TOPOLOGY OPTIMIZATION FOR THIN WALLED STRUCTURES UTILIZING SIMP METHOD BY ADDITIVE MANUFACTURING USING OPTIMIZED CONDITIONS

By

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To my mother C.S. Manjula, father T.R. Anantharaman, brother Ranjth Anantharaman and all my relatives for love and support.

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ABSTRACT

TOPOLOGY OPTIMIZATION FOR THIN WALLED STRUCTURES UTILIZING SIMP METHOD BY ADDITIVE MANUFACTURING USING OPTIMIZED CONDITIONS

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The objective of this research is to manufacture topology optimized structure by additive manufacturing. Topology Optimization is a method of structural optimization which gives the optimum material distribution in a design domain. This material distribution is then manufactured by additive manufacturing. Additive manufacturing can manufacture complex shapes quite easily since it works by layer-by-layer. This is an on-going field of research and not many optimization algorithms make use of the advantages of additive manufacturing. Numerous researches are done in the field of optimization which are directed towards Homogenization and Solid Isotropic material with Penalization (SIMP). But most of the methods force the convergence to either fully dense or void material. Since additive manufacturing can manufacture intermediate densities we propose a method of SIMP with no penalization. The resulting material distribution is manufactured via Fused Deposition Modeling.

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Chapter 1

INTRODUCTION

The goal of this chapter is to give heads up in the basics of research and design optimization. The following sections in this chapter will throw highlight on the motivation for this research, aim of this research, insights on basics of design optimization and literature review.

1.1 Motivation for this research

The motivation for this research comes from the need to make better components or parts than what we use in our world or in other words make parts that are lighter and stiffer and perform better. The need for continuous improvement drives today's world in every aspect say it consumer goods, services, information technology etc. Improvement in terms of structural aspects of design of parts can be in the finding better materials, better ways to manufacture and better design. This process of finding the better things is an aspect of nature in the form of evolution and can be called optimization. Here we try to design and manufacture lighter and stiffer components by using latest manufacturing techniques.

1.2 Aim of this research

The goal of this research is to design optimized part and manufacture the same using additive manufacturing. Designing suitable structures for the performance was studied in **[1]** (Richard H. Crawford, 1999). The optimization is done using Solid Isotropic Material with Penalization (SIMP) method and manufactured using Fused Deposition Modeling (FDM). The reasons for using SIMP will be explained in following chapters. Basically the problem is setup for optimization, and then an iterative optimization algorithm is performed to get the final design. Next the converged values are processed into Stereolithography (STL) file for additive manufacturing.

1.3 Basics of Structural Optimization

Optimization can be defined as the process of selecting the best variable from among many feasible solutions. Optimization has been studied for many decades and still is field of research. Competitive pressure forces engineers to seek better design using formal optimization algorithm approaches. Optimization in larger perspective can be applied to many fields. The following are some of the examples.

- Design of bicycle frame for minimum weight.
- Optimum design of a beam for maximum stiffness.
- Design of a bridge to maximum the lowest natural frequency.
- Design of thermal conduction systems to maximize the heat transfer.

We will discuss about different types of structural optimization problems. As mentioned in **[2]** (Peter W. Christensen, 2009) structural optimization can be viewed as the objective of making assemblage of material that can best sustain the loads. Here objective can be to minimize the weight or maximize the stiffness which is same as minimize the compliance, to name a few. To perform these objectives, certain constraints are imposed into the problem. These constraints to name a few can be on the volume of material, displacements or stresses. The figure below explains this.

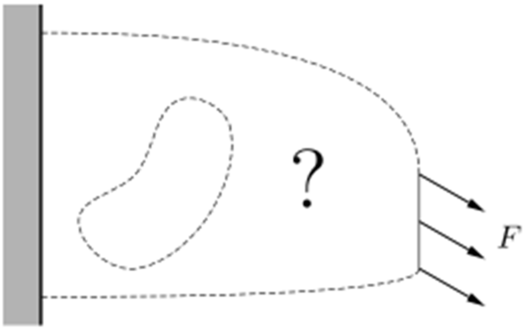

Figure 1-1 Structural Optimization problem [2]

Thus the optimization can be defined as process of finding the best possible way to minimize or maximize the objective function in a design domain, so that the forces (F) applied are transmitted to the support keeping the constraints in check. This in general can be formulated as follows:

$$Minimize\ f(x)$$

Subject to $\begin{cases} g(x) \leq 0\ for\ i = 1,2,..l \\ h(x) \leq 0\ for\ j = 1,2..m \end{cases}$

Where x is the design variable which must belong to a domain Ω and g(x) and h(x) are the constraint functions. In general structural optimization can be broadly classified based on geometric feature into size optimization, shape optimization and topology optimization.

1.3.1 Size Optimization

Here the design variables are the parameters that dictate the size of the structure i.e. they usually involve calculating the optimal thickness in plate. In this method the connectivity, shape of the elements does not change.

1.3.2 Shape Optimization

In this case the design variables represent the shape or contour of the domain. Here the number of holes in the design domain does not change but the shape of the holes changes. This can be observed in the following figure 1-2.

1.3.3 Topology Optimization

Topology optimization involves finding the number, location, shape of the hole and connectivity in the design domain **[3]** (Sigmund M. P., 2002). This is more general class of optimization and is often used before shape and sizing optimization.

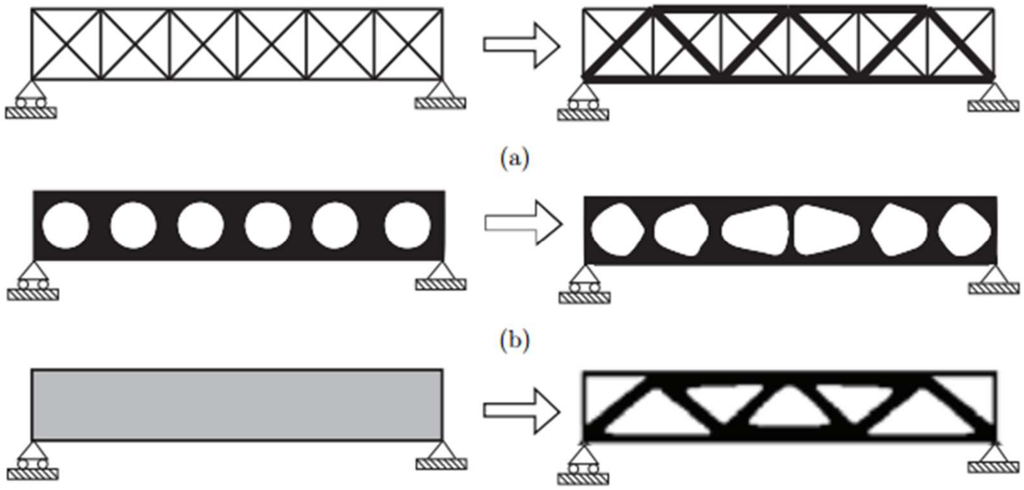

Figure 1-2 Types of Structural Optimization: (a) size optimization, (b) shape optimization, (c) topology optimization [3]

This is particularly used in the initial stage of design cycle when design concepts are to be generated. To quote an example, the software SolidThinking INSPIRE **[4]** (SolidThinking) is based on the algorithm of topology optimization. INSPIRE is a concept generation software. It can also be used for analysis but the sole purpose is concept generation. **[5]** (Korail, 2013).

Chapter 2

ADDITIVE MANUFACTURING

This chapter will give the readers an insight into additive manufacturing (AM), types of additive manufacturing in brief and the process parameters that define Fused Deposition Modeling, AM used in this thesis will be explained in Section 2.4.

2.1 Introduction to Additive Manufacturing

3-D printing was developed by a Massachusetts Institute of Technology team lead by Emanuel Sachs **[6]** (Emanuel M. Sachs, 1993). The technique involves laying down a layer of powder and spraying a liquid binder on the area to be binded **[7]** (http://3dprinting.com/what-is-3d-printing/). Unlike conventional methods of manufacturing called as Subtractive manufacturing by removing material, AM works up layer by layer and is also called layer manufacturing. The development in the field on AM focuses on producing complex metallic parts used for aerospace, automotive and medical applications. The main advantage of additive manufacturing over subtractive manufacturing is the freedom a designer can get while designing in a design domain: constraints and tooling can be eliminated as even most complex parts can be made easily. The freedom in the sense that, when a designer thinks of designing parts, one takes into concern the manufacturability of the part. But in case of AM, the manufacturability need not be considered as a constraint as even complex shapes can be manufactured with ease.

Within the last two decades, additive manufacturing has changed from simple 3D printers in resins to advanced tool less manufacturing **[8]** (Using Additive Manufacturing Effectively: A CAD tool to support decision making, 2010). This is possible because of rapid funding from different agencies into the research and development. The role of National Science Foundation (NSF) has been studied by Science and Technology Policy

Institute and their finding reveal that innovation in AM has been dominated by private sector with regards to the number of patents **[9]** (Christopher L.Weber, 2013)

2.2 Types of Additive Manufacturing

Additive Manufacturing works by building layer by layer and is also called Layer manufacturing. There are several ways of achieving this and the major types are as follows:

- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Stereolithography
- Laser Engineered Net Shaping (LENS)

These methods are classified based on the application of their use. For example FDM is used mainly in desktop printers which are relatively cheap than other methods and builds models by extruding plastic filaments through an extruder and nozzle. SLS is used for printing metals and have relatively better surface finish. The different methods are discussed in the following pages.

Stereolithography uses a combination of photochemistry and laser technology to build parts in photopolymer resins **[10]** (Deckard, 1997). Each part is built in layers and UV laser traces the 2D section onto photopolymer resin surface. Once a layer is made, the build surface is lowered into the resin and the resulting resin is again exposed to laser.

Laser Sintering uses high power laser to sinter powder. New layer of powder is added to the top and the process repeats again. Unfused powder acts as a support during the build **[10]**. In this paper **[11]** (Sanjay Kumar, 2011) the authors have a comparative study on Laser based manufacturing of metals. The authors have discussed the various methods namely Selective Metal Sintering, Laser Engineered Net Shaping

(LENS) and included the issues of materials, applications and comparison. The subjects of this paper are the powder bed techniques namely SLS, SLM and LENS. In SLM and LENS process, the powders are fully melted by the laser beam resulting in the formation of small grains and a new chemical compound but it differs from SLS where some of the powders could be melted to hold other powders together. The author also says both SLM and LENS produces parts of higher strength than SLS. The author does not give a supporting reason for his statement that LENS could be used for modifying/refurbishment of the surface of product. It also gives advantage to create parts with varying composition thus leading to fabrication of Functionally Graded Materials. Further the authors listed the SLM and LENS machines based on the following specification: Build Volume, Laser and scan speed. From which it could be understood that SLM machines have less versatility and are not energy efficient since high amount of powder is required for making products of smaller size.

LENS method used high energy laser beam to create a molten pool of metal on a substrate on which metal powder is injected. Consecutive layers are built upon each other **[12]** (Gill).Authors R.Sreenivasan, A.Goel and D.L.Bourell **[13]** (R.Sreenivasan, 2010) have through this research brought out the sustainability issues in AM in general and have made energy assessment for SLS process through eco-indicators. Sustainability issues were classified as energy consumption, waste generation, and environmental impact of part and water usage. The benefits of AM processes over traditional manufacturing processes were explained first and later the findings of the AM workshop are discussed. The authors say that the exploration of the feedstock for AM process from wastes of manufacturing process is a promising area of research, which leads to bio degradable materials and better eco-friendly products.

The energy assessment on SLS was done by measuring the energy consumption of various SLS components. LABVIEW circuits were designed to acquire power data over period of time. The data were acquired using NI-DAQ USB6251 device by setting a sampling frequency for every 2 minutes. The power drawn by the process was captured and shown. It was found that the heater system used to heat the powder bed consumed maximum power, followed by stepper motor system, roller system and the laser system. To measure the environmental impact, eco indicators and data from ERMD are used. The energy consumption rate is given by, ECR=Power/Productivity, where Productivity is = V x W x T x p x 3600 x k. where V, W, T, P and k are Scanning speed, road width, layer thickness, material density and overall process co-efficient respectively. The Total Energy indicator was found by multiplying ECR with Eco indicator. This indicator was compared with other ALM processes.

Fused Deposition Modeling is abbreviation for FDM, a trademark of Stratasys **[14]** (Stratasys). FDM build by depositing material layer by layer by fusing a heated filament through a nozzle. Acrylonitrile Butadiene Styrene (ABS) and Polylactide (PLA) are the two types of plastics that are available in the market and come in size of 1.75mm and 3mm diameter cables. The plastic filament is unwound from the coil and supplies the material to the nozzle, where it is heated. The nozzle follows a tool path thus depositing the molten material on a heated bed.

2.3 Process parameters of FDM

In a typical manufacturing process the process parameters include feed rate, machining speed, depth of cut etc. But in case of additive manufacturing, since the part is built layer by layer, the process parameters are layer thickness, build orientation, infill percentage, raster thickness to name a few. These are explained in Section 2.4.

2.4 Experimentation on FDM

A typical FDM process can be seen in the figure 2-1.

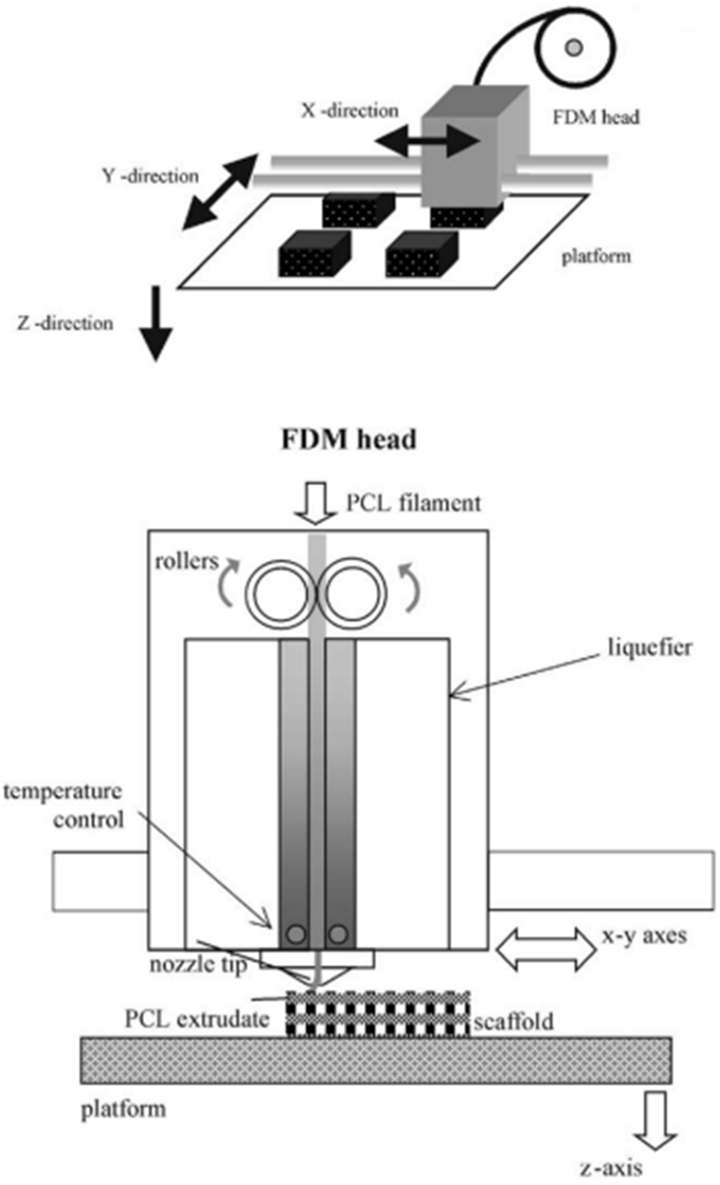

Figure 2-1 Fused Deposition Modeling process

The FDM process builds the part layer upon layer. The plastic filament is fed to the liquefier, which heats the thermoplastic which flows through the nozzle onto the platform. A list of thermoplastics that are used in Stratasys printers can be found in **[14], [39]** (Stratasys). This process is then repeated for each and every layer. A support material is built on the part if it is required. Sometimes the part may consist of extrusions or some portions which overhang that require support material. The support material is same as the build material in FDM process and it can be taken away easily after the part is built by just applying a small force mechanically.

In order for the part to be of good quality the materials and the parameters associated with the printing process should be defined correctly. Studies on process parameter optimization have been conducted by Agnes Bagsik *et al* **[15]** (Agnes Bagsik, 2011). The author has varied the raster angle, filament thickness and the raster to raster air gap. A raster is the infill pattern inside the contour. So it gives the movement of the tool path. A close up view of the terms can be seen in the figure 2-2.

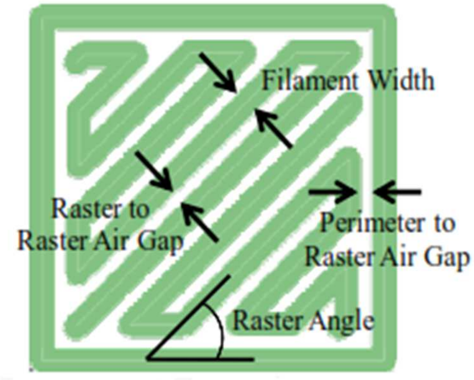

Figure 2-2 Close up view of a layer and tool path. Ref:[5]

But there are numerous process parameters that have to be taken into account. On the basis of several literatures **[16]** (R. Anitha, 2001), **[17]** (Samir Kumar Panda, 2009) the following set of parameters which influence the part characteristics are taken into account for this research:

- Number of shells (S)

- Infill amount (I)
- Layer thickness (L)

Initially the desired geometry of the model was created using Solid Works and the part file was imported in MakerBot Desktop software version 3.4.1. Dog bone type structure which was initially designed but it did not break at the center during tensile test. Since FDM method was used, we decided to build a model which fractures at the centre during tensile test so that experiments gave us more appropriate results. PLA is more preferred to Acrylonitrile butadiene styrene (ABS) because first of all it has less wrapping as compared to ABS **[18]** (Makerbot), **[19]** (Powell, 2014) . Secondly it has bio favorable properties which will be vital when used in a bone structures. Also when cooled properly it has maximum printing speeds, lower layer heights and sharper printed corners. Thin wire of PLA of 1.75 mm diameter was initially inserted into the extruder which extrudes and prints our model. Temperature of the extruder was kept at 205 ^{o}C while the base plate was kept at room temperature. For ABS filament the extruder temperature was kept at 230 ^{o}C while the base plate was kept at 110 ^{o}C. The above parameters are varied in order to find an optimum condition so that the structure produced is of highest quality. In the following part, we will see how varying these parameters affect the quality of finished product.

2.4.1 Effect of number of shell

Number of shells means the amount of time the extruder of the machine goes around the perimeter of an object. During each round deposition, is 100 %. We varied the number of shells between 2 and 25. The given condition for a high resolution object is infill of 100 % with a layer thickness of 0.1 mm. Figure 2-3 shows how stress varies when the number of shells is increased.

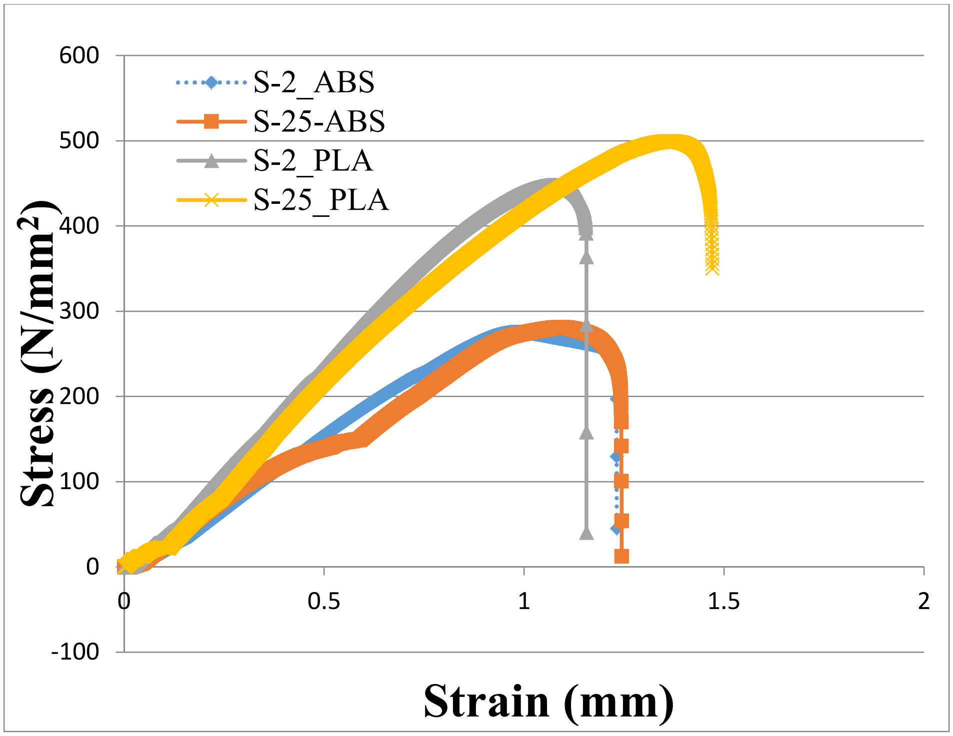

Figure 2-3 Stress vs Strain graph for Shell variation experiment

The Shell 25 experiment has higher stress mainly because of the fracture at the center. Basically, when the number of shells is increased, it means that the infill is 100 % for that amount of times the machine goes around the perimeter. The same result can be obtained by keeping infill 100 % and the number of shells at 2; in this way we can avoid the fracture at the center.

2.4.2 Effect of Infill

Infill means the deposition inside the material. 100 % infill means that there are no void spaces inside. As infill % is reduced, void spaces are created. Infill amount was varied from 15 % to 100 %. For high resolution, the number of shells is 2 and the layer thickness is 0.1 mm; hence, these conditions were used. For PLA material layer thickness was kept at 0.15 mm as we were not able to manufacture 0.1 mm

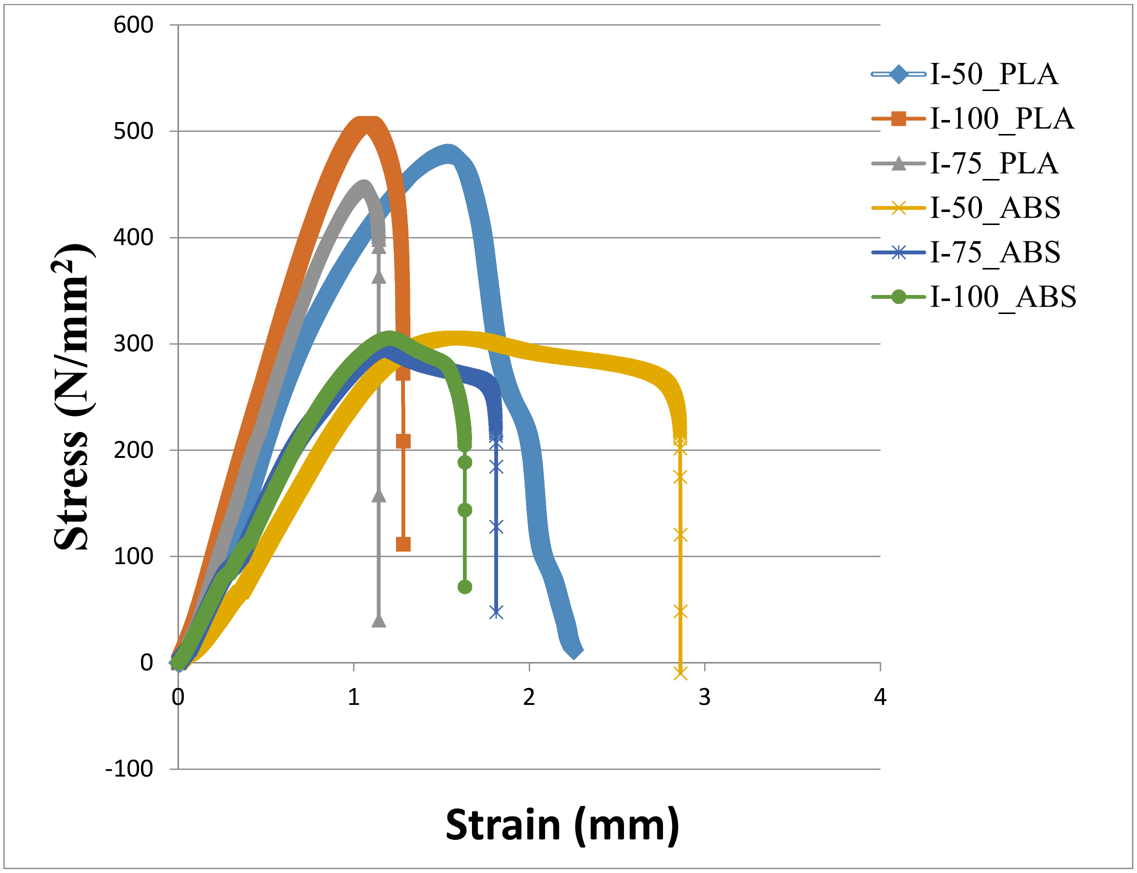

Figure 2-4 Stress vs Strain graph for Infill variation experiment

The results can be interpreted from Figure 3 that as infill is varied stress varies accordingly. Stress is highest for 100 % infill, which means that infill should be maximum to obtain best results.

2.4.3 Effect of Layer Thickness

Layer Thickness means how thick the layer will be in each pass. Thus increasing layer thickness refers to reducing number of passes. Hence layer thickness was varied in order to find out how stress varies when number of passes is reduced, which can be seen in Figure 2-5.

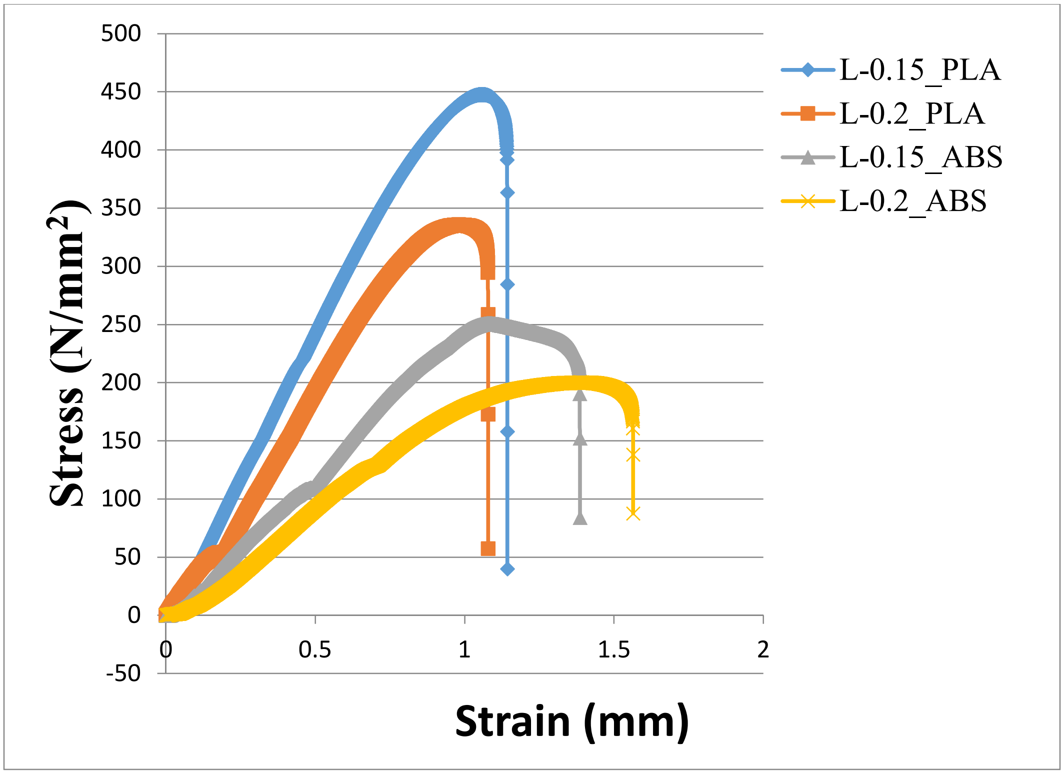

Figure 2-5 Stress vs Strain graph for Layer thickness variation experiment

2.5 Summary

It can see that PLA has higher stress as compared to ABS for all the experiments. Thus the optimum conditions to manufacture in MAKERBOT Replicator 2X will be to keep the number of shells as 2, Infill as 100% and layer thickness of 0.1mm for ABS and 0.15mm for PLA

Chapter 3

TOPOLOGY OPTIMIZATION

Topology Optimization is a type of structural optimization where the problem is defined in a design domain with the boundary conditions and the optimization is done for appropriate objective condition satisfying the constraints defined. This chapter gives an introduction to topology optimization and its types in Section 3.1 and 3.2. Also a review of current topology design methodologies will be discussed. The advantages of SIMP method and the reasons for choosing the same are discussed in section 3.2.The procedure for the implementation of SIMP in MATLAB is discussed in section 3.2. Post processing of topology optimization in MATLAB and interpreting of the solution are discussed in section 3.4.

3.1 Introduction to Topology Optimization

Basically optimization can be classified broadly as Gradient-free algorithms such as Stochastic algorithms and genetic algorithm to name a few, then Deterministic algorithm such as finite difference, sensitivity analysis, then finally as optimization domain such as parameter optimization, topology optimization and shape optimization **[20]** (Wein, 2008). Unlike shape and size optimization, topology optimization takes a different route that it is not constrained by the initial design size and shape hence creating new topologies.

3.2 Types of Topology Optimization

Several researches have been done in the field of topology optimization. Some of the prominent algorithms include Ground Structure Approach, homogenization **[21]** (Martin Philip Bendose, 1988), SIMP **[22]** (G.I.N. Rozvany, 1992) **[23]** (Hong Zhang, 2011). The application of bi-directional evolutionary structural optimization **[24]** (O.M. Querin, 1998) and genetic algorithm **[25]** (K. Tai, 2005) to topology optimization problems have also been studied. A brief overview about the types is discussed in the following sections.

3.3.1 Ground Structure approach

The ground structure approach is one of the earliest findings in the field of topology optimization. As the name suggests, the ground structure can be seen as the basic structure which forms the basis of optimization. Several works have been published in this approach **[26]** (Rozvany, 1997) **[27]** (T. Sukol, 2013). In this approach is the optimization goal is achieved by working from the ground structure. For exmaple, the ground structure consist of n x m links where n and m are the nodal points in X and Y direction. Then for a particular objective function, the links connecting the nodal points will be removed thus affective the design variable in each iteration. Thus optimal solution is a subset of the ground structure. Since there are a lot of links in the ground structure, the number of design variables is also high.

3.2.2 Solid Isotropic Material with Penalization

SIMP stands for Solid Isotropic Material with Penalization. This method was originally introduced by Bendose in 1989. This is based on power law method. Here the finite element formulation is kept fixed and each element in the design domain is associated with a function called density whose values vary between 0 and 1. The objective of the program is to find out this density function which would resemble optimal material distribution. The density of 0 and 1 can be viewed as void and solid material and those values between0 and 1 as grey regions. A complete review of SIMP optimization can be found in **[28]** (G.I.N.Rozvany, 2011) where the author has discussed about history, scope and the formulations of SIMP technique. Several researches on SIMP methods have been done in the past decade. The formulation of the SIMP technique is explained in chapter 3.3.

The suitability of SIMP and BESO algorithms have been studied by Aremu et al in **[29]** (Aremu A, 2010). The author discusses the issues related to SIMP and BESO and the parameters that affect the suitability for additive manufacturing. An example of cantilever beam with end loads are also analyzed for the suitability of two algorithms. The author hints that improvements can be made with iterative mesh refinement since there is continuous change in topology during the optimization.

The feasibility of cellular structures was studied by Albert C.To et al **[30]** (Pu Zhang, 2015). This work may fall in the lines of current research in the area that both deals with variable density model. But this research differs in the way the optimization algorithm is applied. The author has based his research using a relative density model that the density is a spatial function in design domain. The author also states that SIMP method can also be applied for optimizing the density distribution, which is the focus of this current research.

The application of topology optimization to aerospace part was studied by Matthew Tomlin et al. This paper deals with the application of topological optimization of ALM nacelle hinge bracket. The part at present is bulky and isn't ideal and hence needs to be optimized. **[31]** (Matthew Tomlin, 2011). The issues are minimizing the weight of the part and maintaining the stiffness at the same time. Authors have also discussed the general advantages of an ALM part, insisting on design freedom as primary advantage. Here the original part is modeled in CATIA and FEA of the same is carried out. To carryout TO, mesh morphing and shape optimization were done in HYPERWORKS and OPTISTRUCT. The main objective here is to maintain the stiffness while reducing the weight. Hence maximum displacement along the hinge in the part is constrained which thereby constrains the stiffness. Also the maximum resulting stresses must be less than the critical stresses. The part is tested for fatigue of 400,000 cycles and stresses must confirm the requirements.

In Design 1, TO was a trial and error method involving the non-designable areas around the bolt. Since this model did not provide supports near the end pair of bolts, there were increased forces near certain bolts. In Design 2, the forces measured near the 2 bolts of original part were constrained and optimization was repeated. This resulted in better load distribution. This could be seen in the Figure 3-1.

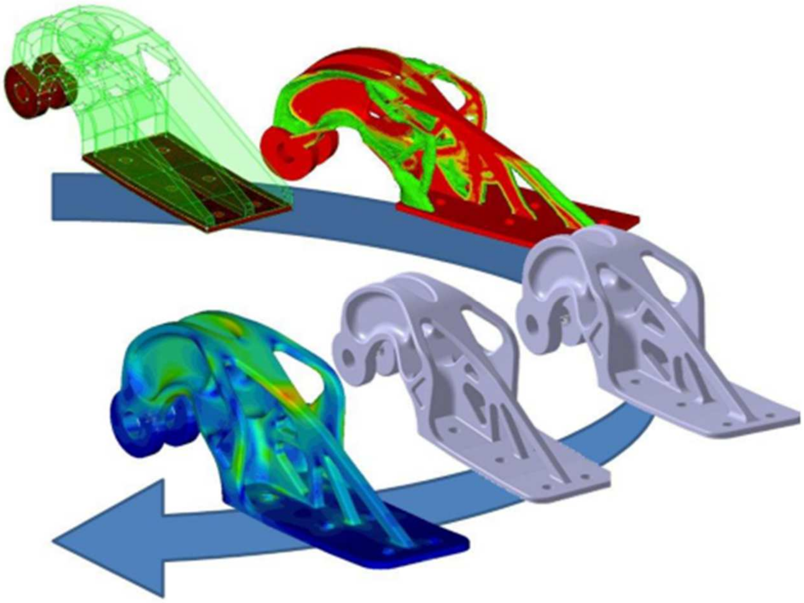

Figure 3-1 Optimization loop two of aerospace part

The author explains though this is advantageous in terms of weight and a viable part, this is time consuming and also applying TO focusing on large parts taking small percentage of the weights delivers large savings. Thus the SIMP approach has the following important advantages of using only one design variable to formulate the problem, which greatly reduces the computational time and effort. It has also been widely studied in the past decade which has been applied for many applications.

3.2.3 Homogenization

Much like SIMP method, homogenization is also based on the idea of material design parameterization. But more rigorous definition of the microstructure is defined in homogenization. This also causes huge number of design variables like geometry of the microstructure, size and orientation of the hole for each void. So whenever a new void is introduced because of optimization, there is a spike three times more because of the design variables. Hence there is a need to find a technique for design variable reduction as the optimization progresses. More details on homogenization can also be found in the references cited **[32]** (Sanchez-Palencia, 1980). Research on density based optimization was carried out by Pu Zhang et.al **[30]** (Pu Zhang, 2015)**.** A method based on homogenization of variable-density cellular structures was proposed. The cells are designed based on the average relative density of each cell. The author discusses the various applications of the cellular structure in the field of automotive sector and how the variable-density structure can maintain the cost and also the structural integrity.

3.2.4 Evolutionary Structural Optimization

This method is one of the new approaches to topology optimization based on following an evolutionary path **[33]** (Y.M. Xie, 1993). Initially a larger material volume than the optimum is selected and finite element analysis procedure is carried out. This was originally proposed with von-Mises stress as constraint and material is removed based on a rejection ratio times the maximum von-Mises stress. And the rejection ratio gets updated by an evolutionary ratio after each iteration that it follows an evolutionary path. But with ESO the elements are only removed to arrive at the optimum. Later on Bi-directional ESO **[34]** (Q.M. Querin, 1998)was introduced in the year 1998 where the deleted elements are also added back to find the optimum. ESO later on were applied to several fields. An example of ESO to design complaint mechanism can be found here **[35]** (Ruben Ansola, 2007)

3.3 Formulation of SIMP

Finite Element methods are often used nowadays to perform structural calculations. There are numerous softwares which carry out these calculations. The usage of optimization with Finite Elements can be traced back to the work by Lucien Schmit in 1960. In this research MATLAB is used to perform the calculations. The problem formulation in SIMP involves the traditional approach in structural optimization. The quantities that we know are the volume domain, support conditions and the forces applied. The connectivity, location and size of holes remain unknown. As discussed in previous section the parameterization forms the basis. The density function is leads to the formation of different topologies. In this research, optimization of continuous linear elastic structure with plane stress formulation is considered. Using the standard notation, the compliance of the structure can be written as

$$C(\rho) = [U]^T [K][U]$$

Where *U* represents the global displacement vector and *K* is the global stiffness matrix. The solution for global displacement is obtained by solving the equilibrium problem as

$$[F] = [K]\,[U]$$

Where F represents the vector consisting of applied loads. More on the finite element formulation can be found in **[35]** (Sigmund O. , Design of Material Structures using Topology Optimization, 1994)

In terms of optimization, the compliance of the structure which is the objective function and the constraints can be written as

$$\min C(\rho) = \sum_{e=1}^{N} (\rho_e)^p \, u_e^T \, k_e \, u_e$$

$$\text{Subject to} \begin{cases} \frac{V(\rho)}{V_0} \leq 1 \\ K\,U = F \\ 0 \leq \rho \leq 1 \end{cases}$$

Where V_0 is the allowable volume which we take as 1.The global displacements are expressed in the form of element displacements u_e and k_e represents the element stiffness matrix. In general the topology optimization procedure can be written as below as in Figure 3-2:

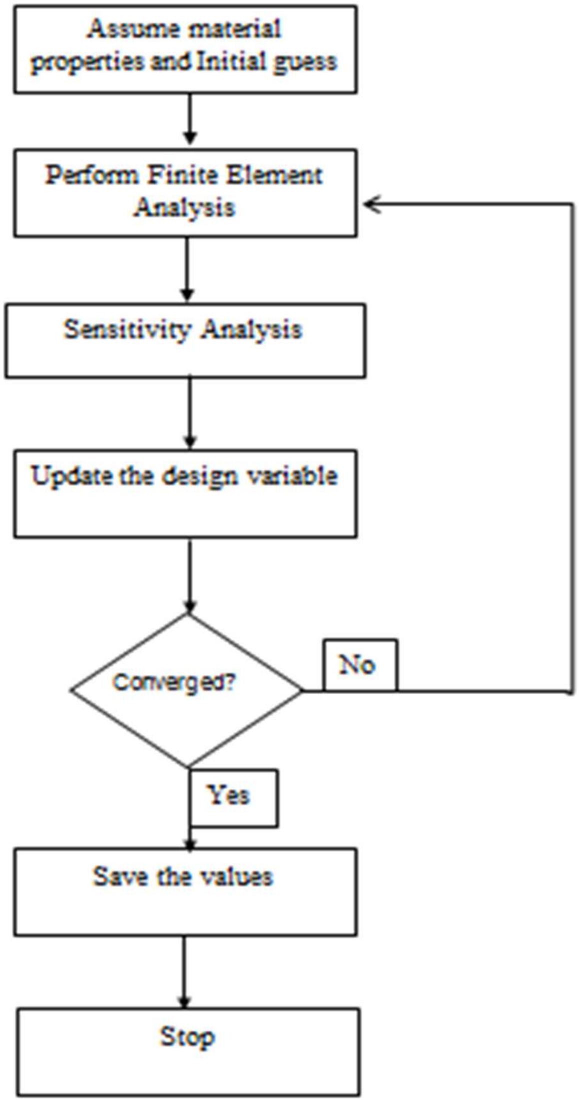

Figure 3-2 Topology optimization procedure

The finite element analysis is performed in MATLAB. Rectangular design domain is considered in this research, though this can be extended. The discretization is done using ”Q4” elements. The representation of element is shown in Figure 3-3.

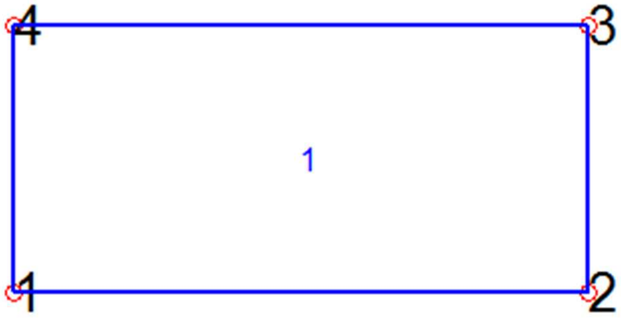

Figure 3-3 Representation of Element

Here an element is represented by the following variables.

IE Rho X(JA) Y(JA) X(JB) Y(JB) X(JC) Y(JC) X(JD) Y(JD)

Where IE is the Element number, Rho is the density of the element, X and Y denotes the co-ordinates of the nodal points. JA, JB, JC and JD are the node number 1, 2, 3, 4 respectively. The number of nodal points desired in X and Y axis are given as user input which results in desired discretization. Figure 3-4 shows the discretization of the domain.

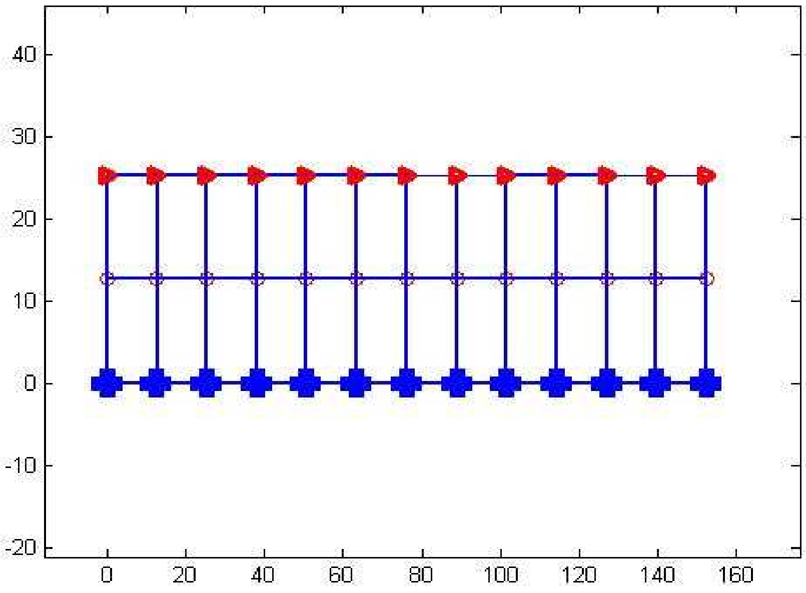

Figure 3-4 Discretization of domain

The red arrows in the figure indicate the application of load and blue dots along X axis represents the domain is constraint along the X axis. To carry out the optimization, few more inputs are necessary. The upper and lower bound of Rho (ρ) is specified and also the percent of material allowable for optimization. This acts as the volume constraint as indicated in previous section.

The stiffness matrix here is same for the entire elements since all the elements are identical. Hence it is only required to calculate one $[K_e]$, which will be the element stiffness matrix. It is a 8 x 8 matrix and the entire expansion of the stiffness matrix for 4 node quadrilateral element can be found here **[36]** (L.Logan, 2007).

To analyze the sensitivity let us consider a simple analytical problem of minimizing a function *f* subjection to single equality constraint *g* as defined below

$$Min\ f(x,p)$$

$$subject\ to\ g(x,p) = 0$$

Here *p* is a constant and *x* is the design variable. For solving this problem, we solve the problem by assigning a value to *p* and find an optimum say x*. If the value of *p* is changed, the optimum x* again changes. Hence inorder to find the effect of *p* it is necessary to find the effect of *p* on the function *f(x*,p).*Accordingly in this research the sensitivity can be formulated as

$$\frac{\partial c}{\partial \rho} = -p(\rho_e)^p\, u_e^T\, k_e\, u_e$$

Optimality Criteria method is used in this work for updating the design variable. In this method the objective function is formulated and the state condition which refers to the design variable is found. Now any effect in changing in design variable can be seen in the state conditions. Let *L* be the lagrangian for the optimization problem, then *L* can be written as

$$L = c + \lambda(V - fV_0) + \lambda_1^T(Ku - f) + \sum_{e=1}^{N} \lambda_{2e}(\rho_{min} - \rho_e)$$

$$+ \sum_{e=1}^{N} \lambda_{3e}(\rho_e - \rho_{max})$$

Where λ and $\lambda_1$are global Lagrangian multipliers.$\lambda_{2e}$and $\lambda_{2e}$are Lagrangian multipliers for side constraints. The scheme for design variable updation is given by

$$\rho_e^{i+1} = \rho_e^i \left(\frac{p(\rho_e)^p\, u_e^T\, k_e\, u_e}{\lambda v_e} \right)^{\zeta}$$

Thus this gives a simple and effective solution in search of the optimum conditions. For more information on the updation criteria the readers may follow **[35]** (Sigmund O. , Design of materials and structures using topology optimization, 1994).

The program was also extended than the part of this research, to analyze the domain in layers. The idea behind this is since the force is not the same throughout the design domain, it is necessary to apply different forces in each layers, which will be a better practical approach. The finite element analysis program in MATLAB works on a 2D domain. The number of layers is defined first which represents how much the domain is split in its depth. Next the optimization is carried out for each layer and the results are saved before proceeding to next layer. The same process is repeated manually for each layer. The output from this is a collection of numbers which represent the artificial density in each layer. This can be post processed as explained in section 3.4.

3.4 Processing of SIMP solution

The results from topology optimization in MATLAB are in the form of numbers. The variables that represent these numbers are explained in section 3.3. Rho is the density, which defines the amount of material present in an element. We can use the following formulation to convert Rho to equivalent microstructure element size.

$$\rho = 1 - \frac{a_h^2}{a^2}$$

Where a_h and *a* refers to the size of hole and size of the unit cell respectively. This can be seen in the figure

Figure 3-5 Unit cell used in SIMP calculation

The final design solutions of SIMP possess black, white and grey regions which denote solid, void and intermediate density regions. Several techniques were formulated which tried to converge the results to black and white only, since the grey regions offered less practical significance. But with the advancements of the manufacturing techniques, these grey areas can be manufactured if they can be interpreted correctly. In order to be processed for additive manufacturing, the output files needs to be in STL file format. I acknowledge the work by Vikram Gopalakrishnan in this field **[37]** (Sundararajan, 2010). The author has used homogenization approach for AM. An STL file is Stereolithography file which contains the surface geometry data. The following table gives an overview about how it is done.

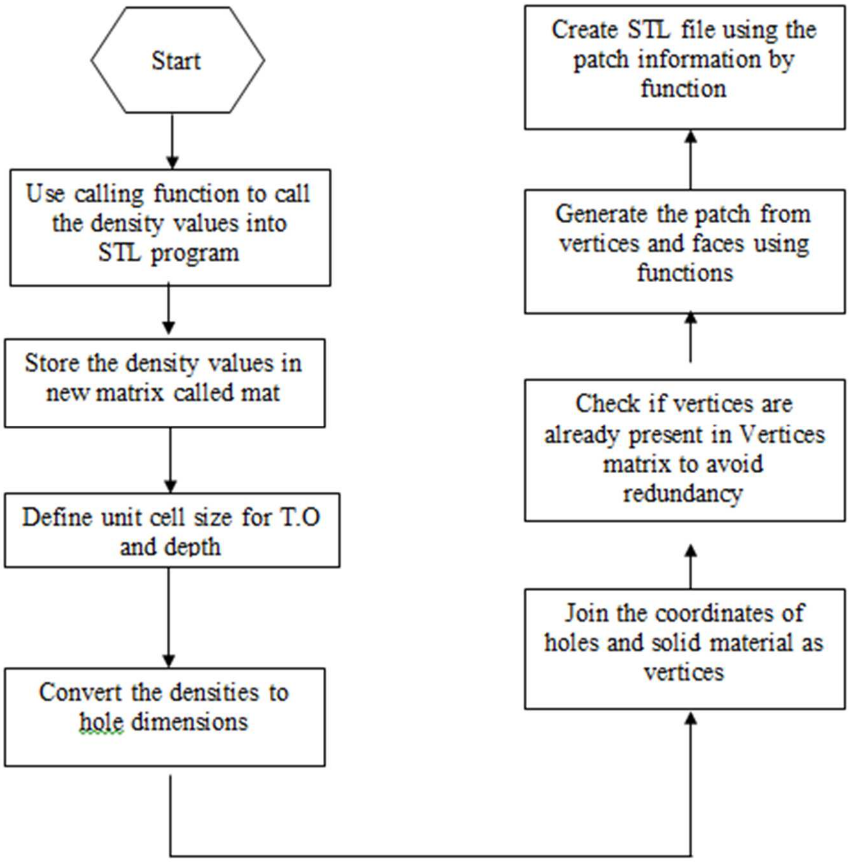

Figure 3-6 Procedure for processing of SIMP solution into STL file

3.5 Manufacturing of Topology Optimized structure

The 3D rendering of the STL file in SolidWorks is shown in the figure 3-7.

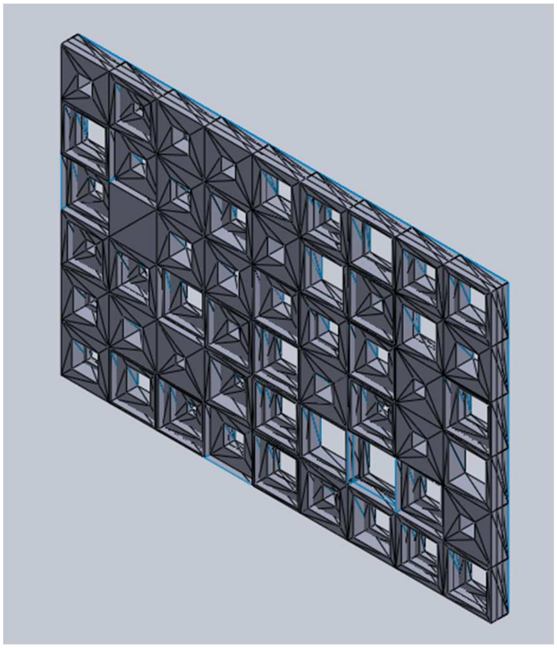

Figure 3-7 STL file viewed in Solid Works

It can be inferred from the figure 3-7 that the cross section is not the same throughout. This is because of the fact that the load is not the same in all the layers

The STL file is the basis for 3D printing. The 3D printer as discussed works layer by layer. The specification of the FDM printer used is given below:

Table 3-1 Makerbot printer specifications

MAKE	MakerBot Replicator 2X
PRINT TECHNOLOGY	FUSED DEPOSITION MODELING
BUILD VOLUME	24.6 L X 15.2 W X 15.5 H CM [9.7 X 6.0 X 6.1 IN]

Table 3.1 - continued

LAYER RESOLUTION	100 MICRONS [0.0039 IN]
POSITIONING PRECISION	XY: 11 MICRONS [0.0004 IN] Z: 2.5 MICRONS [0.0001 IN]
FILAMENT DIAMETER	1.75 MM [0.069 IN]
NOZZLE DIAMETER	0.4 MM [0.015 IN]
BUILD PLATFORM	HEATED, BLACK ANODIZED 356F ALUMINUM
AC INPUT	100–240 V, ~4 AMPS, 50–60 HZ
OPERATING TEMPERATURE	15°–32° C [60°–90° F]

As discussed earlier the optimized conditions to manufacture were taken into consideration. The parts fabricated can be seen in the figure 3-9. Some of the challenges faced while manufacturing are also shown. These include warping of the edges, material not sticking to the plate and filament not extruding from the nozzle.

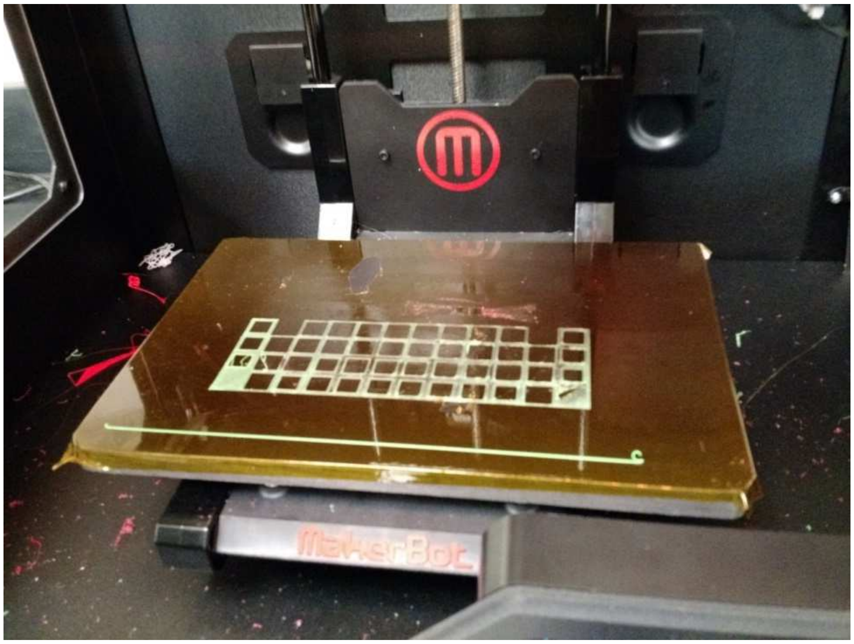

Figure 3-8 Material not sticking to platform

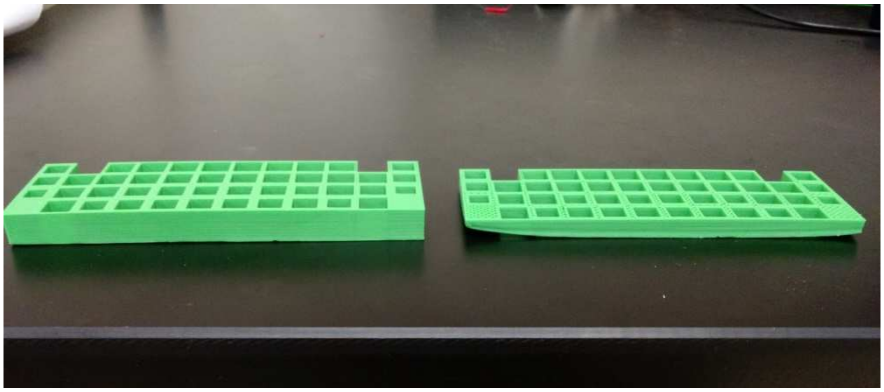

Figure 3-9 Warping of the edges

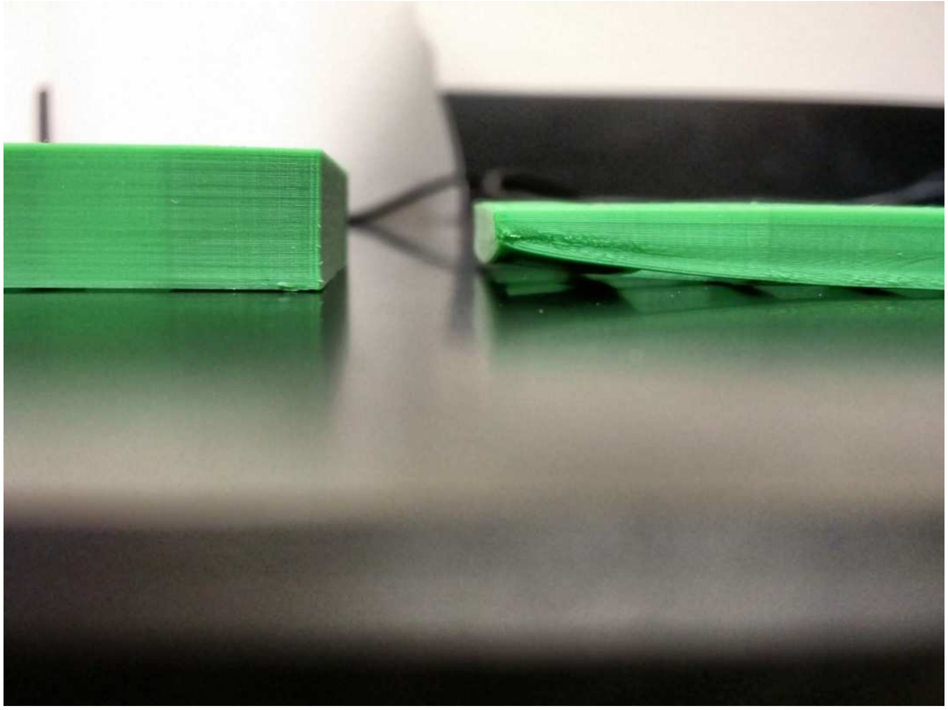

Figure 3-10 Curved eges of the Right. Corrected part on the Left

Figure 3-11 Finished part manufactured using optimum conditions

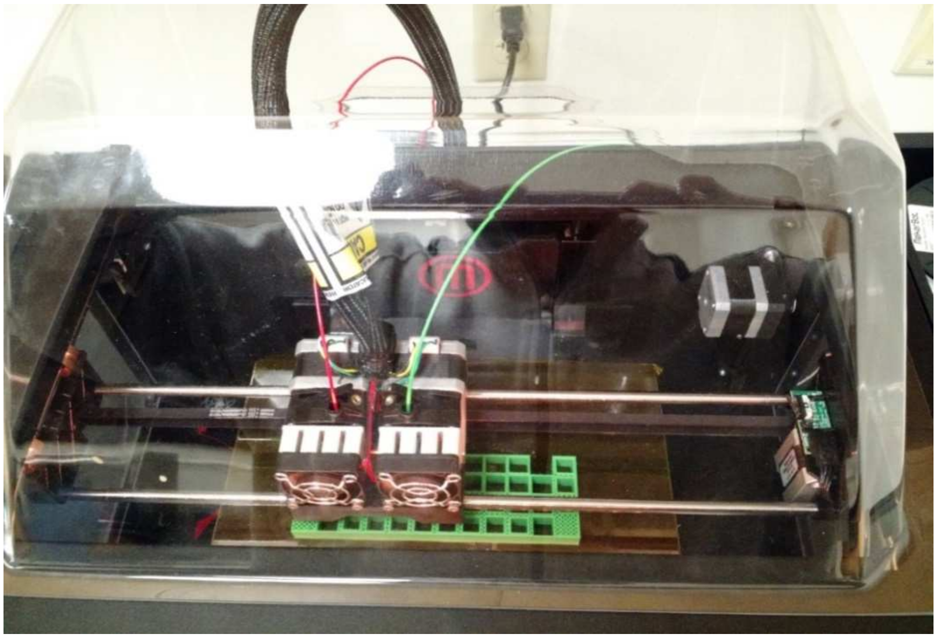

Figure 3-12 View from Top of Makerbot printer

Chapter 4

CONCLUSION

4.1 Summary of Results

This research explores the opportunity to design and manufacture continuous material systems which are have promising applications. An optimization program that can effectively be used for additive manufacturing is designed using MATLAB in this research. The design tool is based on SIMP optimization algorithm without any penalty factor. The density of each element in the domain is the design variable and volume factor is taken as constraint. The design variable is updated using optimal criteria method. The figure shows the history of design variable and its compliance for different iteration values of 30, 60, 10 and 200. This results in a continuous distribution of material in the domain. A square unit cell with voids is introduced in post-processing of the solution that represents the density of each element.

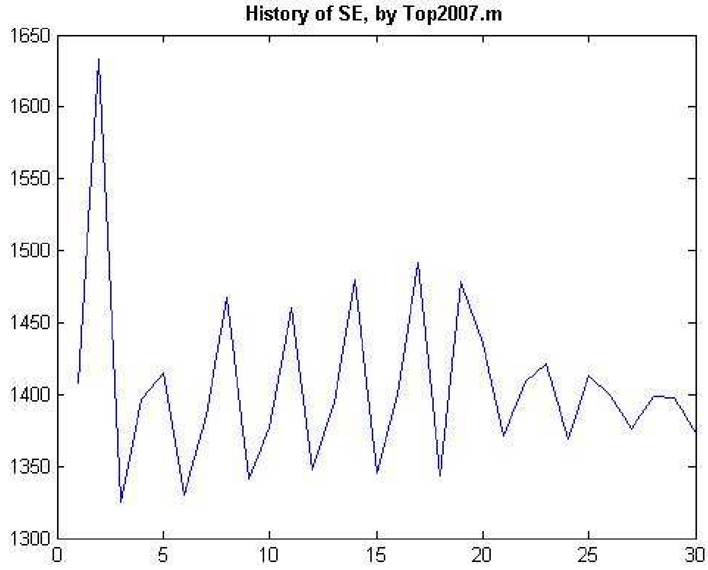

Figure 4-1 Plot of iterations vs compliance for N=30

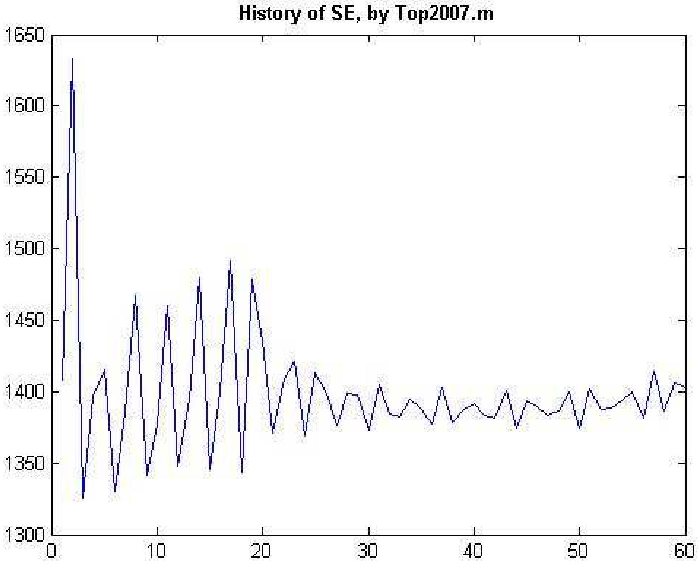

Figure 4-2 Plot iterations vs compliance for N=60

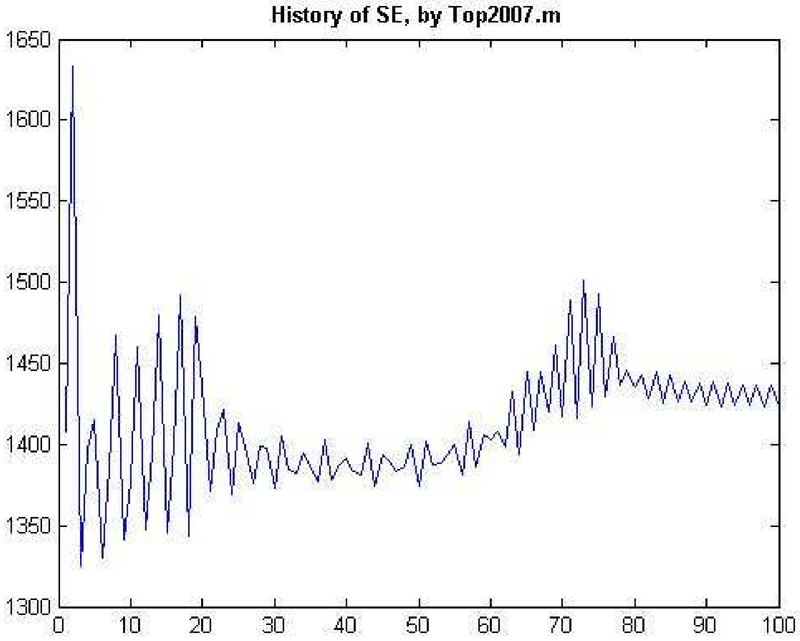

Figure 4-3 Plot iterations vs compliance for N=100

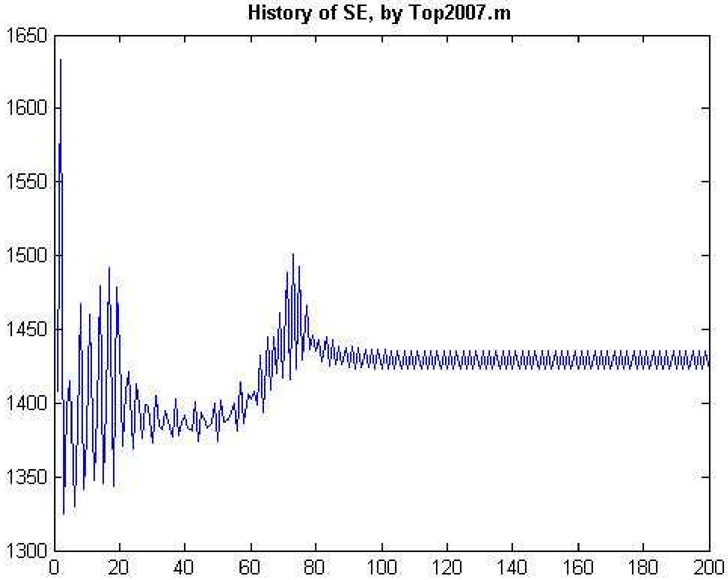

Figure 4-4 Plot iterations vs compliance for N=200

It can be inferred that a good average convergence is obtained when iterations is kept at 80 or more for this problem.

The resulting structure consisting of square unit cell is manufactured using fused deposition modeling. The choice of additive manufacturing is because the results from the optimization contain complex solutions which are difficult to interpret and manufacture using typical manufacturing process. On the basis of literatures, parameters to be optimized for FDM are selected and tensile testing is conducted. Visual inspection is also done to select the best possible parameters for FDM.

4.2 Opportunities for future work

This thesis opens the possibilities to design and implement SIMP method of optimization with no penalty. The possible opportunities include the following

1) Improve the post processing of SIMP solutions. Here square unit cell is used in place of void. Once could extend this idea to use triangular or circular holes which would bring in more design flexibility.
2) Failure analysis is another area which thesis has not focused on. For example the buckling strength could be studied since the size of the voids vary throughout.
3) Use of SLS and SLA for manufacturing could be another avenue for extension. This work limited the manufacturing to FDM since the usage of PLA materials was also being studied. But advanced SLA and SLS machines have better manufacturing capability than PLA, which could provide potential quality to the printed parts.

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BIOGRAPHICAL INFORMATION

Sajith Anantharaman was born in Palakkad in the state of Kerala, India on December 2nd 1989. He studied at Vidya Vikasini Matriculation higher secondary school till 10th grade and then at Lisieux Matriculation higher secondary school till 12th grade in Coimbatore. He completed under-graduate studies in Mechanical Engineering from Amrita Vishwa Vidyapeetham at Coimbatore in May 2011. His work on Image processing techniques titled "*Image based tool wear detection using Artificial Intelligence techniques"* was published in *The International Journal of Composite Materials and Manufacturing; ISSN: 2249-4030, Issue: September 2011.* He then joined Larsen & Toubro Limited (L&T) as Graduate Engineer Trainee soon after graduation.

After working for 2 years, he resigned L&T and joined The University of Texas at Arlington for pursuing Master of Science in Mechanical Engineering in May 2013. He conducted research in field of topology optimization for additive manufacturing under supervision of Dr. Bo Ping Wang. His research was selected for Annual Celebration of Excellence by Students (ACES) in UTA and Society for the Advancement of Material and Process Engineering (SAMPE) conference, Baltimore, Maryland to be held during May 2015.