrial applications, the possibilities are numerous and include qualification of optimal designs, minimization of material usage while increasing stiffness-to-weight ratio, eco-friendliness, cost-effectiveness as materials are located only where they are absolutely necessary, reduction of production time and cost, and quicker iterative process [3].

1.2. Statement of Problem and Research Motivation

Nowadays, across several industries, engineers seek to solve problems such as production of lightweight products which are of high quality; however, such products should be manufactured at minimum production costs through efficient utilization of energy and resources and at a lower production time, while ensuring environmental sustainability. Engineers also look for ways to improve safety, reduce waste, optimize supply chain management, and maintain or improve product performance. Additionally, engineers must consider environmental sustainability when designing processes and products, as well as ways to improve customer experience and satisfaction.

In the context of the abovementioned broader framework, the current research work seeks to integrate topology optimization into additive manufacturing in order to produce functional parts which satisfy the requirements of high quality, light weight, and appropriate stiffness.

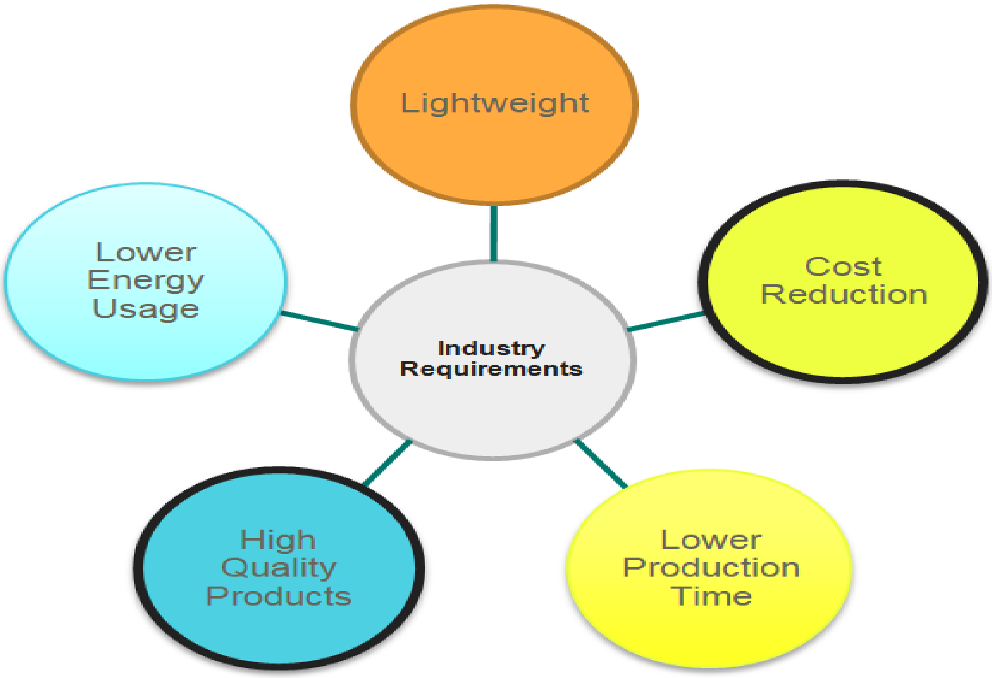

Fig1. Industry Requirement for manufactured parts

1.3. Aims and Objectives

This thesis aims to demonstrate the applicability of this approach in the aerospace and biomedical industries, by topologically modifying a typical aerospace bracket and a biomedical crutch in the context of production with additive manufacturing.

The main objectives are to:

- To modify the components while maintaining, to the extent possible, identical performance to the original ones.
- To investigate how optimization regions influence the achieved results.
- To significantly reduce the weight of the components without sacrificing their mechanical properties.
- To minimize material usage thereby, saving production cost.
- Optimize, 3D print, and test the compliance of the resulting components to ensure achievement of the objectives.

1.4. Thesis Structure

This thesis has been organized into five main chapters. The current chapter introduced the reader to the work by providing a brief research background, the statement of the problem, along with our aims & objectives. Chapter 2 discusses pertinent literature in topology optimization, additive manufacturing, and the integration of topology optimization into additive manufacturing. The methodology adopted for the research work is outlined in chapter 3. Our approach includes numerical computations, topology optimization, mainly based on the Level Set Method, and the validation of the optimized material layout in ANSYS. Presentation of the 3D printing process for the initial and optimized models along with their preparation for mechanical testing is also a part of chapter 3. In chapter 4, the results of the optimization, 3D printing, and mechanical testing are presented and discussed. Finally, chapter 5 summarizes the achievements in this thesis and suggests directions for future research.

2. LITERATURE REVIEW

2.1. Overview

In this section of the thesis, a comprehensive review of current and relevant literature is presented. This review is necessary to help appreciate the subject of topology optimization in additive manufacturing. This chapter is divided into 4 sections which discuss additive manufacturing in general, Topology Optimization (TO), the main TO techniques; incorporation of TO into additive manufacturing, and finally some identified research gaps.

2.2. Additive manufacturing

As opposed to conventional manufacturing, additive manufacturing provides unmatched possibilities for the production of complex geometry with advantages such as minimal manufacturing cost for custom parts and rapid prototyping, time savings, optimal resource usage, reduced post-processing, and environmental friendliness [4].

ASTM (F2792, 2012) describes AM as a process whereby materials are added to create components using data from a 3D model, usually by building one layer upon another, contrary to subtractive processes which remove material. Other terms used for additive manufacturing include additive fabrication, additive techniques, layer manufacturing, additive layer manufacturing, additive processes, and freedom fabrication [5]. Generally, ASTM F2792-12a classifies additive manufacturing processes into seven categories: Material Extrusion, Vat Photopolymerization, Sheet Lamination, Binder Jetting, Directed Energy Deposition, Material Jetting, and Powder Bed Fusion. These processes differ in the ways layers are deposited to form parts, and the printing materials that can be used [5]. Certain methods, such as fused deposition modeling (FDM), selective laser sintering (SLS), and selective laser melting (SLM) a.k.a. direct metal laser sintering (DMLS), produce layers by melting or softening the printing materials, while on the other hand, methods, like Stereolithography (SLA), use various complex technologies to cure and solidify liquid materials. Every one of these methods has its own merits and demerits, and are chosen based on desired objectives. The materials fused by these processes are specifically suited to function in the designated equipment they run on. Take for instance the following examples: while powders intended for fusing have to have the capacity for energy absorption, jetted binders must be able to be dispensed, and polymers must act in line with controlled activation [1]. For further study on the review of the current status, trends and prospect of additive manufacturing, the following comprehensive literature review articles are suggested for the interested reader [6, 7, 8, 9, and 10].

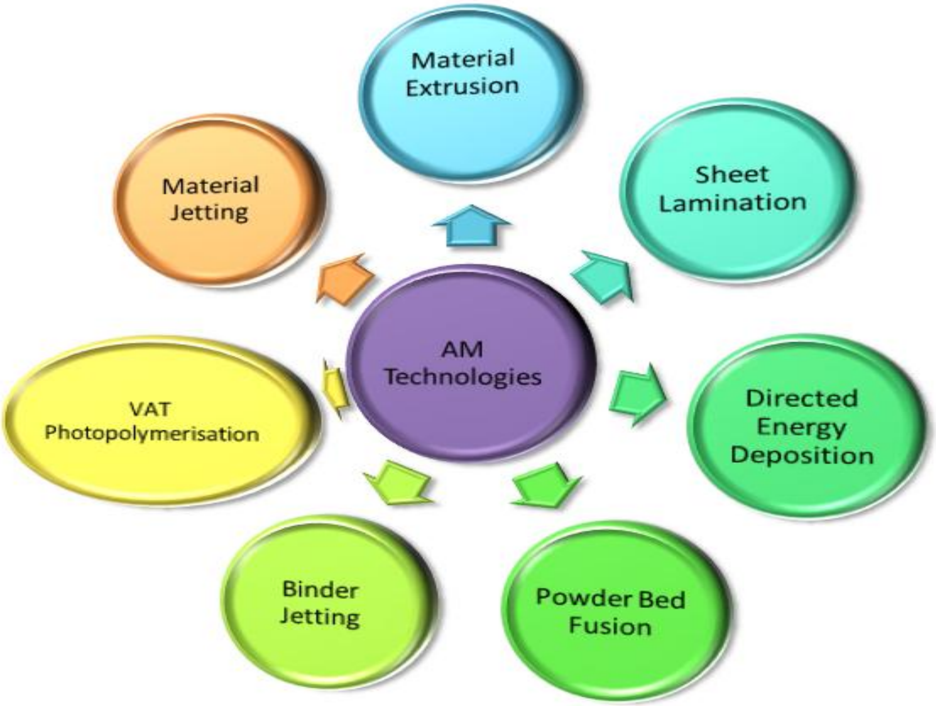

Fig. 2 Process Classification of Additive Manufacturing [5]

In general, for every AM technique used, there are certain process parameters that must be carefully selected in appropriate value ranges so that the desired objectives can be achieved. A comprehensive review of the different AM methods and the process parameters influencing them has been carried out in [11]

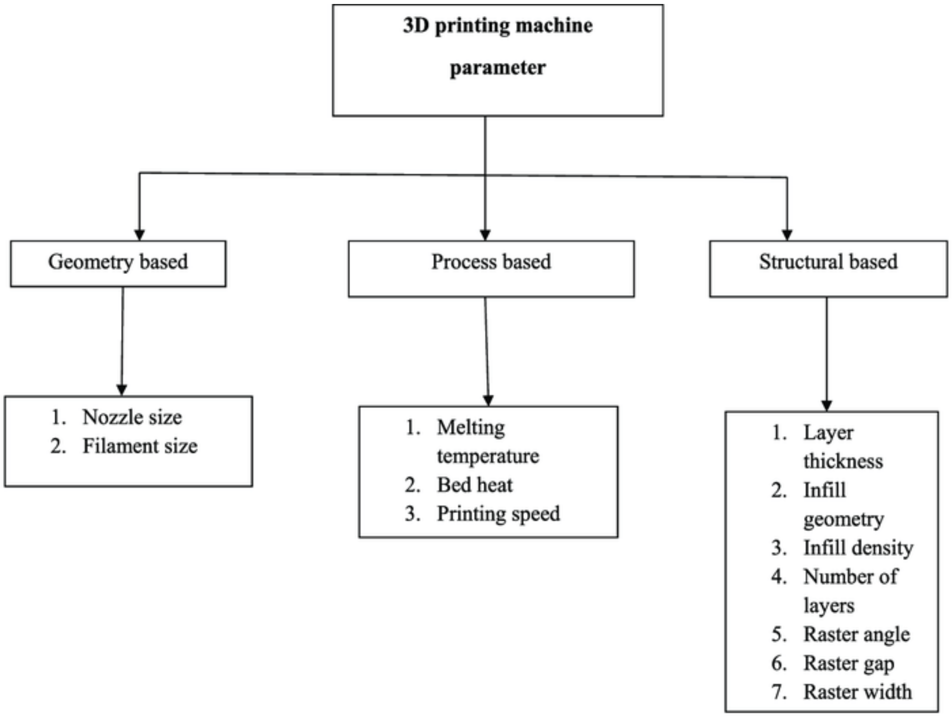

Fig. 3 Classification of common 3D printing Machine Parameters; see [11]

2.3. Topology Optimization Problem

Using the formulation employed in [12] and [13], a typical topology optimization can be generally expressed by the following constrained minimization problem:

$$\boldsymbol{min_{\rho}}\ \mathbf{F},\ \ \mathbf{F}(u(\boldsymbol{\rho}),\boldsymbol{\rho}) = \int_{\Omega} u(\boldsymbol{\rho})\boldsymbol{dV}$$

Subject to:

$$\boldsymbol{G_0}(\boldsymbol{\rho}) = \int_{\Omega} \boldsymbol{\rho dV} - \boldsymbol{V_0} \leq \mathbf{0}$$

$$\boldsymbol{G_j}(\boldsymbol{u}(\boldsymbol{\rho}),\boldsymbol{\rho}) \leq \mathbf{0}\ \ \boldsymbol{where\ j} = \mathbf{1}, \dots, \boldsymbol{m},$$

where:

$\mathbf{F}(u(\boldsymbol{\rho}),\boldsymbol{\rho})$ represents the objective function which is the quantity to be minimized for optimum performance, with the most common one being compliance which when minimized, results in maximization of the stiffness of the given structure.

- The material distribution, which is a function of the density of the material, is given by $\boldsymbol{\rho}(\boldsymbol{x})$; when material is present, it is indicated by a 1, and 0 if absent. $\boldsymbol{u} = \boldsymbol{u}(\boldsymbol{\rho})$ describes a state field satisfying a linear or non-linear function determined by $the\ material\ density, \rho.$ [14]
- The allowable volume within which the design exists is specified by the design space, (Ω)**.** When this space is defined, materials or components outside this specified region are removed as they are considered to be non-design region.
- m functional constraints $\boldsymbol{G_j}(\boldsymbol{u}(\boldsymbol{\rho}), \boldsymbol{\rho}) \leq \mathbf{0}$ specify additional criteria that must be satisfied by the solution, such constraints may involve the maximum amount of material distributed or the maximum values of stress, etc.
- The Finite Element Method (FEM) is mostly used to estimate $\boldsymbol{u}(\boldsymbol{\rho})$ as there are typically no analytical solutions for such equations in general domains [12].

2.4. Topology Optimization Techniques

Different topology optimization methods have evolved over the years, the authors in [3] reviewed the challenges and status of topology optimization, and pointed out that out of the various topology optimization methods proposed over the last 30 years, the most outstanding are the Density-Based Method, the Evolutionary Structural Optimization (ESO), and the Level-Set Method (LSM).These methods shall be discussed in more details in this section.

Right from its initiation by [15], several methods such as density, level set, topological derivative, phase field, evolutionary, etc., have emerged as techniques for topology optimization [14]; nevertheless, the Density-Based Method, Evolutionary Structural Optimization (ESO), and the Level Set Method (LSM) have become the most predominant [3].

The discretization of the design domain into finite elements is one of the broad methods of dealing with the problems of Topology Optimization. Within these elements (which should be large in number to ensure sufficient topological complexities) is the material density that is considered as a binary variable of interest; with material density of one implying the presence of material, while a value of zero entails absence of material. However, achieving complex topology through increased number of elements corresponds to numerous expensive FEM calculations. Again, the unavailability of algorithms capable of handling large number of discrete variables having multiple constraints, coupled with the insensitivity of such algorithms to parameter variations, make the method somewhat disadvantageous [14].

In order to address the aforementioned challenges of the density based method, Bendsøe (1989) proposed the Solid Isotropic Material with Penalization method (SIMP) [16], an interpolation (mainly a power law) technique which models the density with continuous variables and permits material density to assume any value between one and zero. These algorithms can deal with a large number of continuous variables and many constraints when material properties are modeled in a continuous setting. The material's Young's modulus is interpolated to the selection field. In general, the penalty factor $\boldsymbol{p}$ ranges between **{1, 3}.** In order to see that the derivative of the objective function does not attain no-zero values when the density takes zero value, addition of a lower bound on the Young's modulus has to be ensured. Using non-binary densities, SIMP panelizes the algorithm when the penalization factor becomes higher. However, in [17], it is noted that non-convexities are introduced by such penalization parameter. The next subsection discusses the level set topology optimization method.

2.4.1 The Level Set Topology Optimization

As stated already above, the Density-Based Method, ESO, and LSM are the prominent topology optimization methods. Among these dominant TO methods, the Level-Set Method though relatively newer, continuously receives more attention due to its multiple benefits. The well-defined and smooth structural boundary throughout the optimization makes the Level Set Method advantageous [18]. Using the LSM topology optimization, a topology that minimizes the objective function and still satisfies specific constraints is found by updating the structural boundary given by an implicit function [19]. Level Set structural optimization has been noted by its pioneer users [20], as being able to naturally handle changes in topology alongside a crisp and smooth interface representation. Recently, the Level Set method has become a capable option to conventional topology optimization methods like SIMP and ESO [21, 22, as cited in 23]. In this work, to optimize components for aerospace and biomedical applications, the level set topology optimization implemented in ANSYS. Apart from ANSYS, an open source software package implementing the Level Set Method is the OpenLSTO[4] package, which has been a rather recent addition to the arsenal of TO tools.

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[4] http://m2do.ucsd.edu/software/

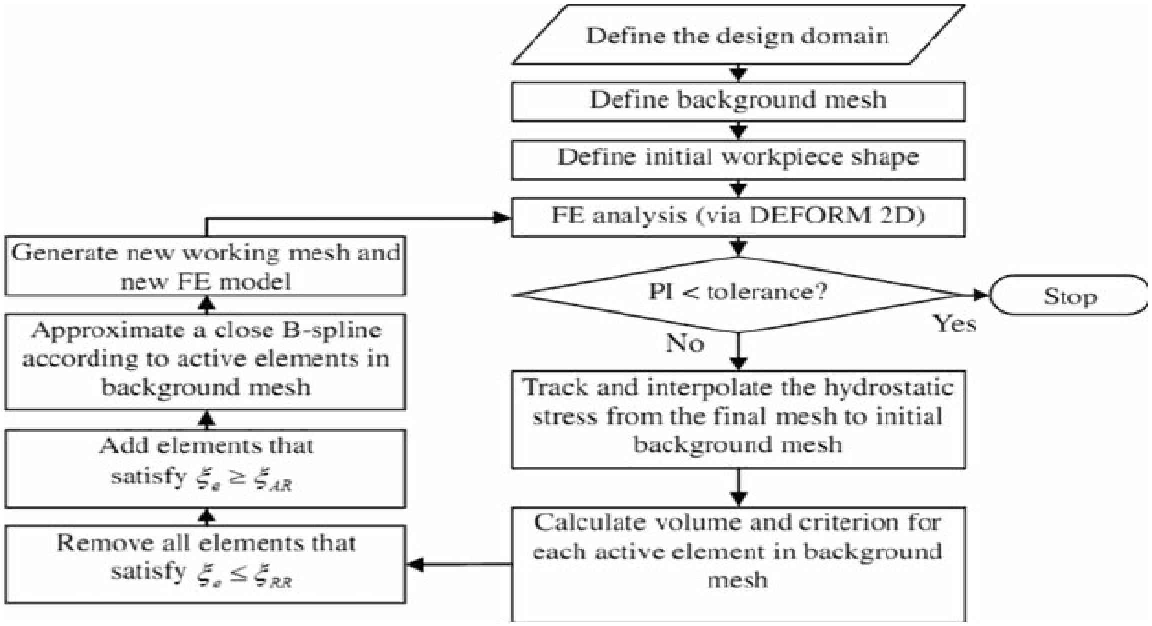


Fig. 4 Schematic representation of the general Topology Optimization Process [24]

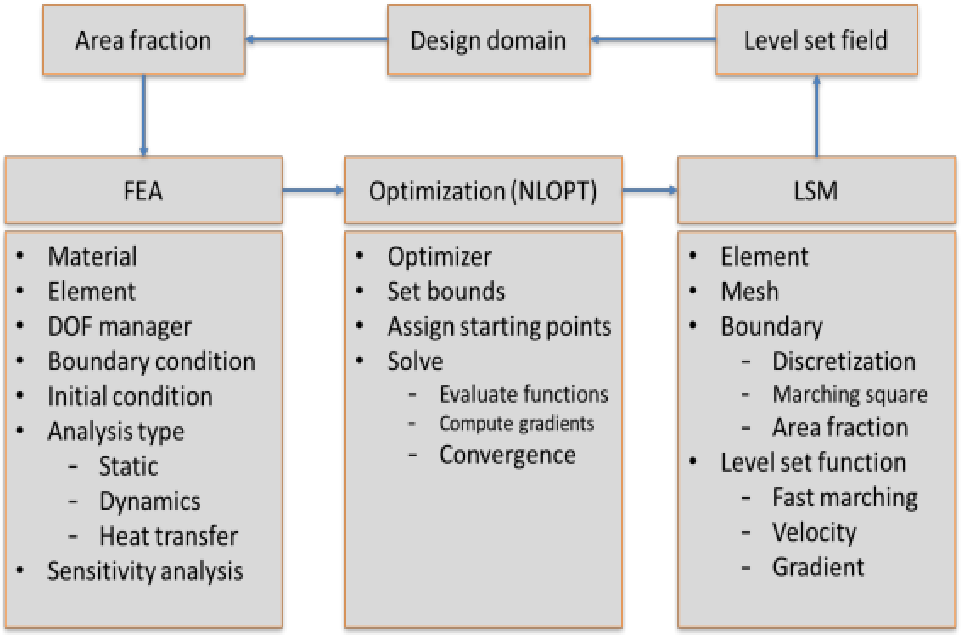


Fig. 5 the OpenLSTO Framework [25]

2.5. Topology Optimization in Additive Manufacturing

In the pursuit of the full exploitation of the design freedom and manufacturing complexities which AM technology permits, topology optimization becomes of great importance. Structural optimization leads, in most cases, in complex geometries. Consequently, topologically-optimized designs are commonly difficult to produce with conventional manufacturing techniques. Hence, it is not uncommon for researchers and engineers working with topology optimization to resort to AM techniques. At the same time, the limitations of AM need to be also taken into account so that complex topologically optimized designs of high quality can be achieved [26].

Although a precise mathematical definition of topology optimization exists, a more practical descriptive definition from an engineering perspective states that, “Topology optimization is a shape optimization method which uses algorithmic models to optimize material layout within a user-defined space for a given set of loads, conditions, and constraints” [27].

Topology optimization produces such lightweight components without sacrificing strength. Topology optimization optimizes an object’s geometry by modifying its topology and shape which ultimately enables the production of parts with improved performance and/or mechanical strength. Topology optimization software packages coupled with computation tools for structural analysis can calculate stresses and reduce or eliminate regions with redundant material usage. Designers are therefore able to optimize material distribution as dictated by the objective functions of choice, including load-maximization, stiffness, deformation etc. This permits the identification of the best possible geometry of a given component subject to given performance criteria and engineering constraints [28].

In modern manufacturing, a wide range of application objectives are achievable through the advantages and possibilities made possible by the integration of topology optimization and additive manufacturing. Research in this area reveals that creating high-performing, multi-functional, and lightweight products relies on a holistic approach which considers simultaneously, materials, structure, manufacturing processes, and performance**.** [3].

In their review of “additive manufacturing and topology optimization process for weight reduction in various industrial applications”, the authors in [28] proposed two main reasons for the integration of topology optimization into AM; the first reason being that optimized components can be produced through additive manufacturing as they are very complex and difficult to manufacture by conventional processes. The second consideration is cost, as it is directly related to the material and weight. Hence, they concluded that by combining topology optimization and additive manufacturing techniques, less and lightweight components are produced that simplify assembly and consequently result in reductions of cost, material usage, and elimination of design failures [28]**.** This integration of TO and AM lends us a production approach for the fabrication of lightweight and high performing structures [29]**,** and relative to sizing and shape optimization, TO does not depend on the initial configuration and has a wider design space [3].

2.6. Research Gap

When the potential of topology optimization in additive manufacturing is fully maximized, the possibilities of high quality and lightweight customized products are endless. From the literature reviews carried out above, it has been found that the Level Set Method of topology optimization is more advantageous relative to the other methods. However, despite these many advantages, there seems to be a lack of adequate literature on the application of the Level Set Method in additive manufacturing. The majority of the literatures are based on the Density Based Method of topology optimization. Therefore, more research on the practical application of LSM in additive manufacturing becomes necessary.

3. Methodology

3.1. Overview

In this chapter, the methodology employed in this work is presented in detail and covers:

- ANSYS Static Structural Setup for topology optimization,
- mesh refinement and convergence,
- slicing of the STL file for additive manufacturing,
- 3D printing of the original and optimized components using the fused deposition modeling technique, and
- subsequent mechanical testing of the printed parts.

3.2. ANSYS Static Structural Setup for Topology Optimization Analysis

The ANSYS WORKBENCH was deployed for the setup of topology optimization and structural analysis of both employed components, i.e., the bracket and the crutch. The Objective function is set to minimize compliance which implies minimizing the strain energy (when only mechanical loads exist) given that lower strain energy leads to increased stiffness. This is achieved by adding material in regions with higher stress values and removing it from areas that exhibit no or low stresses.

Within the ANSYS workbench, the Geometry, Static Structural, and Structural Optimization modules were selected and set up as shown in figure 5 below. As noted in [30], in the ANSYS Workbench, Static Structural and the Topology Optimization modules are mainly utilized for carrying out topology optimization via the density-based method; the level set method, or other methods. The original models were modeled in a separate CAD package, imported into the workbench, through the Geometry import function, and then transferred to Static Structural and Structural Optimization for meshing, structural analysis, and subsequent topology optimization. After successful mesh generation, analysis, and optimization, the optimized models are transferred back to the Static Structural module for design validation.. The protocol used in this setup is based on [31] which noted that the modified geometry resulting from each iteration of the optimization algorithm is transferred to another Static Structural module where the new structural behaviors are analyzed. The coupled modules are linked in a way that permits information retrieval from the first module while passing outputs for optimization and analysis [31].

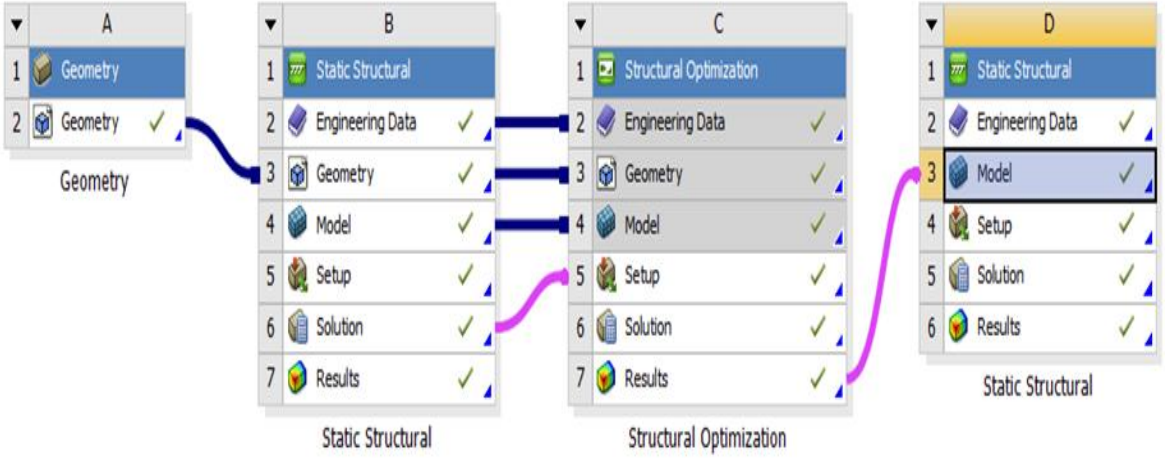


Fig.6 ANSYS Module Setup

3.2.2. Mesh Refinement and Convergence

High quality results can be achieved with relatively low processing time when appropriate element and mesh sizes are selected for a given geometry. Hence, sensitivity analysis and mesh convergence were carried out by refining and adjusting the mesh settings in ANSYS accordingly. The models’ mesh quality was analyzed using the maximum equivalent (von-Mises) strain and total deformation. This enables the analysis of the strain energy and total deformation experienced by the bracket and crutch under the applied loads.

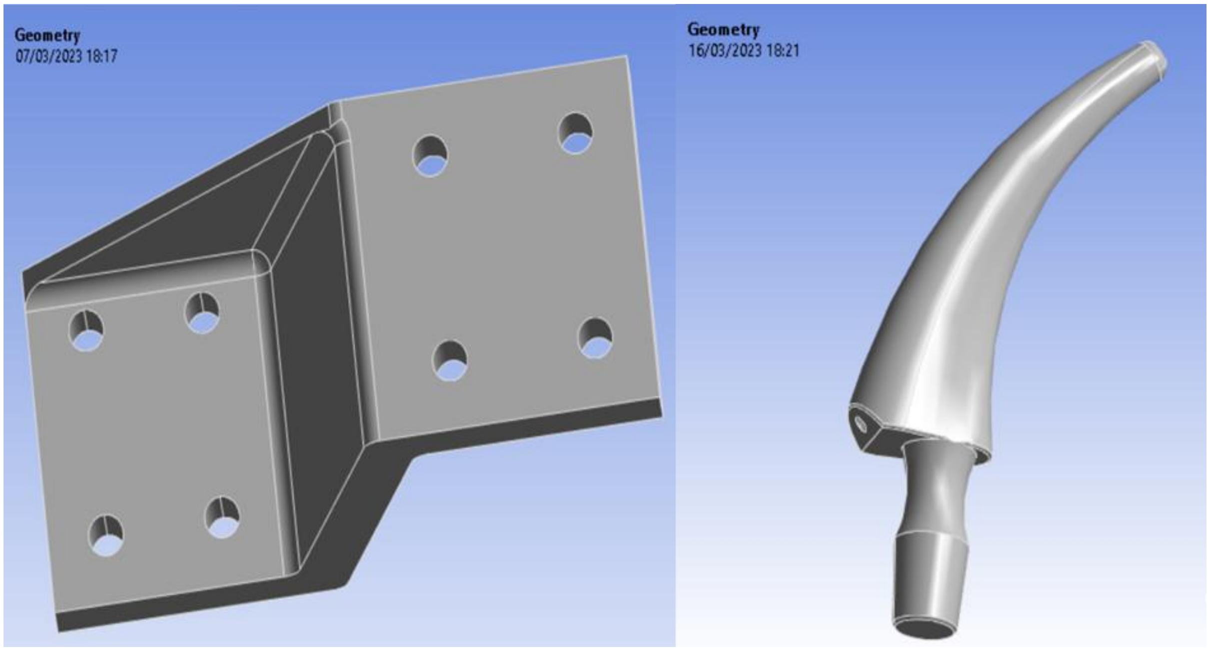
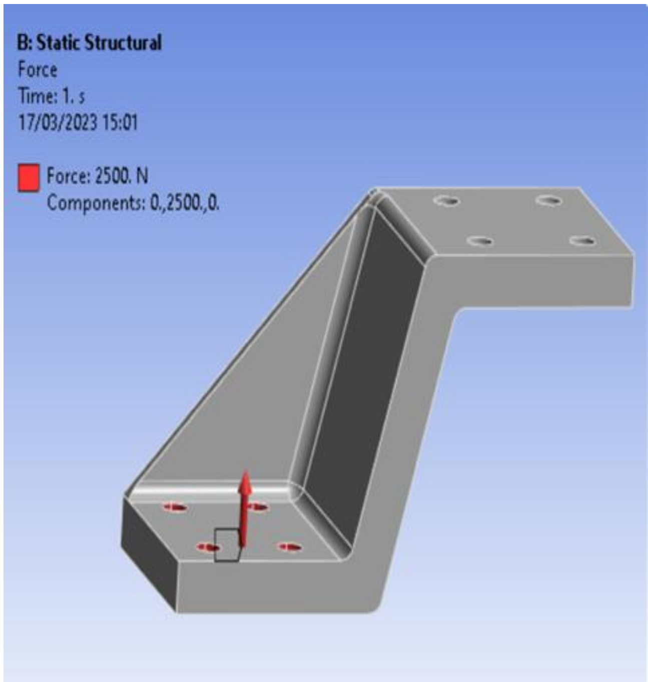


Fig. 7 Initial geometry of the Bracket and Crutch for Meshing Analysis

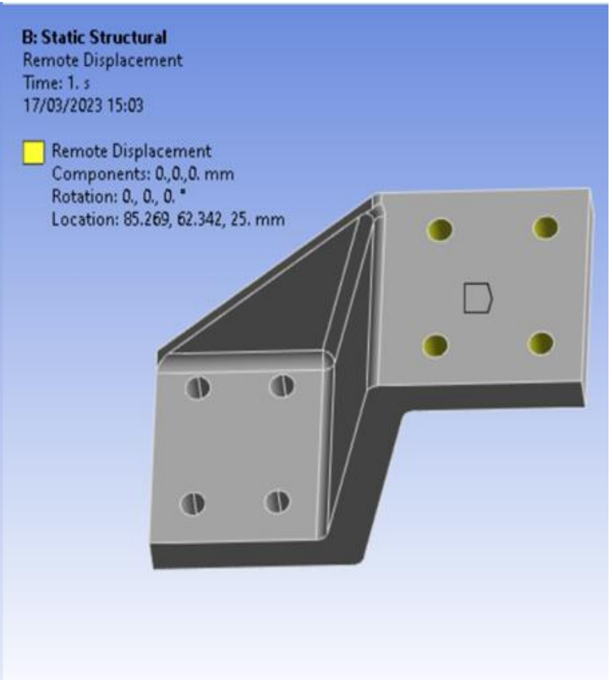
For the purpose of simulation, structural steel which is the default material in ANSYS Workbench was used. The bracket model has a volume of 77444mm^3 and weighs 0.608kg (assuming structural steel). Figure 8a depicts an applied compressive force of 2.5kN on the lower end of the bracket, while figure 8b shows the boundary condition which is a fixed support applied on the upper end of the bracket,



B: Static Structural
Force
Time: 1. s
17/03/2023 15:01

🟥 Force: 2500. N
Components: 0.,2500.,0.

Fig. 8a Applied Compressive Force



B: Static Structural
Remote Displacement
Time: 1. s
17/03/2023 15:03

🟨 Remote Displacement
Components: 0.,0.,0. mm
Rotation: 0., 0., 0. °
Location: 85.269, 62.342, 25. mm

Fig. 8b Remote Displacement

Using the mesh convergence tool built into ANSYS, the criteria for convergence of the mesh was set <1% for a change in the Root Mean Square (RMS) error of the equivalent (von-Mises) strain. The mesh sensitivity was analyzed using an element size of 3mm

Similarly, the crutch has a volume of 17303mm^3 and a weight of 0.136Kg (assuming structural steel). The applied compressive force of 0.1knN and the fixed support boundary conditions are shown in the figures below. The mesh convergence criterion is the same as in the bracket above, except that the element size was set at 2mm.

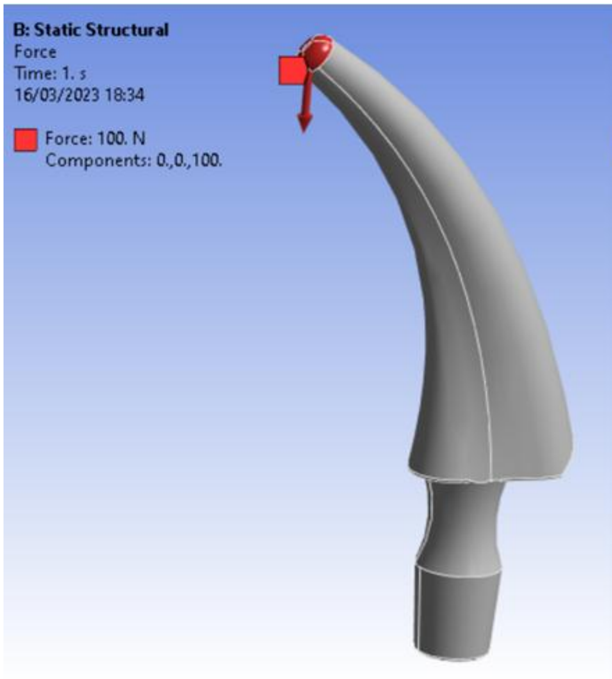


Fig. 9a Applied Compressive Force

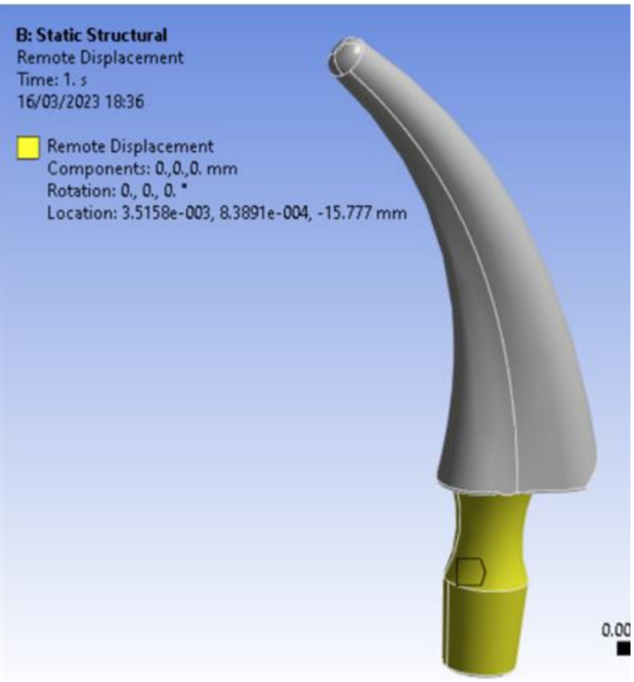


Fig. 9b Remote Displacement

For the bracket, three optimization scenarios were studied. Firstly, the optimization region was set at the default option which is based on the boundary conditions only. In this case, the boundary conditions are used to specify the region of the design domain to be excluded during the optimization process. Secondly, the optimization region was specified using the geometry selection option which allows the designer to specify regions to be excluded from the optimization in addition to the boundary conditions. In the third instance, as in case two, the exclusion region was slightly varied in order to ascertain whether it has a significant effect on the mechanical strength of the optimized model. The figures of the three cases are shown below.

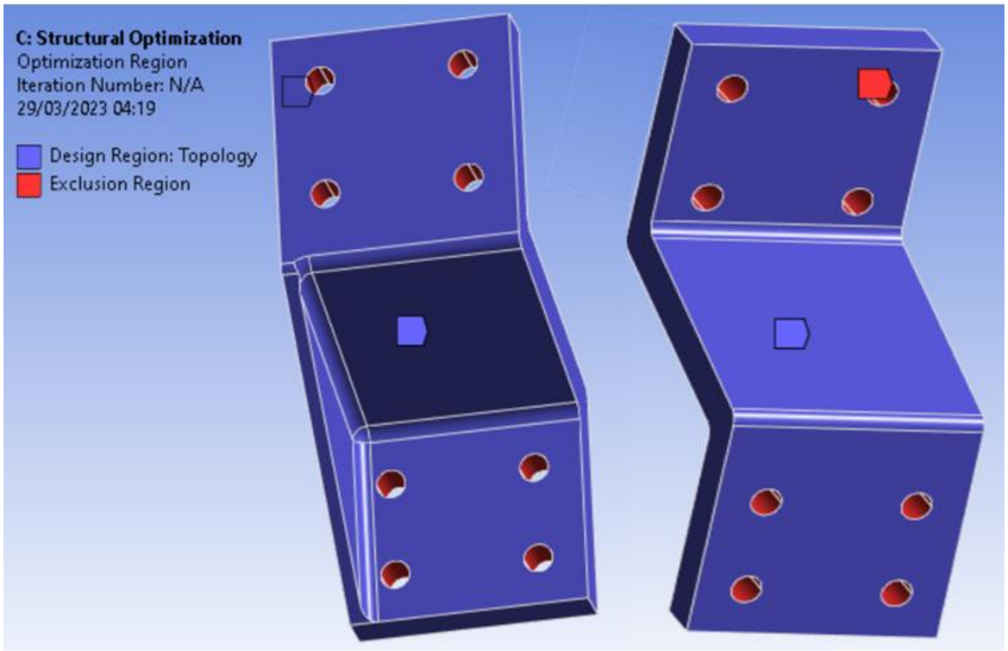


Fig. 10 Optimization Region Case 1

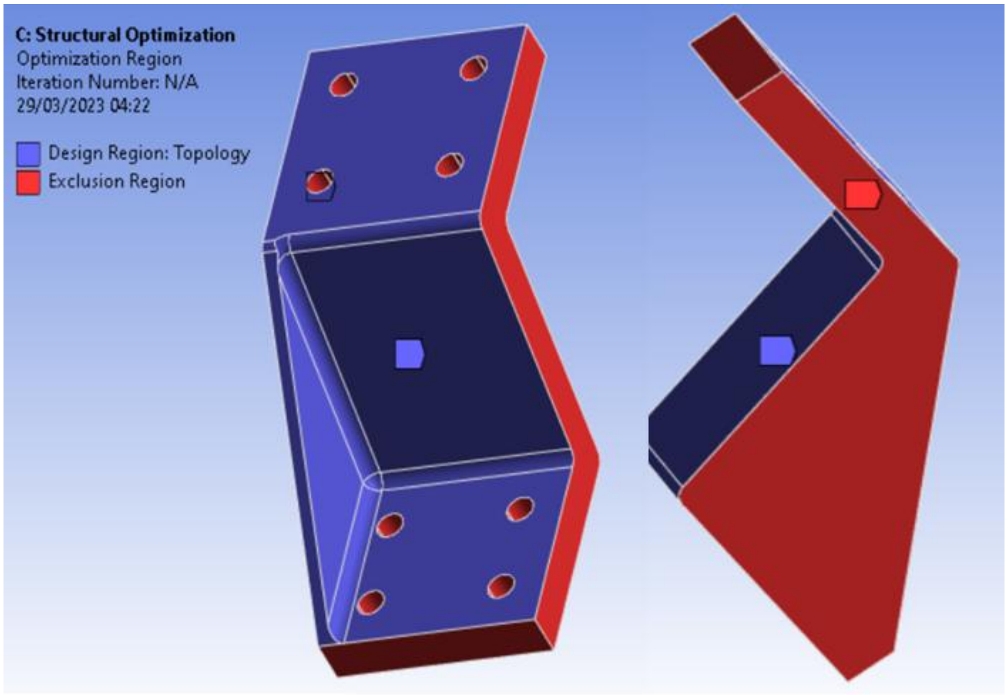


Fig. 11 Optimization Region Case 2

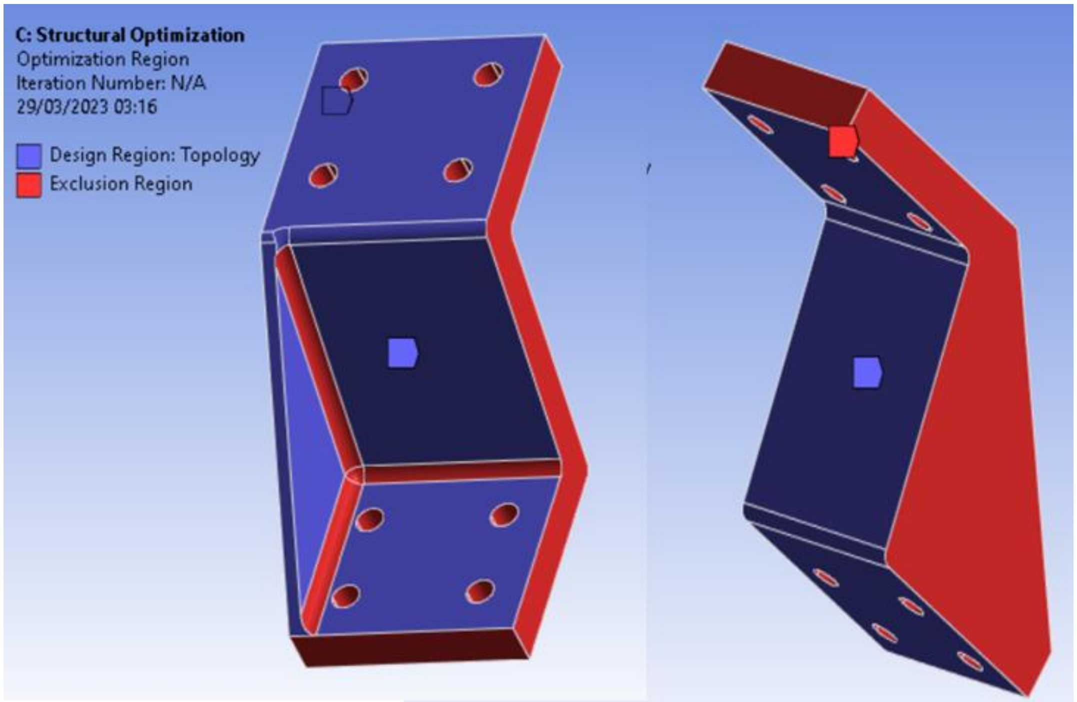


Fig. 12 Optimization Region Case 3

The results of the three optimization scenarios are presented in chapter four which is the result and discussion chapter.

3.3 Fused Deposition Modeling

The fused deposition modeling AM technique was used for prototyping in this project for many reasons. The FDM additive manufacturing technique which finds applications in such important areas as aerospace, biomedical, education, fashion, design industries, etc, has been noted as one of the most widely and frequently used AM technology especially for non-commercial applications as it is versatile in the production of functional parts which have complex geometry in reasonable production time; its process simplicity, low operational cost, relatively high printing speed; readily available 3D printers, and a wide range of available thermoplastics [32, 33,34,35]

FDM follows similar processing steps commonly found in several additive manufacturing techniques, i.e., Modeling, Printing and Finishing [36]. Generally in additive manufacturing, an appropriate software package “slices” CAD data to generate the layers that will be printed. The slicer commonly accepts 3D discretizations (triangulations) of solid models described in the standard Stereolithography (STL) format. These discretizations are generated from the original 3D solid model which is commonly generated in an appropriate CAD software package. Parallel cross sections are taken from the model in the STL file, which constitute the slices/layers that will be printed on top of each other, i.e., the desired 3D object is created by the gradual deposition of layers. Based on the printing technique, the printed object may require post-processing steps, such as surface finishing, support material removal, and sintering. The process can be summarized below

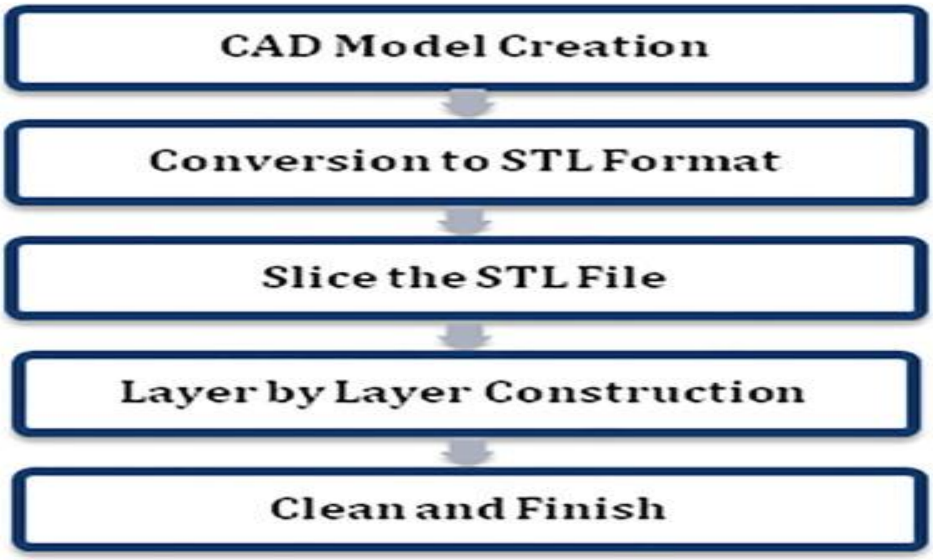


Fig. 13 FDM Printing Steps [34]

In the employed FDM 3D printing technique, polymer filament is used to build components layer upon layer via a hot extruder. In this method, the filament is heated to a molten state at the nozzle and afterwards extruded to build successive layers on the build platform [37]. The FDM printing technology is illustrated in the figure below.

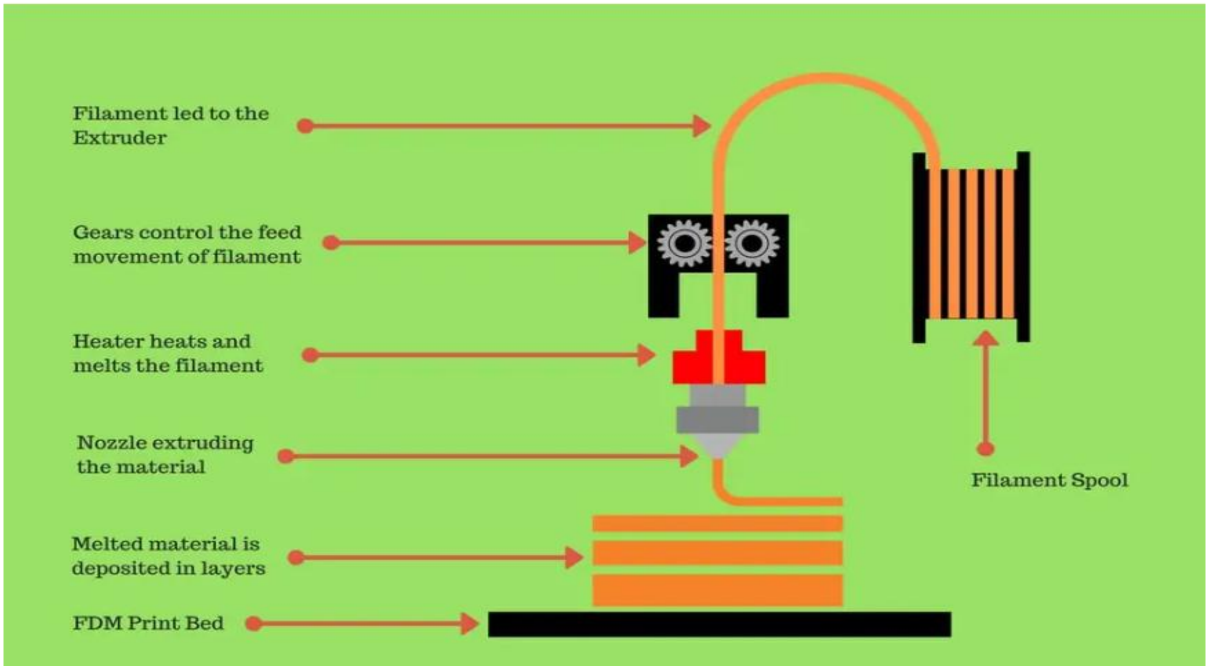
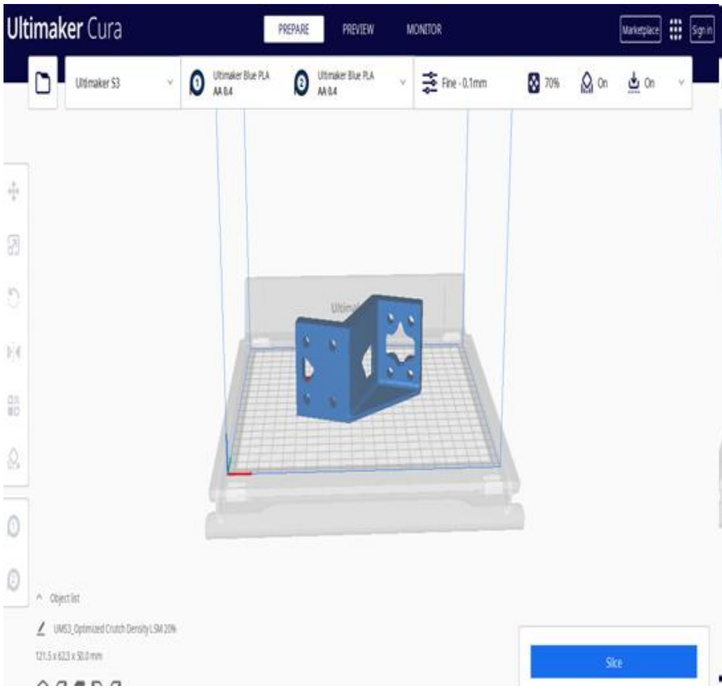


Fig. 14 Process flow of a typical FDM Printer [38]

3.3.1. 3D Printing Setup

The 3D printing setup involves the conversion of the optimized model into an STL file, slicing of the STL file, as well as the calibration of the printing machine. After the topology optimization of the bracket using the ANSYS workbench, the optimized modeled was converted into an STL file which was subsequently sliced using the Ultimaker Cura 5.3.0 software [39]. In the Cura Software, after importing the STL file, the printing material, printing parameters, and printing conditions were carefully selected in accordance to the desired printed component functionality



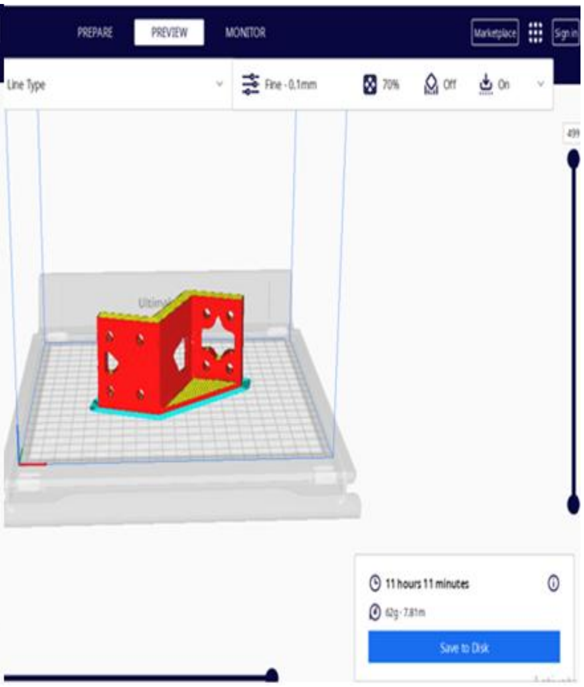


Fig. 15a Ultimaker Cura [39] **Fig. 15b**

Figures 15a and b show the STL file being prepared as well as the final prepared model ready for 3D printing

3.3.2. Printing Material and Parameters

The printing material used in this work is Ultimaker PLA (Blue PLA)[40] due to its desirable qualities. According to Ultimaker, PLA (Polylactic acid), which is available in 11 colours, is very versatile and easy to print; it is reliable and prints with high dimensional accuracy and produces surface finish of high quality thereby making it a good option for different applications such as detailed prototypes, simple manufacturing jigs and gauges [40]. As noted from relevant literature, the following printing parameters affect the quality of the printed part as well as the total cost of production; hence they must be carefully selected.

1. The printing speed which defines the material deposition rate and printing time [8, 34, and 41]

2. Layer height influences the quality and dimensional accuracy of the printed parts [41, 42, 43, 44, and 45].
3. Extrusion temperature which is the temperature of the nozzle affects the viscosity of the melted polymer and so impacts the quality [41, 46, 47, and 48].
4. Based on the aforementioned reviews, the following values for the printing parameters were identified: printing speed of 60 mm/s, 70% infill density, overhang angle of 85 degree for the support material (in the case of the crutch), Triangle infill pattern, and layer height of 0.1mm were selected. The extrusion temperature was set at the recommended default setting which is 60 and 200 °C for the build plate and printing temperatures, respectively.

3.3.3 3D printing of the Optimized Component

Printing was done using the Ultimaker S5 3D printer. After selecting the appropriate printing parameters and slicing the initial and optimized models using Cura software, the generated codes were transferred to the Ultimaker S5 3D printer where the models were built. The figure below shows the Ultimaker S5 FDM 3D printer as well as printing spools of various colours. Picture 13a shows the front view of the printer which contains the control panel for selecting the sliced STL file, which is supplied through a USB drive, loading and unloading of the spool, calibration of the printing parameters; the transparent door enables the monitoring of the printing in progress, also the printed parts can be removed through it. In the same way, picture 13b is the rear view of the printer and shows the placement of the spool holder and the spool. The spool is fed to the print head inside the printer through the thin tubes. Finally, Fig. 13**c** depicts the collection of Ultimaker printing spools of various colours.

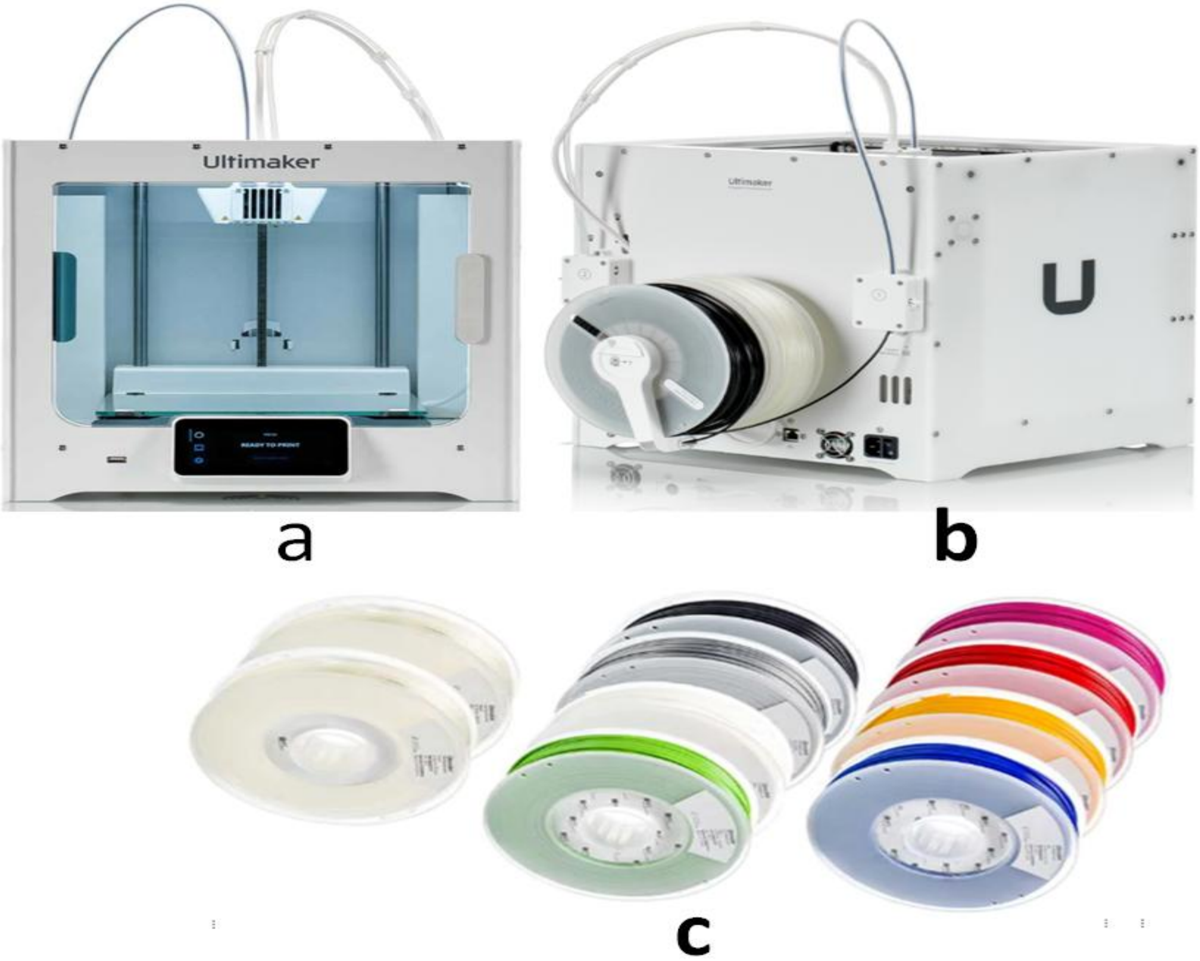


Fig. 16 Ultimaker 3D Printer and Spools [49, 50]

In total, eighteen samples of the bracket were printed: six copies of the original model and 12 for the optimized model (6 for Optimization Region Case 2 and 6 for Optimization Region Case 3). The results of the optimization process, 3D printing, and the mechanical testing are presented in the next chapter.

4. Results of Optimization and Additive Manufacturing

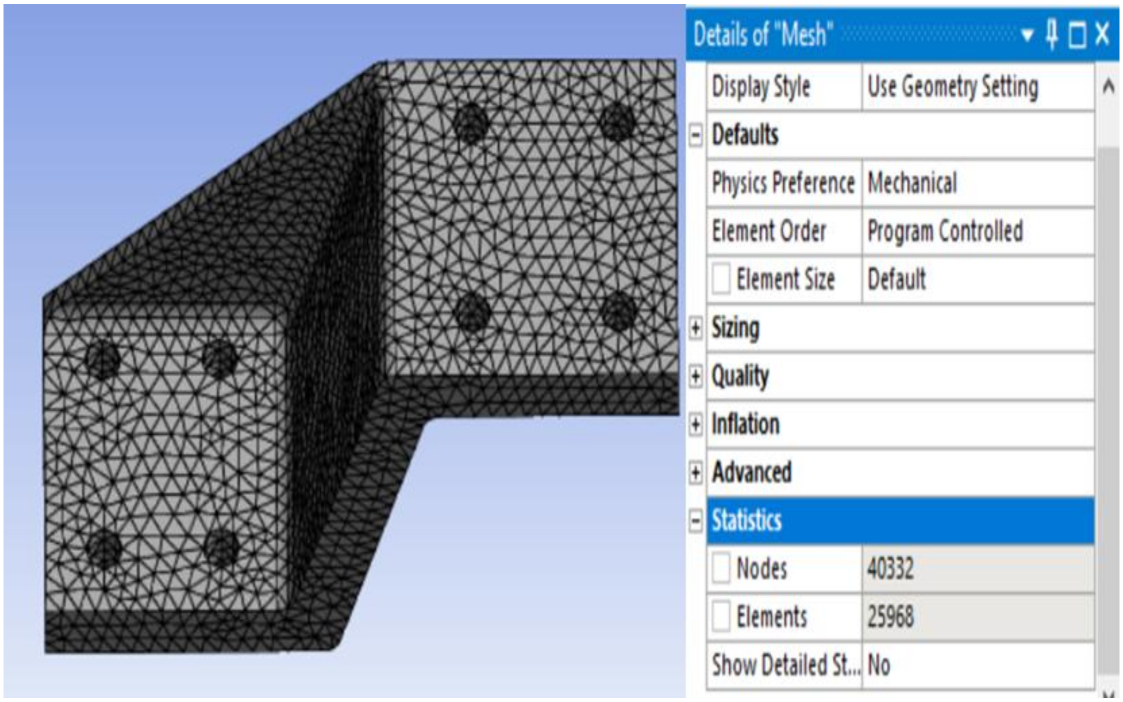
4.1 Overview

In this section, the results of the topology optimization, FDM 3D printing of the initial and optimized models, and the mechanical testing are presented and discussed. Overall, the results obtained from the whole process are satisfactory as the objectives and expected outcomes were met. In this case, the objective is to minimize compliance which implies minimizing the strain energy as lower strain energy leads to increased stiffness.

4.2 Topology Optimization Results

As noted in the previous chapter, the optimizations were carried out using the ANSYS Workbench The process involves importing of the predesigned geometry using the geometry module, transfer of the imported module to the statics structural module which in turn is linked to the structural optimization module where the structural analysis and topology optimization were respectively carried out, and then results of the optimized model are transferred back to the structural optimization module for validation as illustrated in figure 6 in chapter 3 above.

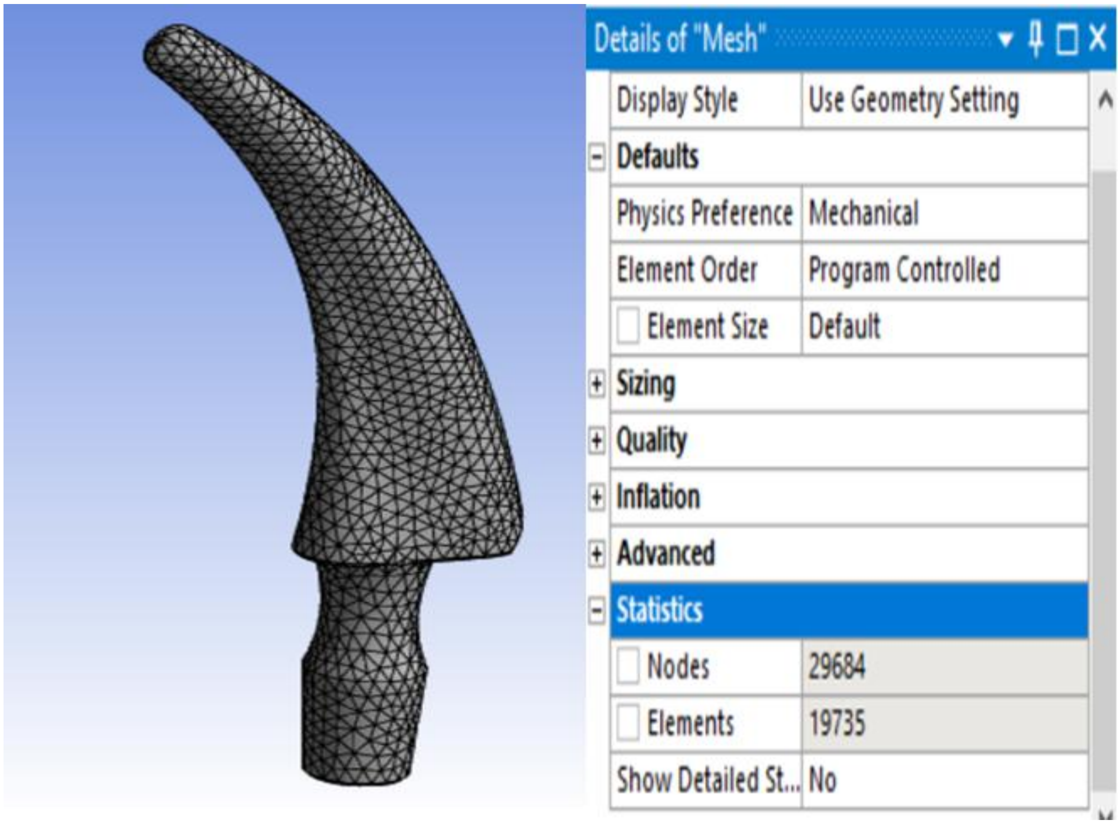
The results of the mesh analysis for the Bracket and Crutch are shown in figures 17 and 18, respectively. For the Bracket, the mesh was descritized into 40332 nodes and 25968 elements, and the optimization solution converged on the 23rd iteration as shown on figure 21; in the case of the crutch, it was discritized into 29684 nodes and 19735 elements as shown below.



Details of "Mesh"

Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
☐ Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
☐ Nodes	40332
☐ Elements	25968
Show Detailed St...	No

Fig. 17 Meshed Model of the Bracket (Element size= 3mm)



Details of "Mesh"

Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
☐ Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
☐ Nodes	29684
☐ Elements	19735
Show Detailed St...	No

Fig. 18 Meshed Model of the Crutch (Element size= 2mm)

The total deformation and equivalent strain are shown in the figures below. From the figures, it can be observed that red-colored regions indicate high values, while lower values are represented found in the blue-colored regions. The maximum deformation and strain are concentrated on the regions with the red colour.

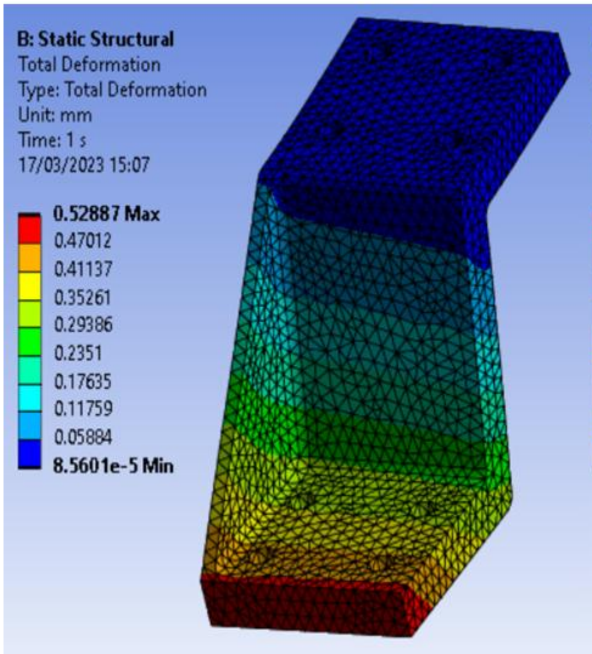


Fig. 19a Total Deformation (Bracket)

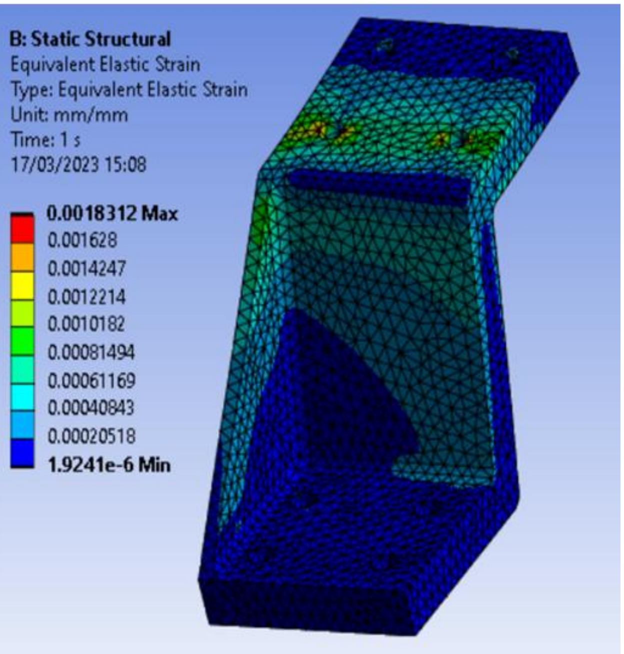


Fig. 19b Equivalent (von-Mises) Strain

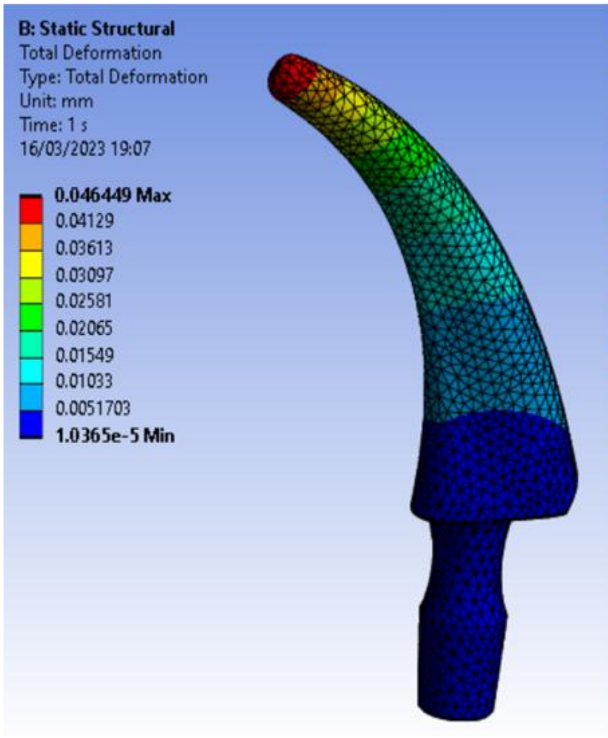


Fig. 20a Total Deformation (Crutch)

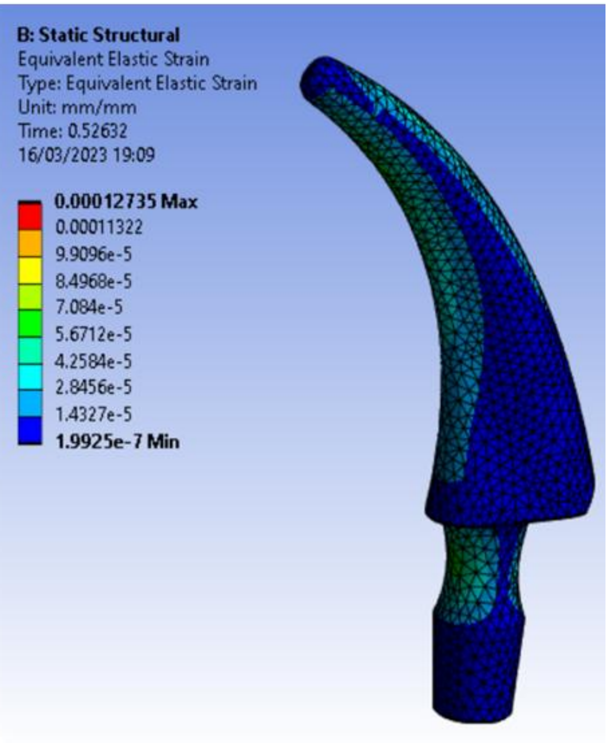
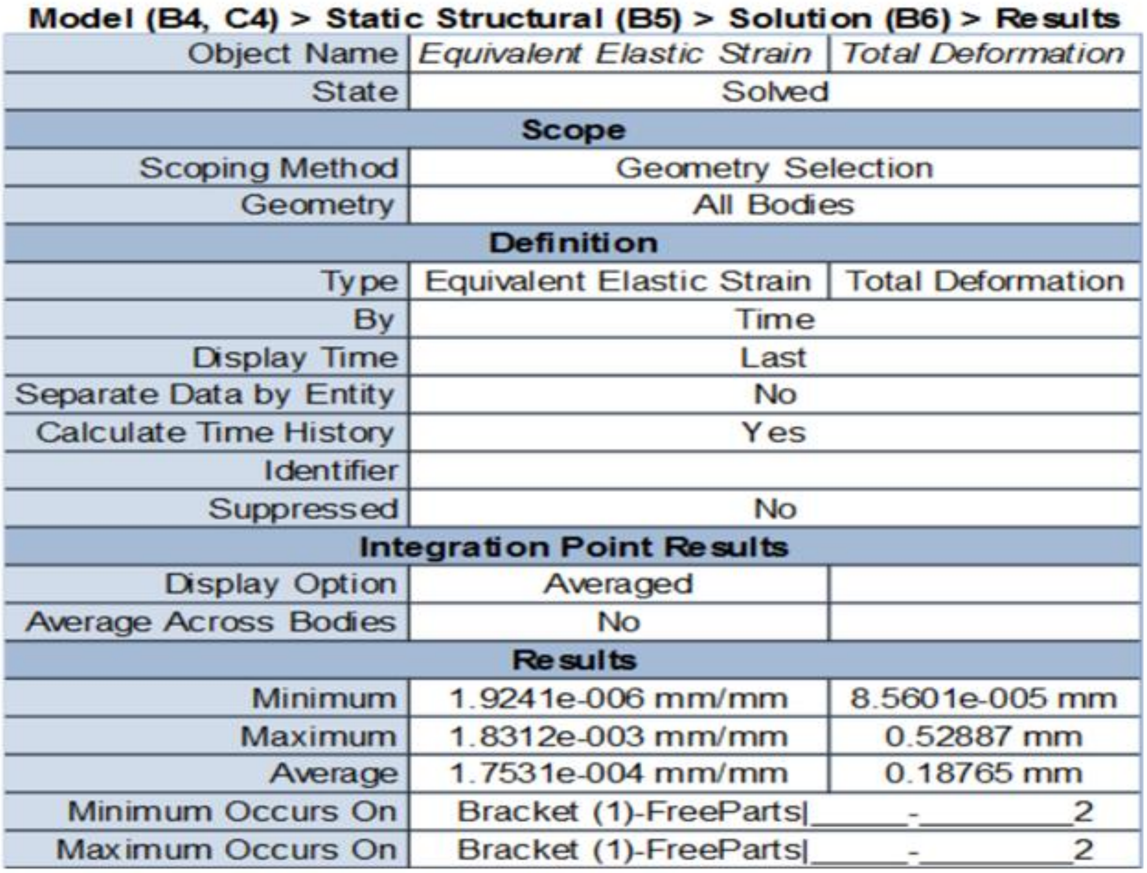


Fig. 20b Equivalent (von-Mises) Strain

The tables below summarize the results of the total deformation and equivalent elastic strain. From the table, it can be observed that 8.5601e-005mm, 0.52887mm and 0.18765mm are the minimum, average, and maximum total deformations respectively for the Bracket. The values 1.9241e-006mm/mm, 1.8312-003, and 1.7531e-004 correspond to the minimum, average, and maximum equivalent elastic strain, respectively.

Similarly for the Crutch, the minimum, average, and maximum values of the total deformations are 1.0365e-005, 4.6449e-002, and 7.9651e-003 in that order; whereas 1.9925e-007mm/mm, 1.2735e-004mm/mm, and 2.1235e-005mm/mm are respectively the minimum, average, and maximum equivalent elastic strain values.

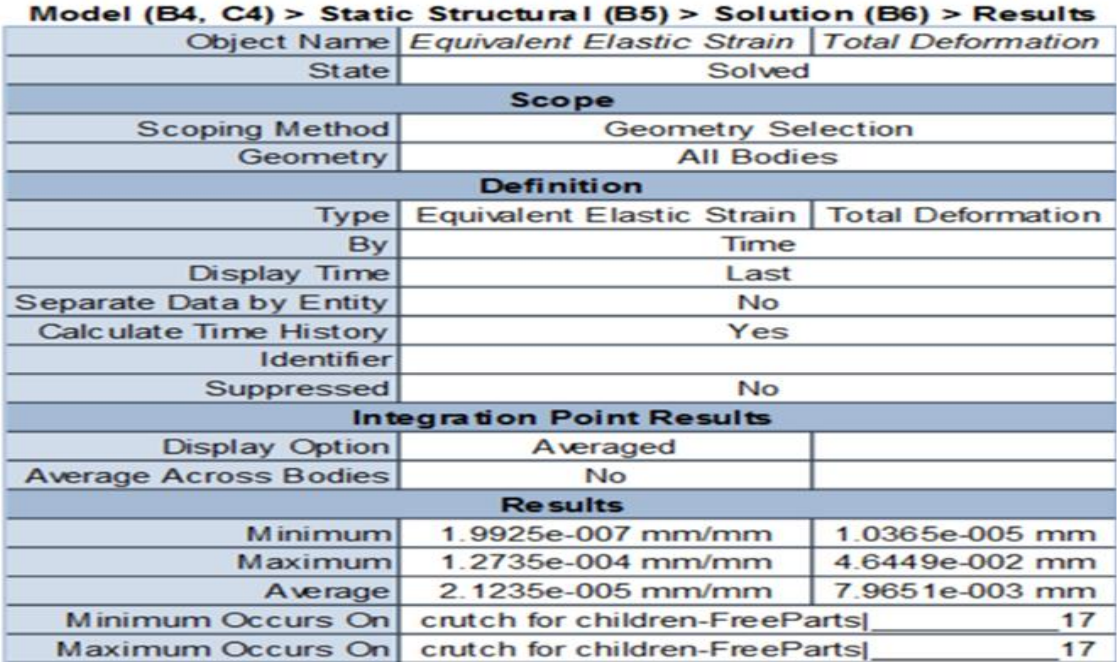
Table1 Static Structural Solution Results (Bracket)



Model (B4, C4) > Static Structural (B5) > Solution (B6) > Results

Object Name	*Equivalent Elastic Strain*	*Total Deformation*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Equivalent Elastic Strain	Total Deformation
By	Time	
Display Time	Last	
Separate Data by Entity	No	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Integration Point Results		
Display Option	Averaged	
Average Across Bodies	No	
Results		
Minimum	1.9241e-006 mm/mm	8.5601e-005 mm
Maximum	1.8312e-003 mm/mm	0.52887 mm
Average	1.7531e-004 mm/mm	0.18765 mm
Minimum Occurs On	Bracket (1)-FreeParts|_____-_________2	
Maximum Occurs On	Bracket (1)-FreeParts|_____-_________2	

Table2 Static Structural Solution Results (Crutch)



Model (B4, C4) > Static Structural (B5) > Solution (B6) > Results

Object Name	*Equivalent Elastic Strain*	*Total Deformation*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Equivalent Elastic Strain	Total Deformation
By	Time	
Display Time	Last	
Separate Data by Entity	No	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Integration Point Results		
Display Option	Averaged	
Average Across Bodies	No	
Results		
Minimum	1.9925e-007 mm/mm	1.0365e-005 mm
Maximum	1.2735e-004 mm/mm	4.6449e-002 mm
Average	2.1235e-005 mm/mm	7.9651e-003 mm
Minimum Occurs On	crutch for children-FreeParts|__________17	
Maximum Occurs On	crutch for children-FreeParts|__________17	

The convergence histories for the weight reduction in topology optimization are included in figures 21 and 22 for the Bracket and Crutch, respectively. While the optimization of the bracket converged on the 23rd iteration, the crutch converged on the 14th iteration. Overall, there was a 20% weight reduction for the Bracket as well as the Crutch.

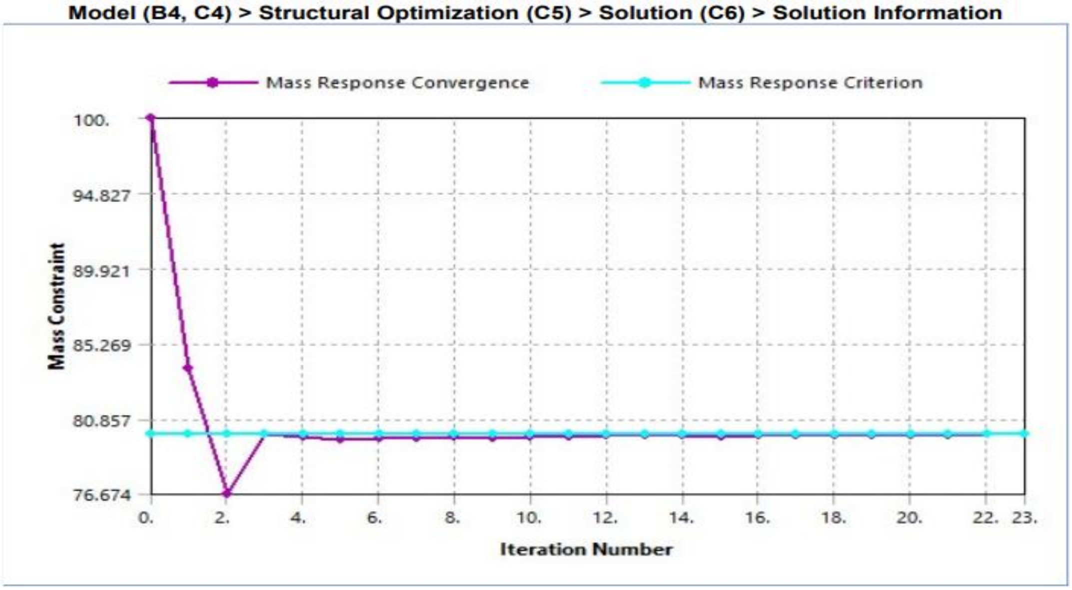


Fig. 21 Mass Response Convergence and Mass Response Criterion (Bracket)

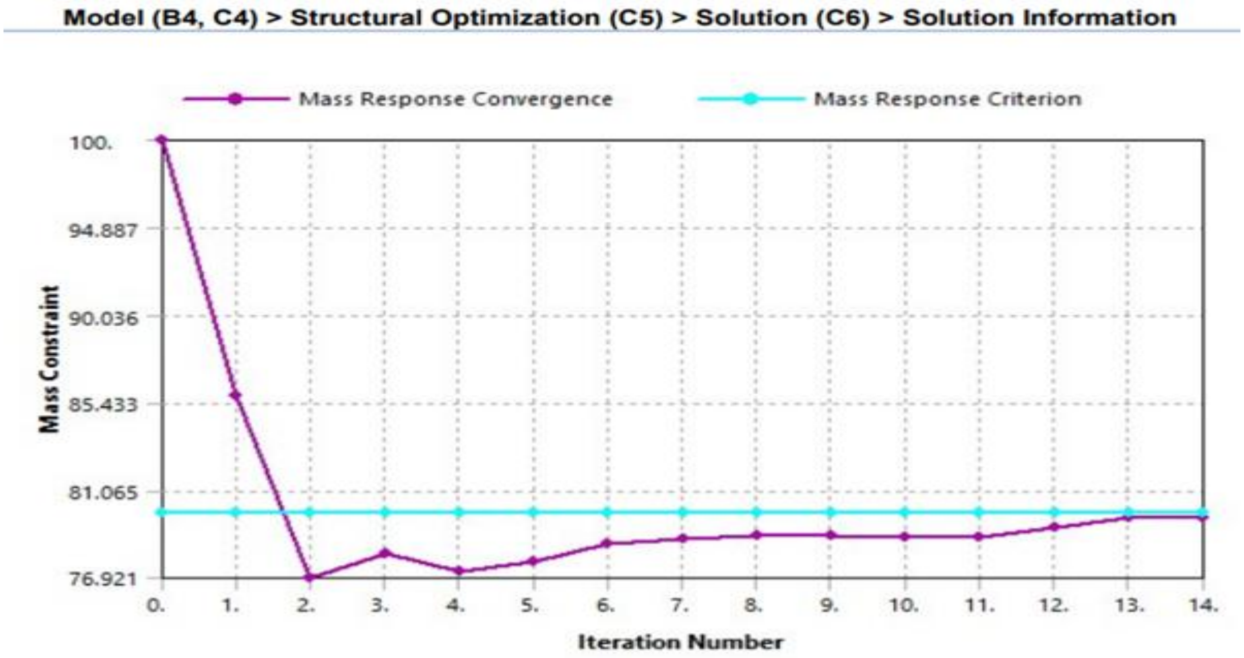


Fig. 22 Mass Response Convergence and Mass Response Criterion (Crutch)

In order to ensure that the optimization results are reliable, the resulting models were transferred to the statics structural module in ANSYS for validation, and the results are presented below. The results were validated and demonstrate that the simulations are accurate and reliable.

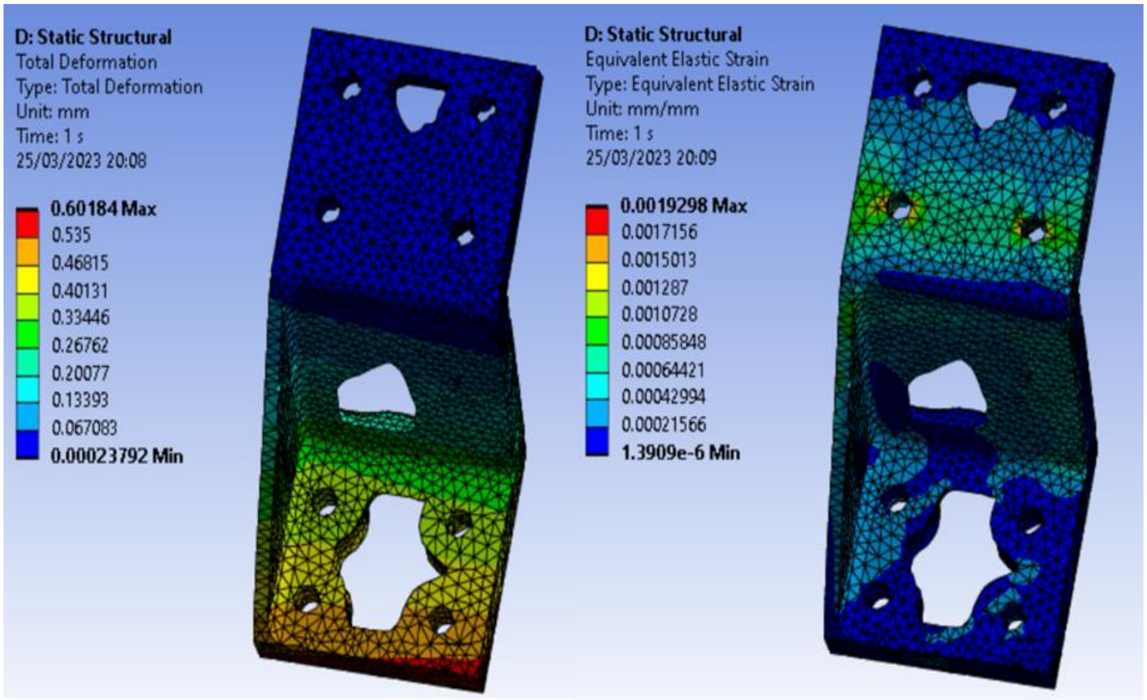


Fig. 23 Validation Results of the Optimized Bracket

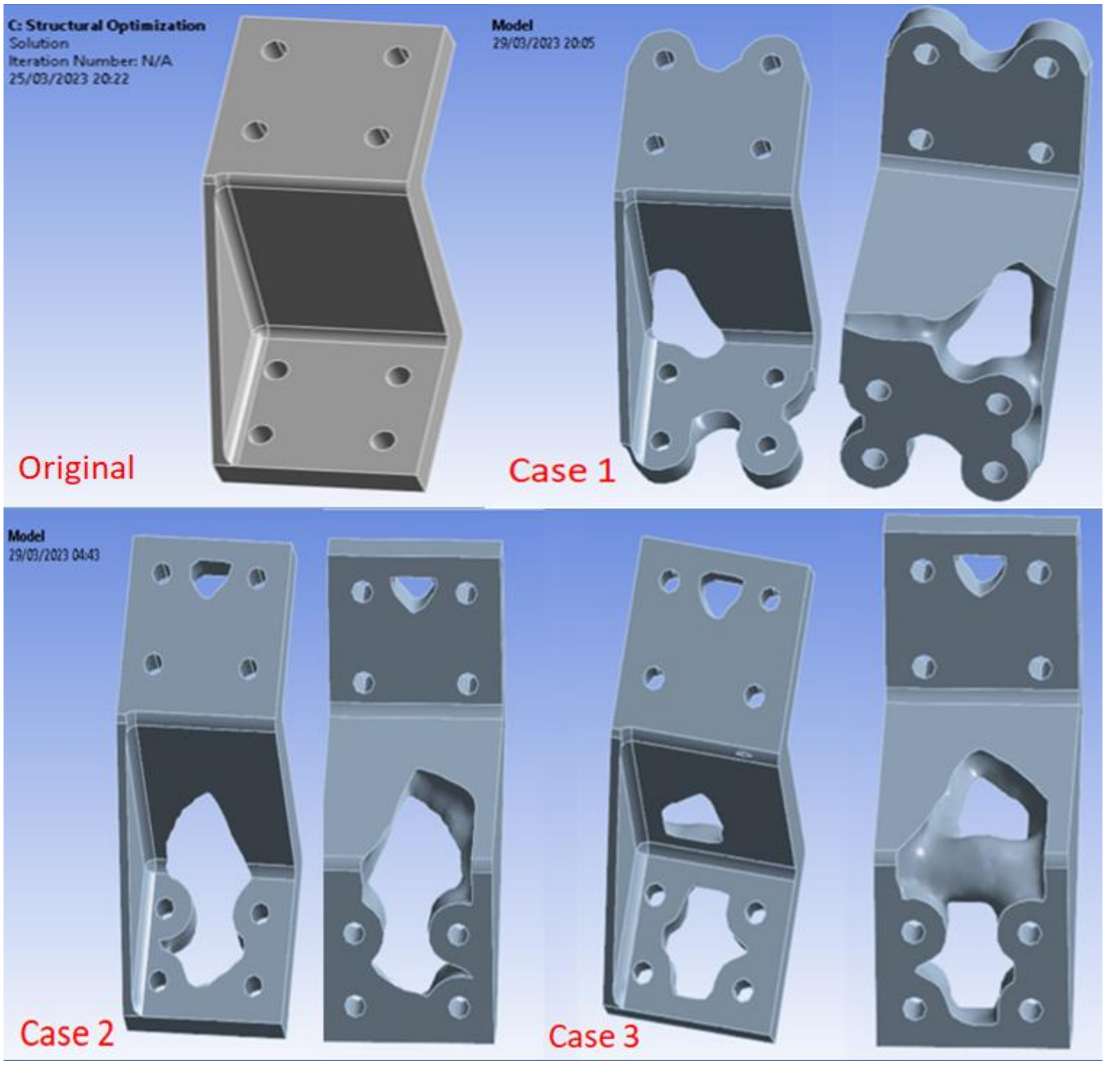


Fig. 24 Original Model Vs Optimized Result (Bracket)

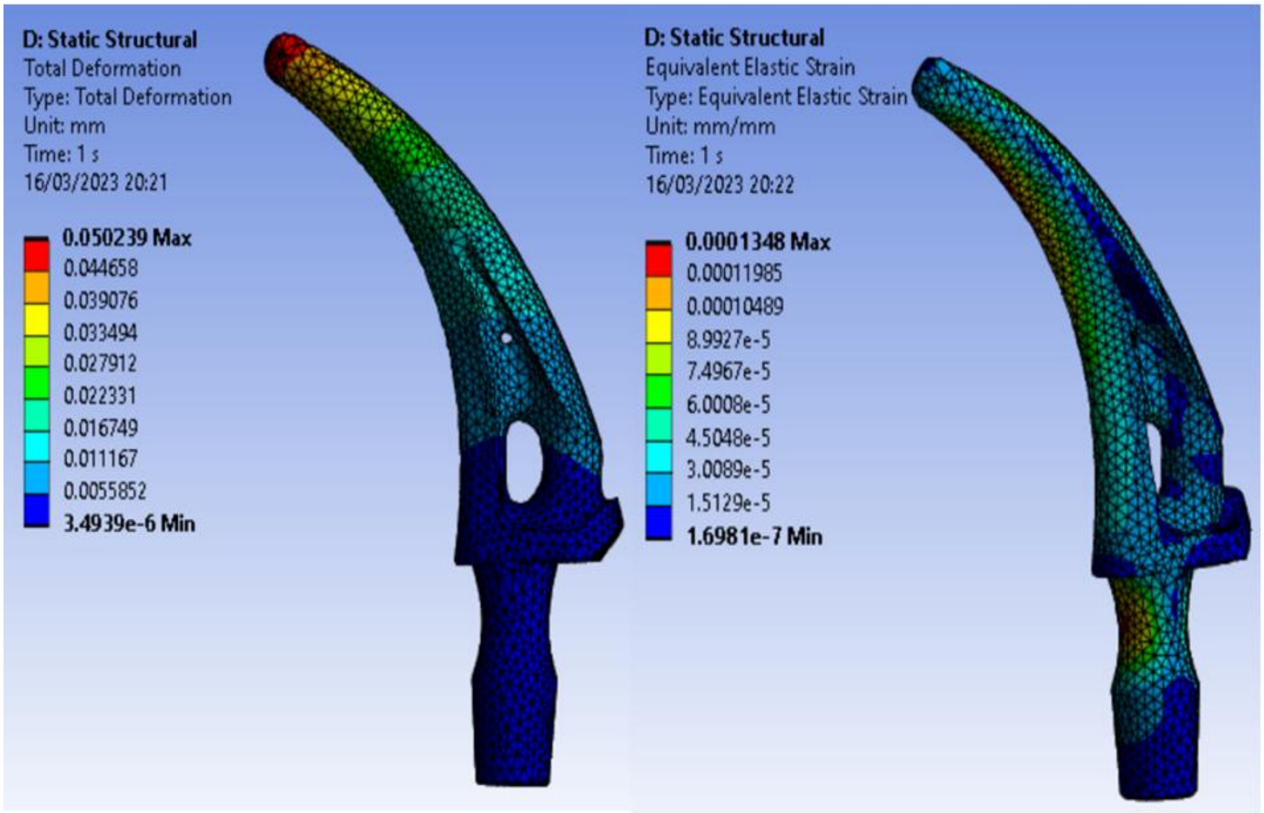


Fig. 25 Validation Results of the Optimized Crutch

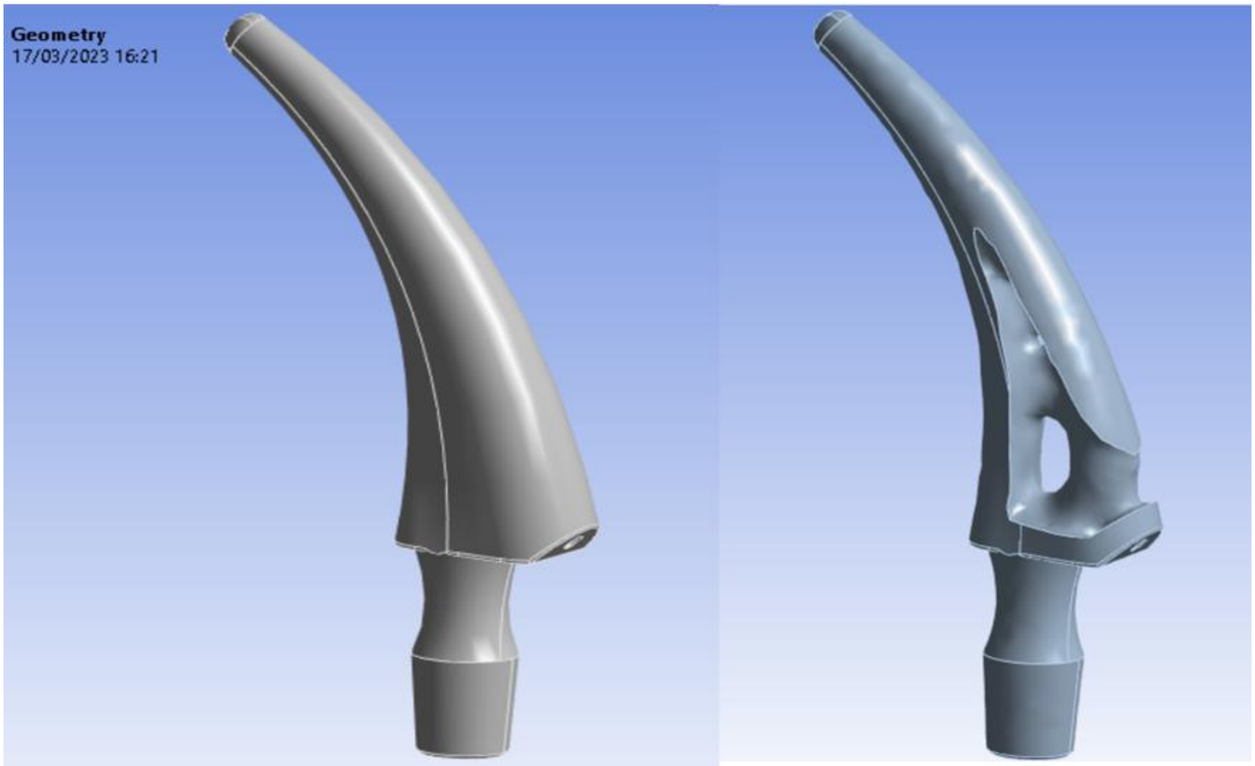


Fig. 26 Original Model Vs Optimized Result (Crutch)

4.3. Additively Manufactured Components

The results of the 3D printing of the original and optimized models are presented here. We print all components so that we can experimentally compare the stiffness of the optimized models to the original ones, to ensure that they satisfy the objective of the project which is to optimize the components in such a way that under the same loading conditions, approximately similar displacements would be experienced by both the original and optimized models. As noted already in the previous chapter, the 3D printing of the Bracket and Crutch was done using the Ultimaker 3D printer with the Ultimaker Blue PLA as the printing material.

In the case of the Bracket, only case 2 and case 3 of the optimized models were used and printed as they demonstrated displacement results much similar to the original.

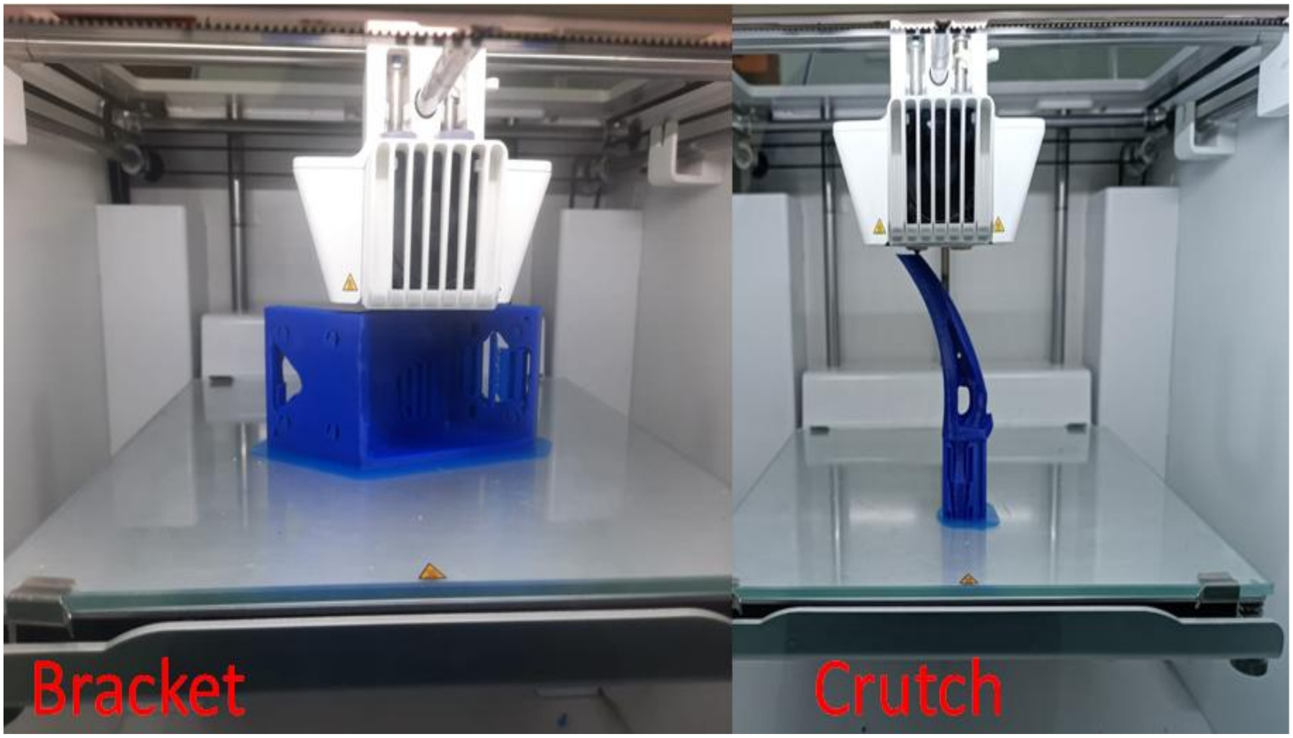


Fig. 27 Printing Work in Progress

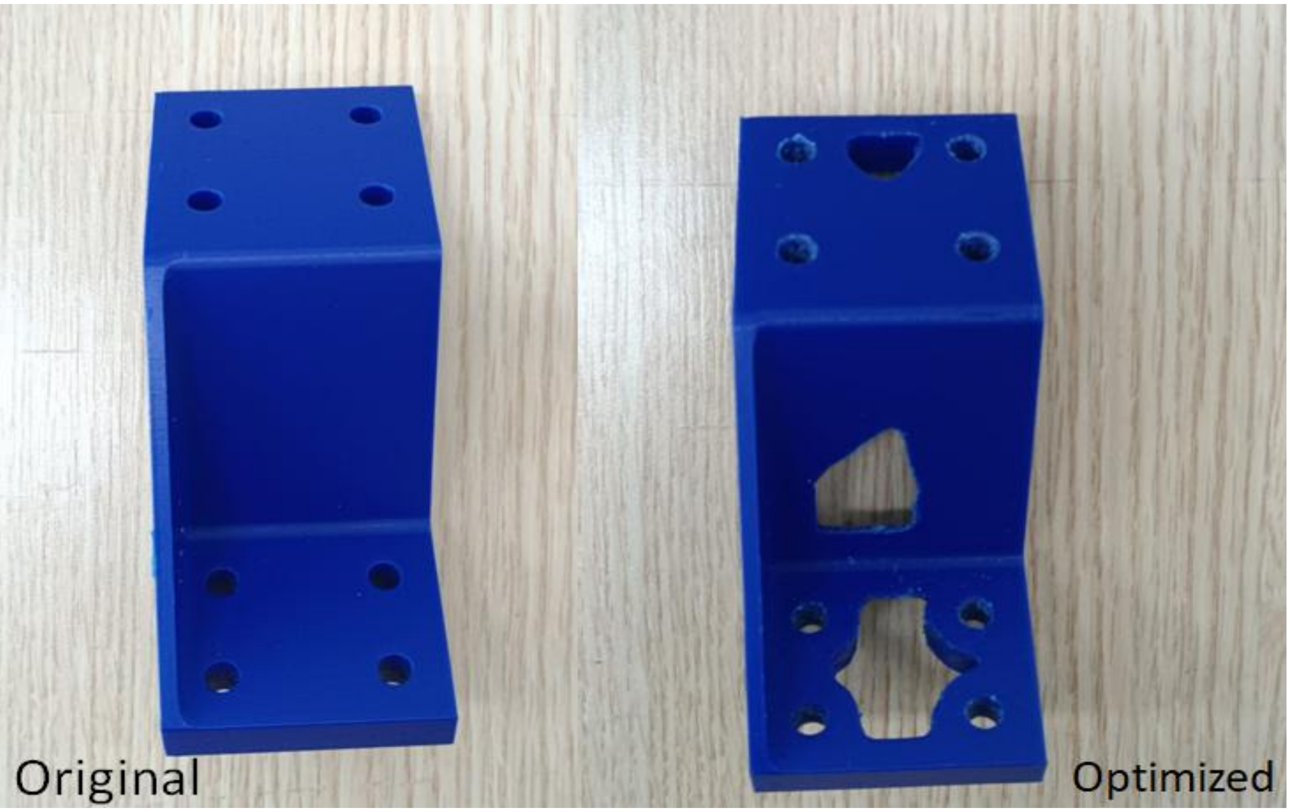


Fig. 28 3D Printed Bracket

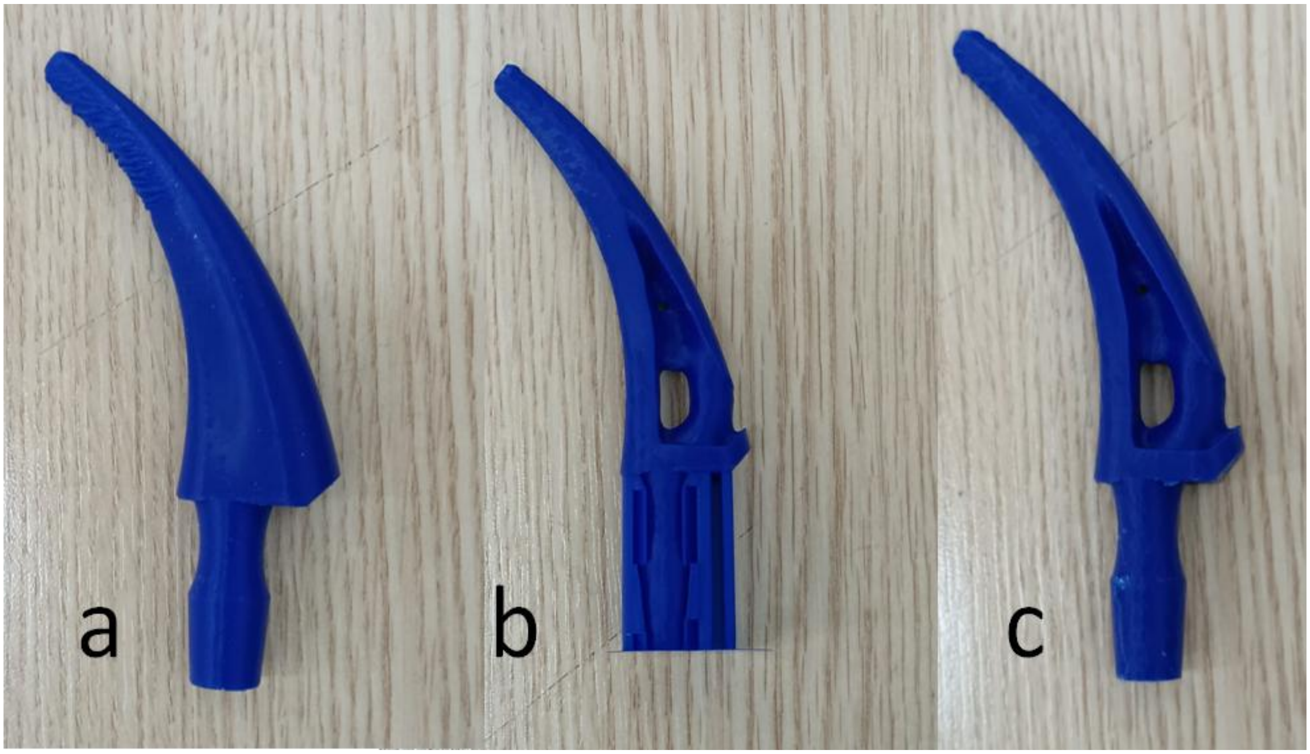


Fig. 29 3D Printed Crutch

From left to right, figure 28 shows the printed original and optimized parts for the Bracket case. Figures 29 a, b, and c depict the printed original, optimized with support structure and the optimized after removal of support structure.

Six original components, twelve optimized models (six case2 and six Case3) were printed in case of the Bracket. Similarly, twelve Crutch models (six original and six optimized) were also printed. The originals and optimized components were printed under the same printing conditions so as to ensure comparability and accuracy of the results. As noted before, the printing conditions were set at 60 mm/sec printing speed, 70% infill density, triangular infill pattern, 60 and 200 °C for the build plate and printing temperatures respectively, 01.mm layer height, and 85 degree overhang support angle for the optimized Crutch. The support angle for the crutch was set at the possible minimum value in order to eliminate or reduce to the barest minimum post-processing after printing. Due to the careful orientation of the component before slicing, the bracket was initially printed with an overhang angle of 65 degrees and later printed without an overhang, and the latter with no overhang produced exact same results, hence the need for support material was eliminated. On the other hand, the Crutch required a small support structure in order to balance on the build plate, hence an overhang of 85 degree was used as shown above. Overall, no post-processing was required except for the removal of the support material on the Crutch, and that was done easily by hand.

4.4. Mechanical Testing of Printed Parts

The mechanical testing of the printed parts was conducted in order to compare the stiffness of the optimized components to the original ones. The LG SmartTester compression machine shown below was used for the testing. The machine comprises of two main parts- the mechanical and electronic parts. While the mechanical part is responsible for holding the work piece and carrying out the compression, the electronic part is used to configure the testing conditions and parameters as well to provide visuals of the testing in progress. The two main sections of testing machine are as shown in the figures below.

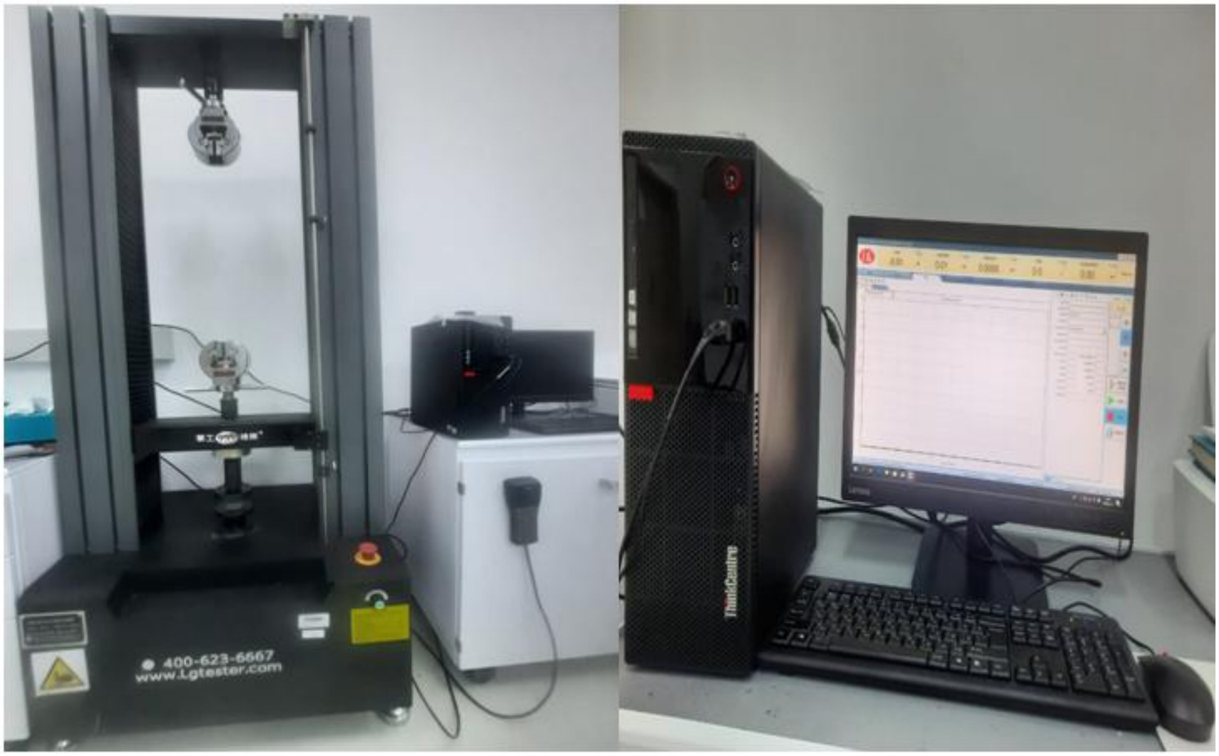


Fig. 30 LGTester Compression &Tensile Machine

Due to the complexities of the geometries, they could not be tested directly; therefore fixtures were fabricated and used to secure them in good testing positions. They were fastened to the fixture using nuts and bolts, and then placed on the machine as shown below.

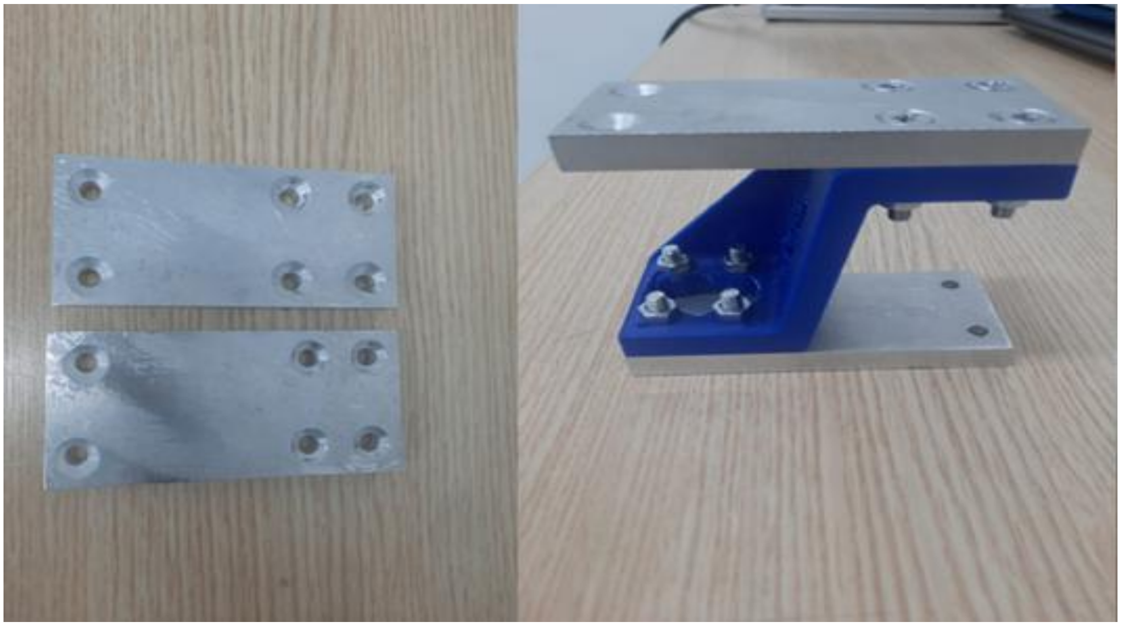


Fig. 31 Bracket Fastened to the Fixtures

Fig. 32a Bracket under Compression

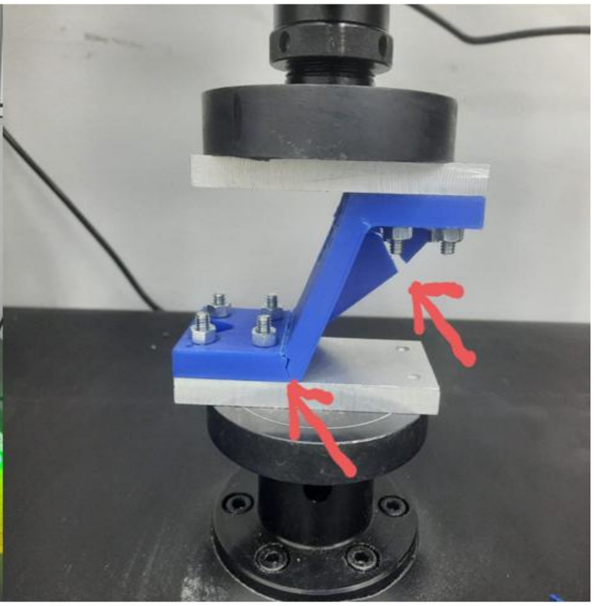


Fig. 32b Bracket Fractured due to Compression

Particularly, compression testing was carried out for the original and optimized parts and each of the printed parts were tested as shown in the figures above and the results of the displacements of the Bracket under a load of 2.5kN are shown on the graphs in the figure and table below. Due to the highly complex nature of the geometry of the Crutch, it could not be tested at the moment using the available machine as it could not be well secured to the machine for testing. Several attempts were made; however, the component was displaced during the compression testing which made it difficult to estimate the load-displacement test results.

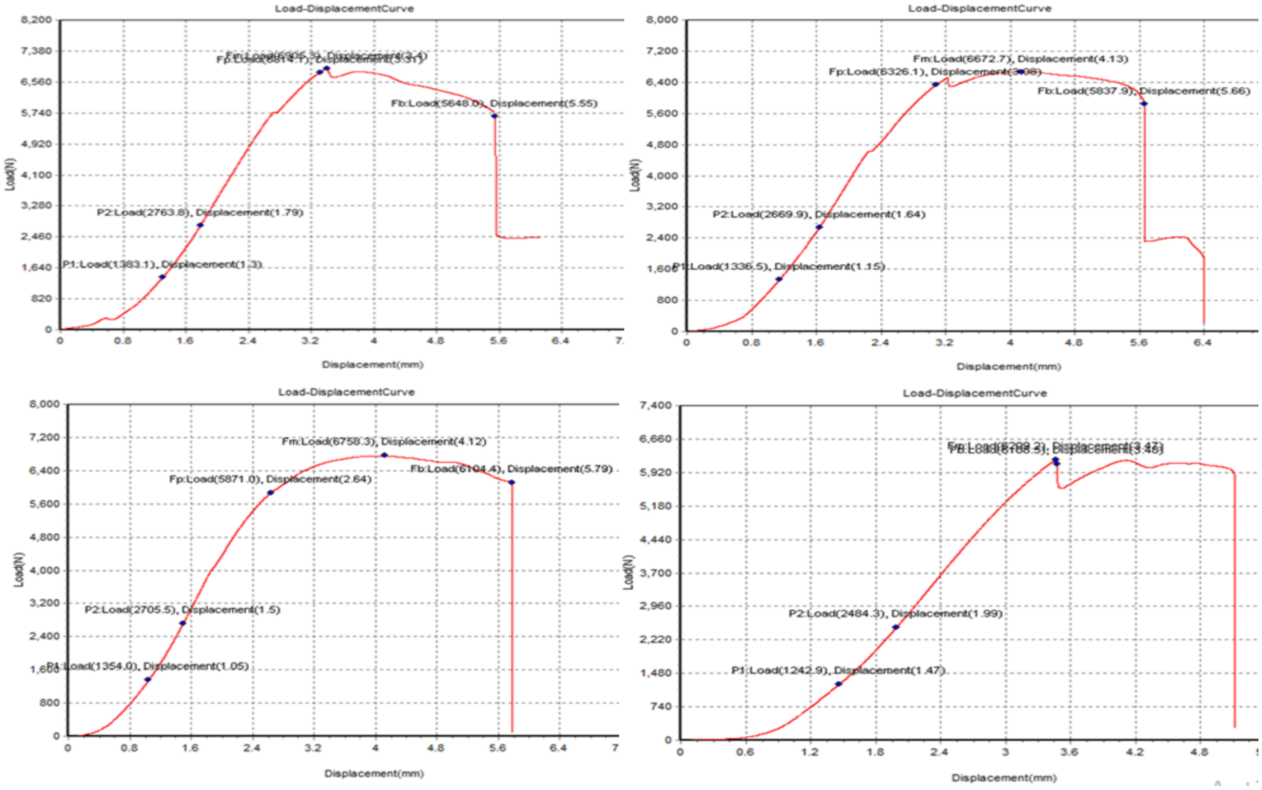


Fig. 33 Load-Displacement Curve of 3D-printed Original Bracket

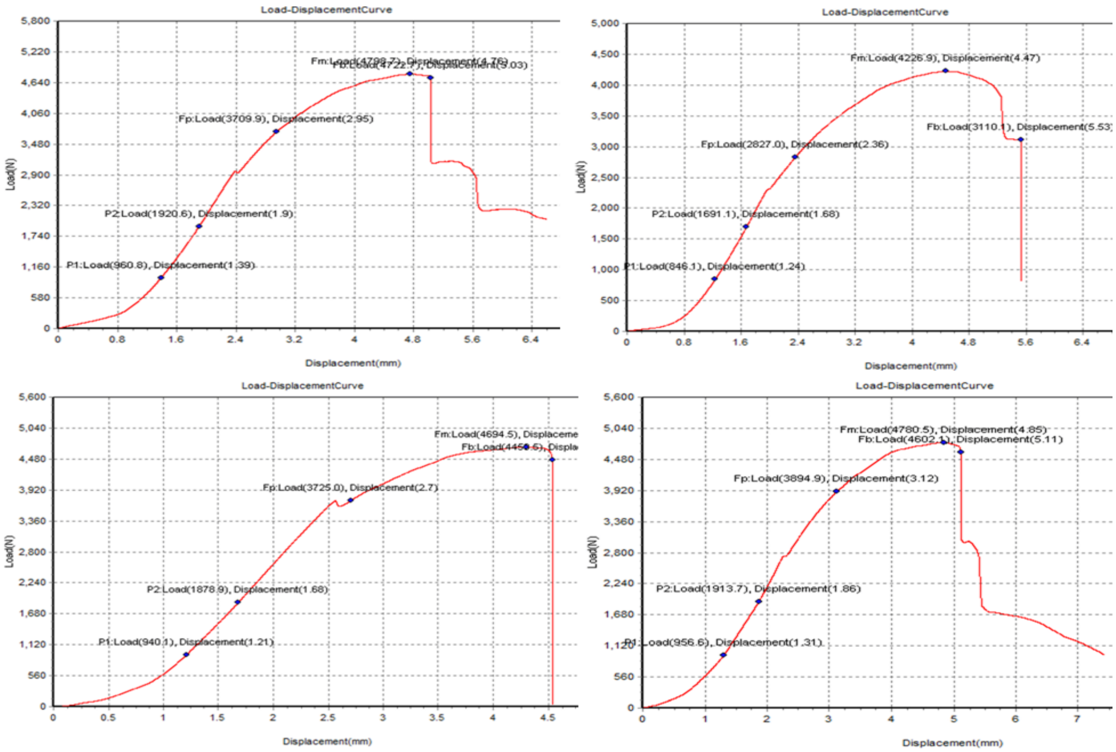


Fig. 34 Load-Displacement Curve of 3D-printed Optimized Bracket (Case2)

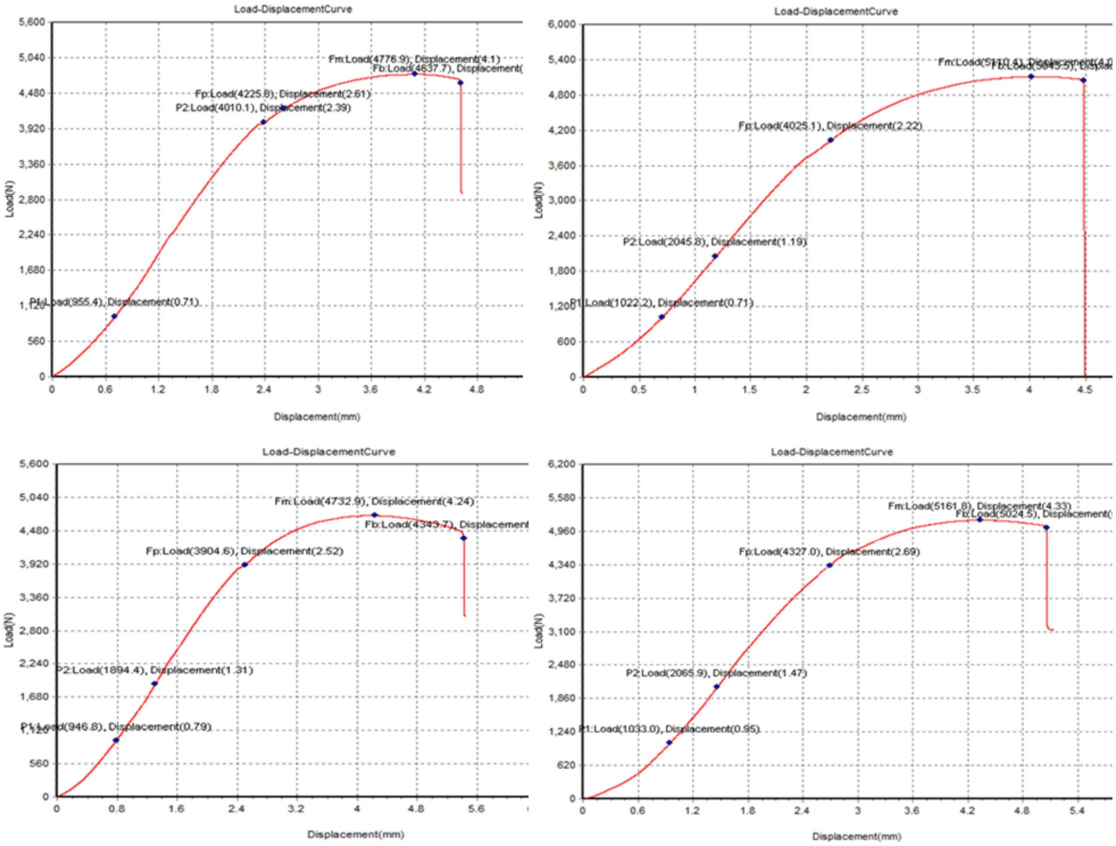


Fig. 35 Load-Displacement Curve of 3D-printed Optimized Bracket (Case3)

Table 3 Displacements (mm) of the 3D Printed Brackets under 2.5kN

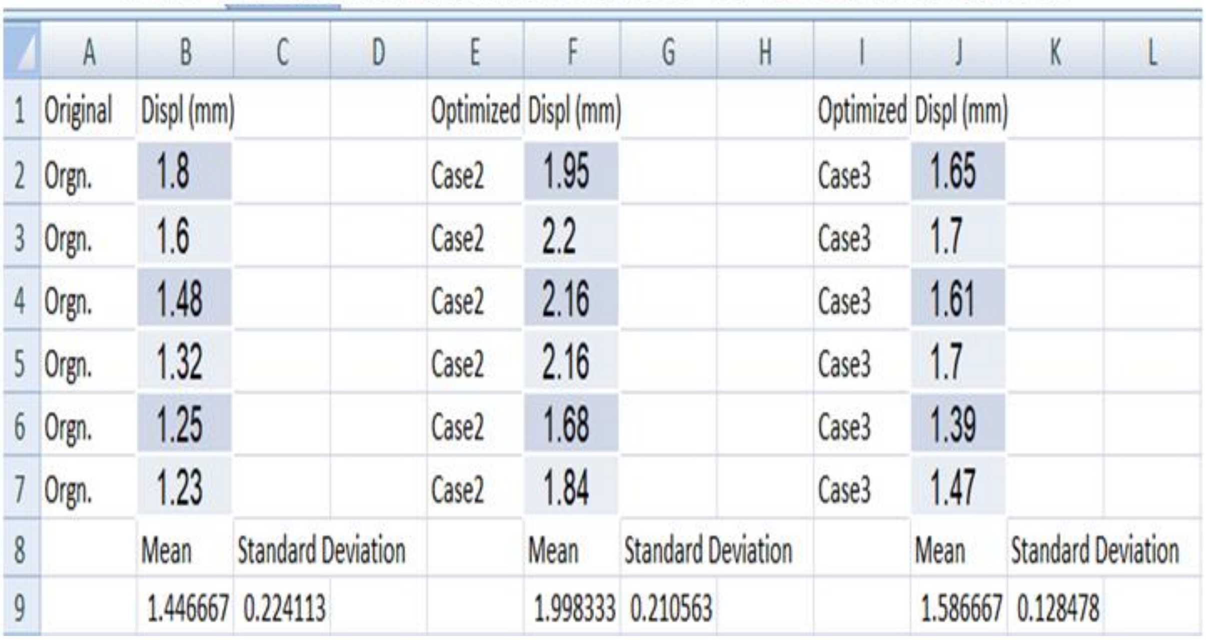
Trials	Original Component	Level Set Case2	Level Set Case3
1	**1.8**	**1.95**	**1.65**
2	1.60	2.20	1.70
3	1.48	2.16	1.61
4	1.32	2.16	1.70
5	1.25	1.68	1.39
6	1.23	1.84	1.47

In order to ensure the accuracy of the results, as much as possible, both the original and optimized printed models were placed in the exact same positions and under the same testing conditions. This is necessary given that when the testing positions of the brackets were altered, the results varied significantly. However, with exactitude in positions, the deviations were practically negligible.

From the results obtained in the tables above, statistical analysis was carried out to compare the nature of the variations encountered**.** The Standard Deviation was particularly used to check the variation in the components. In Engineering, the standard deviation is one of the statistical measures used for the analysis of data set; it provides information regarding the variability of a process and how reliable it is; it is used by engineers to compare the performance of products or systems [51, 52].

The built-in function of Mean and Standard Deviation in Microsoft Excel was used to tabulate the standard deviations for the original bracket, optimized cases 2 and 3, and the results are shown below.

Table 4 Mean and Standard Deviation for the Printed Brackets



	A	B	C	D	E	F	G	H	I	J	K	L
1	Original	Displ (mm)			Optimized	Displ (mm)			Optimized	Displ (mm)		
2	Orgn.	1.8			Case2	1.95			Case3	1.65		
3	Orgn.	1.6			Case2	2.2			Case3	1.7		
4	Orgn.	1.48			Case2	2.16			Case3	1.61		
5	Orgn.	1.32			Case2	2.16			Case3	1.7		
6	Orgn.	1.25			Case2	1.68			Case3	1.39		
7	Orgn.	1.23			Case2	1.84			Case3	1.47		
8		Mean	Standard Deviation			Mean	Standard Deviation			Mean	Standard Deviation	
9		1.446667	0.224113			1.998333	0.210563			1.586667	0.128478	

From the results, we could see that under the same load of 2.5kN and exact same printing and testing conditions, the mean value of the displacement experienced by the original bracket is 1.45 and 1.59 and 2.0 for the optimized cases 3 and 2, respectively. From the results, we conclude that the optimized case 3 outperformed case 2 and is comparable to the original.

5. Conclusion and Future Work

5.1 Conclusion

In this thesis, a critical review of relevant literature was conducted on the subjects of topology optimization, additive manufacturing, and integration of topology optimization into additive manufacturing. Based on the outcome of the literature review, the level set method of topology optimization was selected as it was revealed to have certain advantages lacking in other techniques. Consequently, the Level Set Method was used to carry out the topology optimization of the bracket and crutch; and overall, there was a 20% reduction in weight of the bracket as well as the crutch. Three cases of variation of optimization regions were considered for the bracket, and the case number 3 outperformed the others and hence was chosen as the optimum model.
The optimized models were additively manufactured alongside the original ones, and a mechanical testing of the printed components was carried out for the bracket in order to compare the mechanical strength of the optimized model to the original which is in line with the objective of the thesis. From the results of the testing, the mean values of the deformation from the compression of the six original and six optimized (case 3) components were 1.45mm and 1.59mm respectively, representing a small difference, negligible if we were to consider strains.

The overall objective of the thesis which is to produce a lightweight component with less amount of material at a reduced production time and cost, without sacrificing their mechanical properties was achieved.

From this work, regarding topology optimization, it was observed that a careful selection of the optimization region ultimately influences the mechanical properties of the optimized models.

In the broader sense of the project, the incorporation of topology optimization into additive manufacturing provides us with unmatched possibilities for the production of more intricate, lighter and customized parts with less material usage at a relatively lower production cost and time.

5.2 Future Work

The following recommendation is proposed for future direction in the area of topology optimization in additive manufacturing:

Given that in this work, an appropriately optimized model was obtained by carefully adjusting and specifying the optimization region on the software, it therefore becomes of interest to seek more robust and efficient techniques for predicting the stress concentration regions within the design domains so as to eliminate manual input in selecting the optimization regions during the process.

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