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Topology Optimization of an Aircraft Bracket Without Shape Control

Mohammed Viquar Mohiuddin*, Md Muqtar Ahmed Khan**, Syed Ferhatullah Hussainy***

**(Professor and Associate Head, Mechanical Engineering Department, Muffakham Jah College of Engineering and Technology, Banjara Hills, Hyderabad - 500034, Telangana, India.Email:mdviquar@mjcollege.ac.in)*
***(M.E. Student, Muffakham Jah College of Engineering and Technology, Banjara Hills, Hyderabad - 500034, Telangana, India)*
****(Professor and Dean student affairs, Mechanical Engineering Department, Muffakham Jah College of Engineering and Technology, Banjara Hills, Hyderabad - 500034, Telangana, India)*

ABSTRACT

Topology optimization is a simulation driven design technique used for creating an efficient material layout for a given design region, constraints and loading conditions. The goal is to maximize the system's performance while minimizing the weight and meeting other functional requirements. The aim of this work is to optimize an existing aircraft bracket using Topology optimization technique. Topology optimization is performed in Altair Inspire software without using any shape control on the basis of five-volume retentions. Volume is specified as 20%, 30% 40%, 50% and 60% of the total design space volume. Post optimization analysis of all the five optimized geometries is carried out. Finally, one model based on optimum results is selected and the smoothing process is carried out using Polynurbs fit tool. The Final optimized model has a weight reduction of 46% and a significant stress reduction of 28%, 54.4%, 49.8% and 47.7% in vertical, horizontal, oblique and torsional load cases respectively.

Keywords-Aircraft bracket, Design and Non-design space,DFAM, Topology Optimization, Weight reduction

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I. INTRODUCTION

Topology optimization is a powerful approach for determining the best distribution of materials within a given design domain. Optimized topology is always complex and, due to manufacturing constraints, it typically involves either simplification following the optimization phase or constraining the design space to allow only manufacturing designs. AM permits the manufacture of topology regardless of the complexity and the cost of development does not typically increase with complexity [1].Optimization of topology allows the identification of optimal structural connectivity for a given design situation, boundary conditions and usable spatial envelope [2]. Topologically optimal geometry is also geometrically complex and incompatible with conventional manufacturing methods. Additive manufacturing can handle considerably more complex geometries than conventional manufacturing [3]. Topology optimization is predestined for the optimization of additive components. In this way it is possible to produce a product that is desirable for purpose and efficiently with minimal use of materials, thus saving money without the external constraints that occur in traditional manufacturing [4]. Topology optimization exercise removes material from all locations where it is not necessary to support the specific loads or satisfy specific boundary conditions. Topology optimization has a wide range of applications in aerospace, mechanical, bio-chemical and civil engineering [5]. Topology optimization is revolutionising and improving performance in many areas, from race cars to industrial machinery to aerospace engineering. Traditional structural simulations allow engineers to check if the design supports the necessary loads. Topology optimization improves this process by creating a new material layout within a package space using loads as input. Topology optimization aims at finding the optimal distribution of material inside a prescribed design domain for a given amount of material, with its ability to reduce the material used and further redistributing it to achieve optimal structure capable of sustaining applied loads within available boundary conditions [6]. Density-based topology optimization is the best method for distribution of material within a prescribed domain.

It does so by discretizing the design domain and optimizing density variables associated to each element within the discretization. It is a systematic tool to produce a strong part with less waste of material [7]. In this work, Altair Inspire is used to carry out Topology optimization. One of the main challenges of Industry 4.0 is to reduce the resource consumed during industrial manufacturing process. Therefore, it would be interesting to explore other materials which may be able to offer similar mechanical properties but with a lower cost [8].

Inspire is a very powerful software for performing topology optimization which enables simulation-driven design to produce light weight designs with improved strength and manufacturability. The topology optimization solver used by Inspire is the same as that in Optistruct [9]. It allows users to rapidly and efficiently build and explore structurally efficient ideas. The part is an aircraft engine bracket. Its function is to support the weight of the cowling during engine service. It must not break or warp during engine handling. It stays on the engine at all times. It plays no active role during the operation of the engine. The bracket is used only periodically. Reducing the weight of any aircraft component has an impact on fuel usage and emission levels [10].The original bracket is made in Titanium alloy Ti6Al4V. The bracket weighs 2050 grams and has a volume of 463 cm^3.

1.1 Research Objective

The goal of this work is to optimize an existing aircraft bracket using Topology optimization technique and to emphasize its importance. Topology optimization is performed without using shape controls. Based upon the output of Topology optimization, the bracket is smoothed and verified for structural stability.

II. METHODOLOGY

The CAD design is modelled in SolidWorks 2013 then Pre-Optimization analysis is performed to verify the feasibility of optimization. The Pre-Optimization analysis is carried out in Aluminium 7075. Aluminium 7075 is selected because of its high yield strength of more than 500 Mpa. It's low density and high stress resistance makes it fit for highly stressed structural applications which provides weight saving over Titanium. After confirming the feasibility of optimization, Topology optimization is performed.Topology optimization process begins with gross model. In Gross model, Part is divided into design and non-design regions. In order to execute a topology optimization, objective functions must be established. Optimization objectives and constraints are used to define the purpose of a topology optimization. A single objective is set, and then a number of complimentary constraints can be assigned [11].

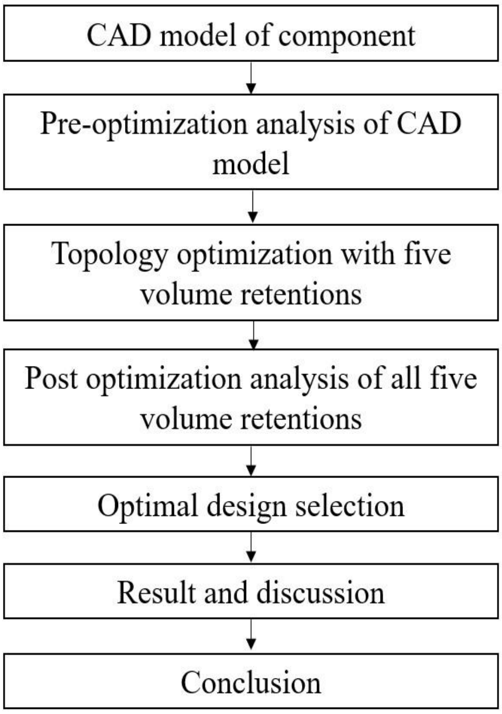
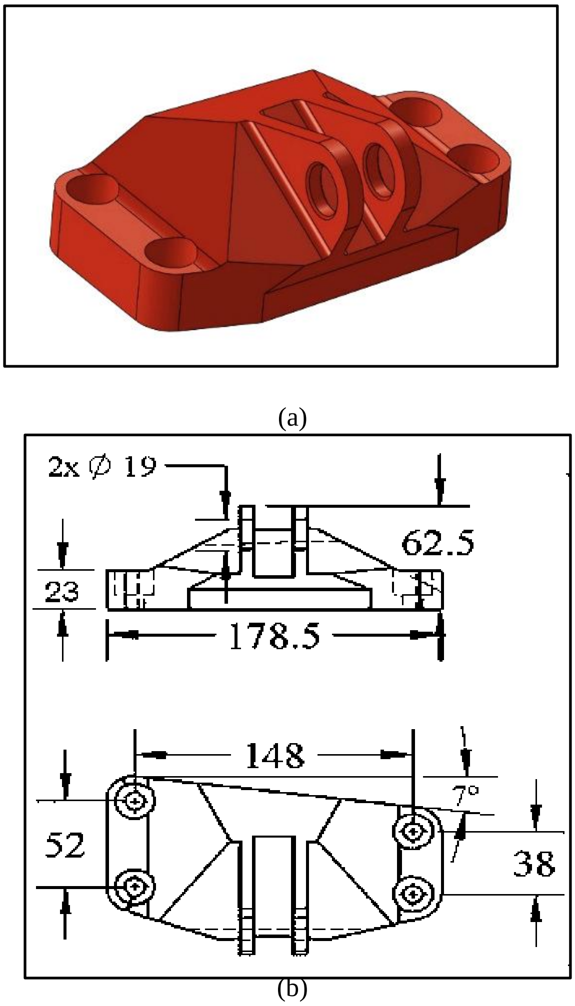


Figure 1. Methodology

Topology optimization is carried out based on five volume retentions, which results in five geometries. Mass targets are used to specify the amount of material to keep, the mass target can be defined either as a percentage of the total volume of the design space or as the total mass of the entire model. For this study, volume is selected as variable for mass targets constraint. Volume is specified as 20%, 30% 40%, 50% and 60% of the total design space volume. Symmetry constrain is applied but not Shape control. Post optimization analysis of each optimized geometries is performed. The minimum factor of safety should be 1.5 for an Aircraft part to be airworthy in accordance with Federal Aviation Regulation (FAR 25). The final model is selected based on optimum results. Smoothing operation is performed on final selected model using Polynurbs Fit which accurately and efficiently represents curved surfaces.

2.1 CAD Modelling

A CAD design of bracket is modelled in SolidWorks 2013 as shown in the Fig 2. FEA analysis is performed in Altair Inspire 2019.1, tetrahedral element is used for meshing as it is the only default option available in the software, with element size of 2.9 mm.



(a)

(b)

Fig. 2 (a) CAD Model of Bracket and (b) Part drawing

2.2 Loads and boundary conditions

The part is subjected to the 4 load cases. The defined loads are applied to the 19 mm diameter clevis hole at interface 1 while the 2-5 interfaces are fixed. In all load situations, the interfaces where the bolts are in contact with the bracket (four holes) are restricted in all directions.

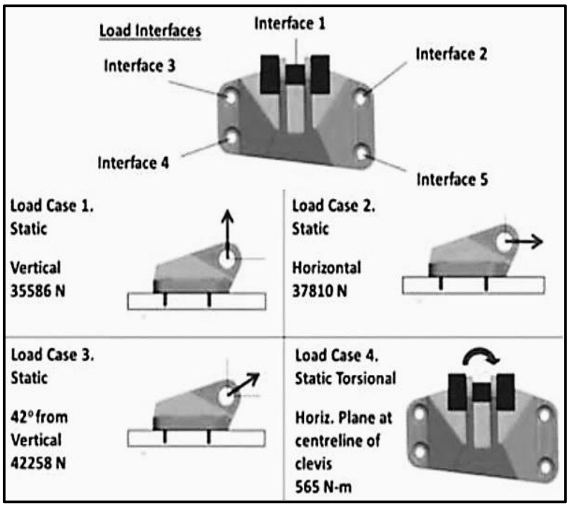


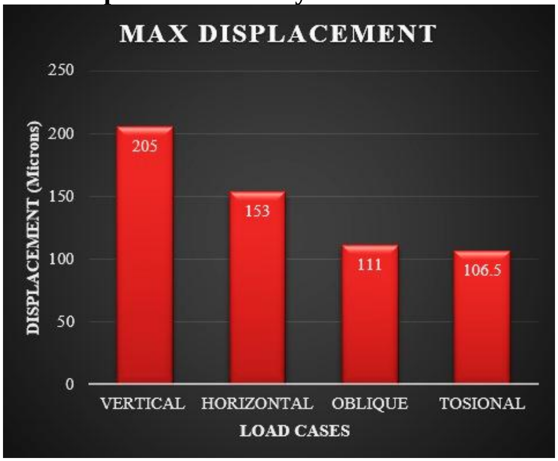
Figure 3. Loading conditions

For load case 1, a concentrated force of 35586 N is applied in the direction of Z. In the case of load case 2, a concentrated force of-37810 N is applied in the negative direction of Y. For load case 3, a concentrated force of 42258 N is applied along a line 42 degrees from the vertical. Finally, for load case 4 a 565 N-m (564924 N-mm) moment is added to the middle line of the clevis.

Table 1. Load Cases

DIRECTION	**FORCE**
Vertical	35586 N
Horizontal	37810 N
42 from vertical	42258 N
Torsional	565 N-m

2.3 Pre-Optimization Analysis



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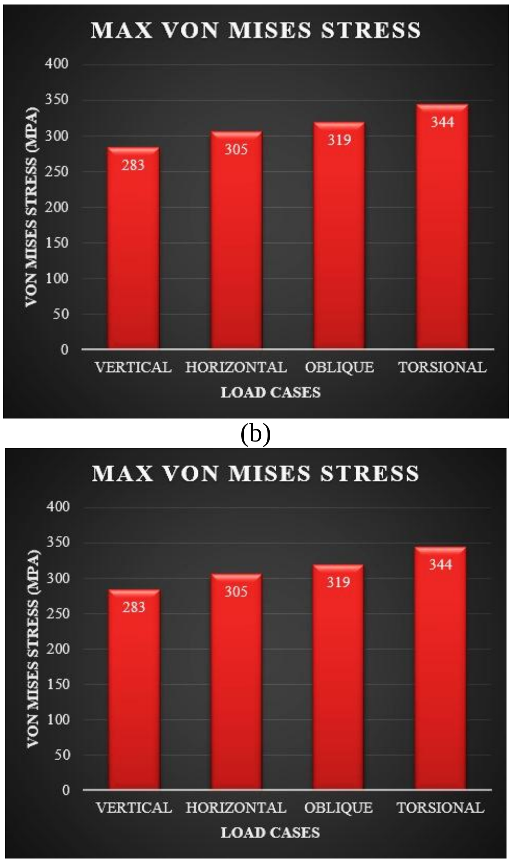


(b)

(c)

Figure 4. (a), (b), (c) Pre-Optimization Analysis Results

The pre-optimization study of the aircraft bracket is performed in Altair Inspire by considering Aluminium 7075. The shift of material from Titanium Ti-6Al-4V to Aluminium 7075-T6 is suggested. Pre-optimization is conducted to check the feasibility of using aluminium alloy as an alternative to Titanium for optimization. As a consequence of material change, the bracket weighs 1294 grammes.

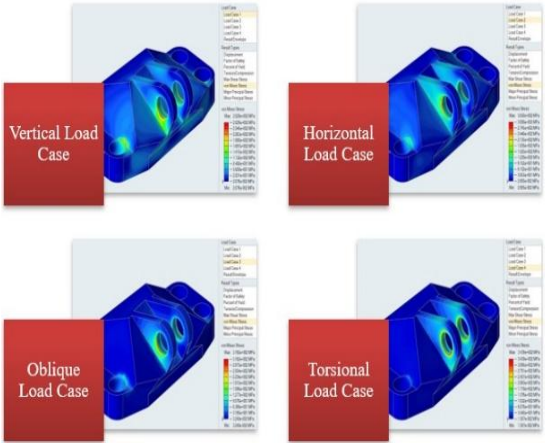


Figure 5. Max Von Mises Stress of each load case

The study of the original part showed higher displacement and Von Mises stress only in areas near the upper holes of the part, as all loads are applied from the clevis arm as shown in Fig 5. The displacement increased as a result of material change. The safety factor for horizontal, oblique and torsional load cases is 1.4, 1.3 and 1.2 which is below the minimum safety factor of 1.5 for the part to be airworthy, in compliance with the Federal Aviation Regulations (FAR 25). The peak stress correlates to the contact stresses between the pin and the clevis arm. The high levels of stress and relatively unstressed material indicate the inefficient use of the material in the part. Stress concentrations restrict the potential strength of the part and therefore adversely affect the stiffness of the part. Thus, we keep the material that is necessary and therefore we can optimise the weight of the bracket.Therefore, this Pre-Optimization analysis suggest that it is possible to optimize the bracket with Aluminium 7075.

III. TOPOLOGY OPTIMIZATION

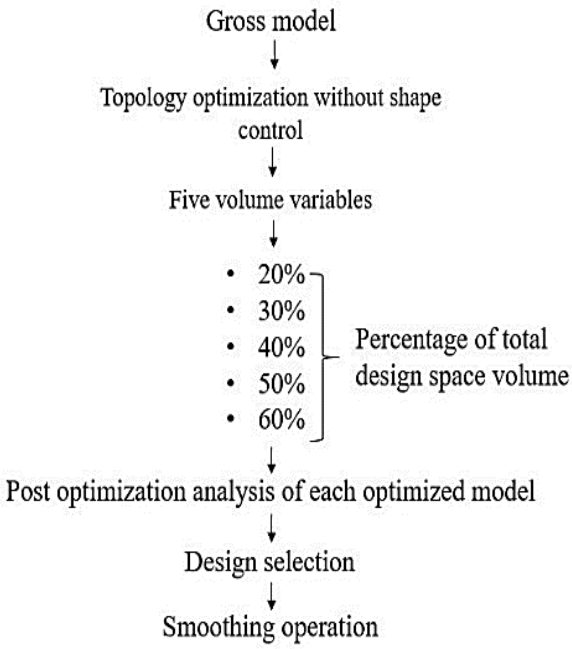


Figure 6. Topology Optimization Methodology

3.1 Gross Model

The design process starts from the gross model; this model does not describe the shape of the part but contains just the information of the boundary dimension that the part can occupy and the interface that cannot be modified [12].

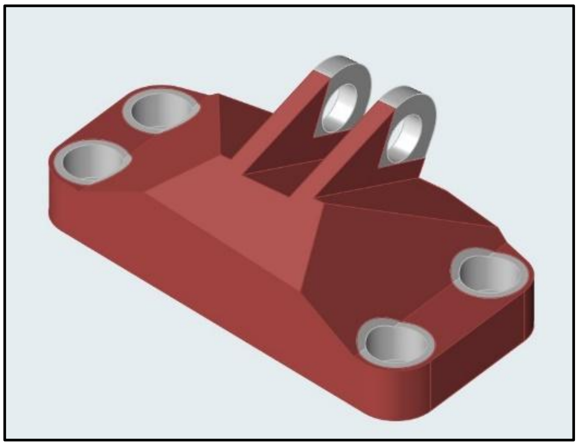


Figure 7. Design and Non-design regions in gross mode

Topology optimization starts with the assignment of design and non-design regions. Using the partition function, the bracket is divided into design and non-design domains[13]. Design region and non-design region are depicted in red and white colour as shown in Fig 7. Design space is lined with finite elements. Each iteration determines which of the elements will be empty and which will represent the material[14]. Interfaces where the bolts are in contact and the clevis arm is designated as a non-design region, the rest of the component is designated as a design region. Non-design regions are areas which are not removed during optimisation. The design regions are areas where the algorithm is used to meet the structural requirements of the component. After the design of the gross model, the boundary restriction, the material properties and the loads shall be imposed on the part[12].

3.2 Topology Optimization Run

Using Altair Inspire 2019.1 software, topology optimization is performed in iterations by considering the boundary conditions set out in section 2.2. At each iteration, the design is subjected to analysis in order to verify the structural stability which is then compared to the pre-optimization results. The analysis of the optimized model is also carried out in the Altair Inspire software. Five separate topology optimizations are performed on the basis of volume variables. The goal of this topological optimization is to optimize stiffness while minimizing mass. The minimum thickness constraint of 9 mm is chosen and the minimum safety factor should be 1.5, as stated by the Federal Aviation Regulation (FAR 25), in order for the component to be airworthy. For all topology optimizations performed, the objective function is defined as the maximum stiffness of the bracket. Five topology optimization iterations without a shape control are performed along with a symmetry constrain and analyzed in order to create an optimized design. The mass target can be defined either as a percentage of the total volume of the design space or as the total mass of the entire model. For this study, volume is selected as mass target constraint. Five volume targets are selected. The volume is specified as 20%, 30%, 40%, 50% and 60% percentage of the total design space volume. The total weight of the bracket in aluminium is 1294g and original part volume of design space is 433cm^3.

3.3 Topology optimization without shape control

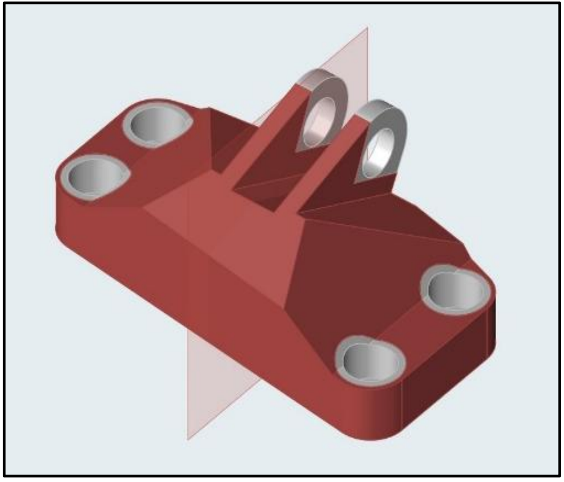
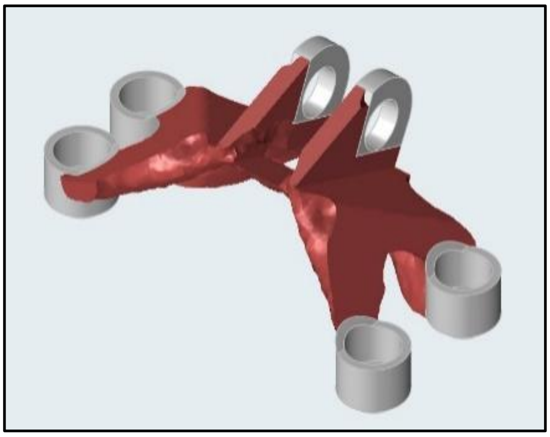


Figure 8. Symmetry plane

Five topology optimization iterations are performed without shape control. The volume is specified as 20%, 30%, 40%, 50% and 60% percentage of the total design space volume. Shape control is not applied. Only symmetry constraint is applied as it is used to generate symmetric shapes, even under asymmetric conditions. The direction of symmetry plane is perpendicular to the bracket from the centre of the two clevis arms as shown in Fig 8.The Topology optimization parameters are set for a target mass of 20%, 30%, 40%, 50% and 60% percentage of the total design space volume with a 9 mm minimum thickness constraint. The optimized geometries for all five-volume retentions are shown inFigs 9 to 13. As the optimization is performed, simultaneously at the end of each iteration, the optimized models are subjected to analysis to check for the structural stability by applying same boundary conditions as described in the section 2.2.



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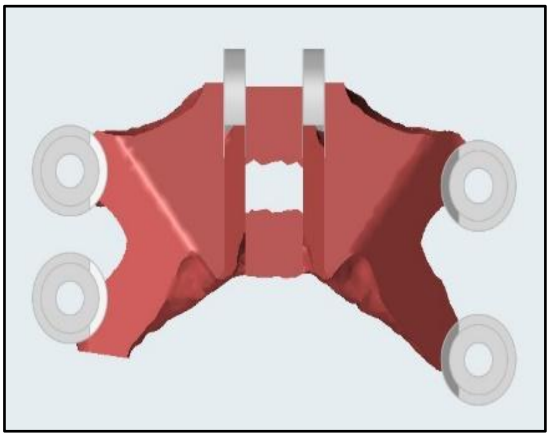
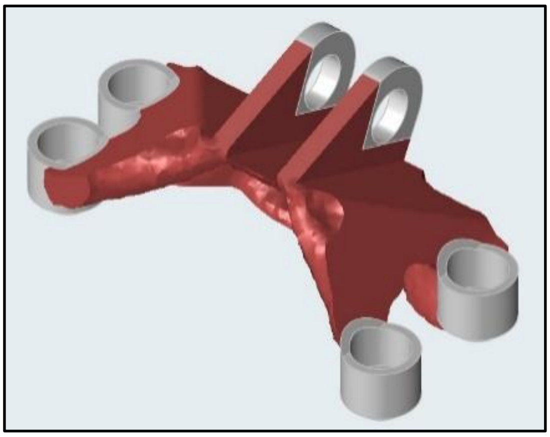


(b)

Figure 9. (a) (b) Optimized model for 20% volume retention



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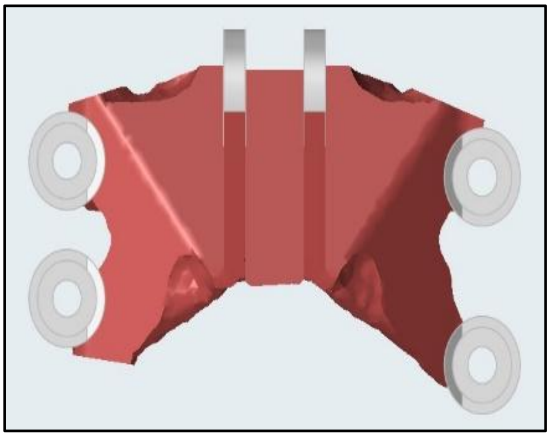

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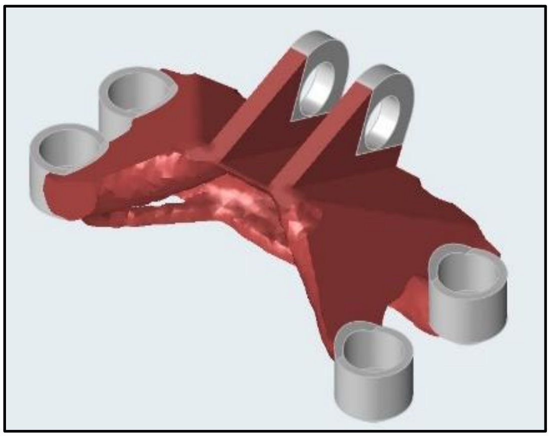
Figure 10. (a) (b) Optimized model for 30% volume retention



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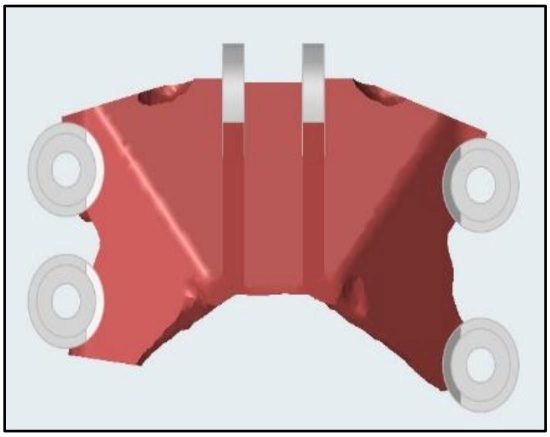
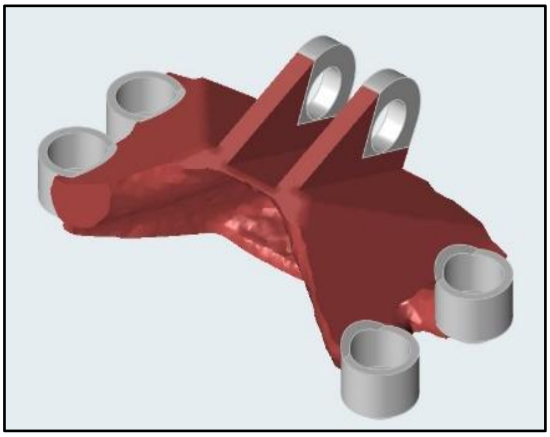


(b)

Figure 11. (a) (b) Optimized model for 40% volume retention



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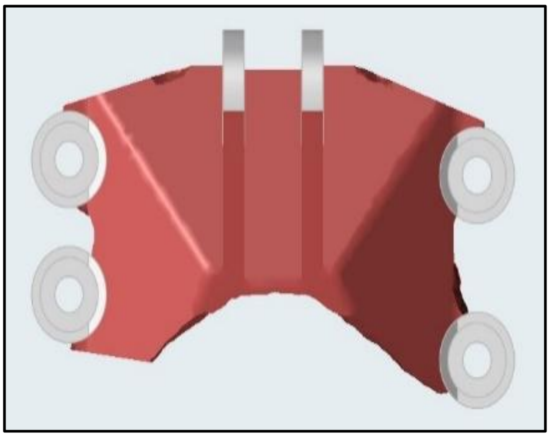
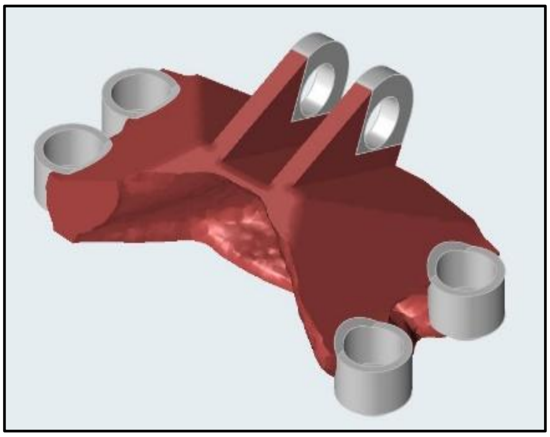


(b)

Figure 12. (a) (b) Optimized model for 50% volume retention



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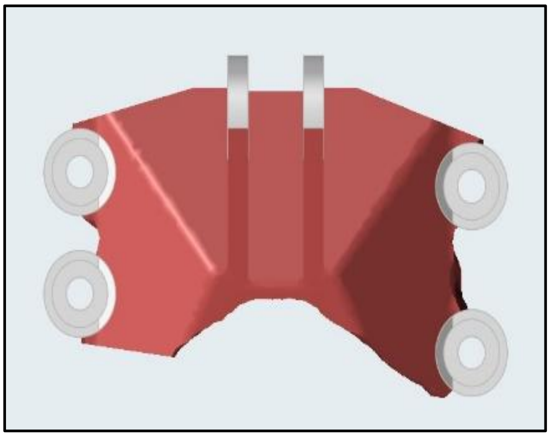
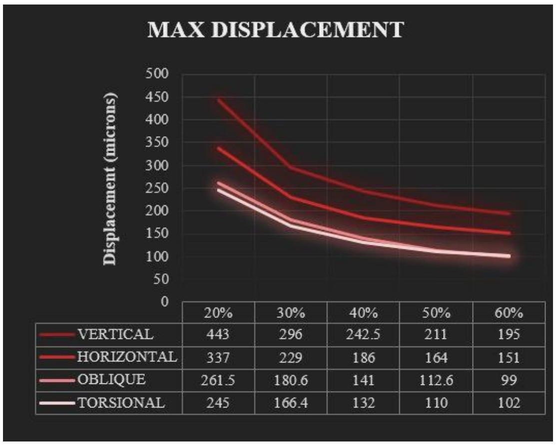


(b)

Figure 13. (a) (b) Optimized model for 60% volume retention

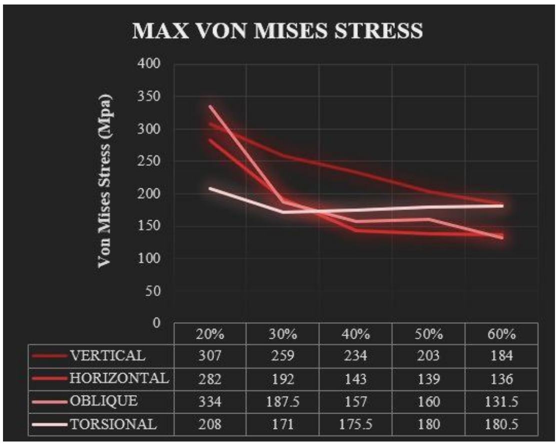
3.4 Post Optimization Analysis of all fiveoptimized models without shape control

Since the study of all five optimized models is carried out it is very important to compare the results of the topology optimization and the different structural parameters for each iteration. The post-optimization structural stability study is carried out. The findings are presented in the graphs below. The X-axis represents 4 load cases and the Y-axis represents a minimum safety factor, maximum displacement and a maximum von mises stress. In compliance with the Federal Aviation Regulation (FAR 25), the minimum safety factor should be 1.5, the optimized model should therefore have a minimum safety factor of 1.5. Topology optimized geometry for 20 percent volume retention is rejected as it does not satisfy 1.5 Safety factor as specified by FAR. The remaining four optimized models are compared on the basis of displacement, von mises stress and weight.



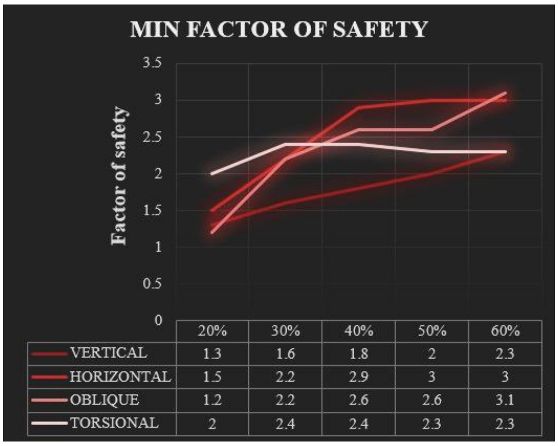
	20%	30%	40%	50%	60%
VERTICAL	443	296	242.5	211	195
HORIZONTAL	337	229	186	164	151
OBLIQUE	261.5	180.6	141	112.6	99
TORSIONAL	245	166.4	132	110	102

(a)



	20%	30%	40%	50%	60%
VERTICAL	307	259	234	203	184
HORIZONTAL	282	192	143	139	136
OBLIQUE	334	187.5	157	160	131.5
TORSIONAL	208	171	175.5	180	180.5

(b)

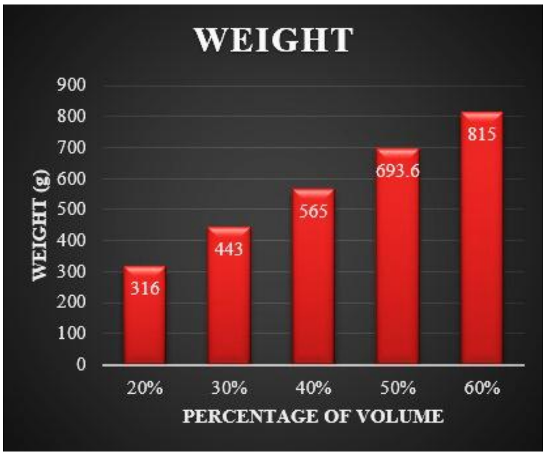


	20%	30%	40%	50%	60%
VERTICAL	1.3	1.6	1.8	2	2.3
HORIZONTAL	1.5	2.2	2.9	3	3
OBLIQUE	1.2	2.2	2.6	2.6	3.1
TORSIONAL	2	2.4	2.4	2.3	2.3

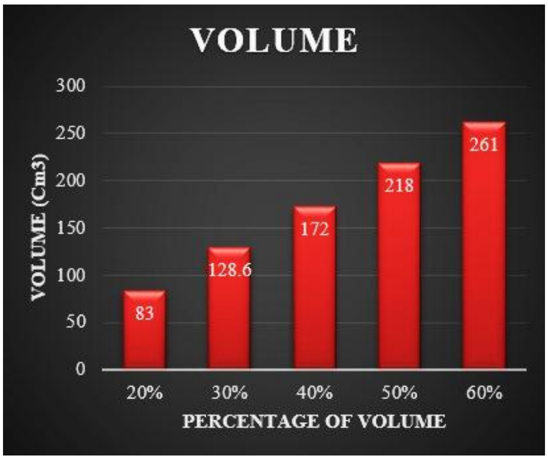
(c)

Figure 14. (a), (b), (c) Post-Optimization analysis results of all five optimized models without shape control

From the above graphs, it can be shown that as the percentage of total design space volume of optimized models increases, displacement and stress decreases with increased safety factors. As a result, the volume and weight of the bracket also increase. Optimized model with 50% volume retention has lower displacement and stress compared to optimized 30% and 40% volume retention models. Although the displacement and stresses are marginally higher compared to the optimized model with 60% volume retention but has less weight. There is very little difference between the 50% and 60% models. The result with the best balance between displacement, von mises stress and volume-to-weight ratio is therefore an optimized bracket with a 50% volume retention. Thus, optimized bracket with a 50% volume retention is selected on the basis of optimum results.



(a)

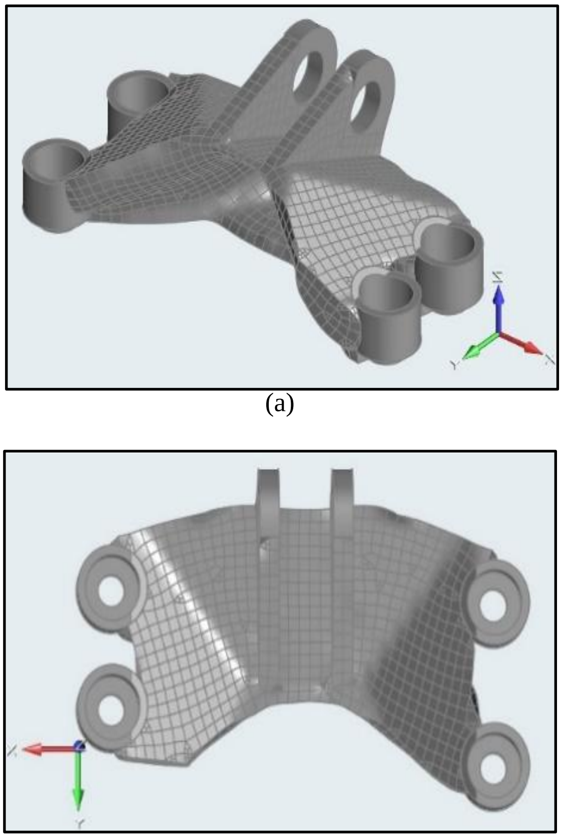


(b)

Figure 15. (a) Weight and (b) Volume of all five optimized models

3.5 Smoothing Operation

Final geometry resulting from the optimisation is rough in the sense that it is based on the initial tetrahedral finite element mesh. The Inspire generates topology designs in a tessellated format, which may not be manufacturable. It is important to smooth the optimized model. To make the topology design manufacturable, post-processing is usually required to identify, smooth and parameterize the structural boundary [15]. Smoothing is the process of converting an optimised 3D mesh into a manufacturable form. Polynurbs Fit tool is used to accurately and efficiently represent curved geometry. It automatically fits a Polynurbs to an optimized shape.The optimized design can only be exported in STL format (.stl) to other CAD software for a re-design phase or it can directly be sent to an additive manufacturing machine.



(a)

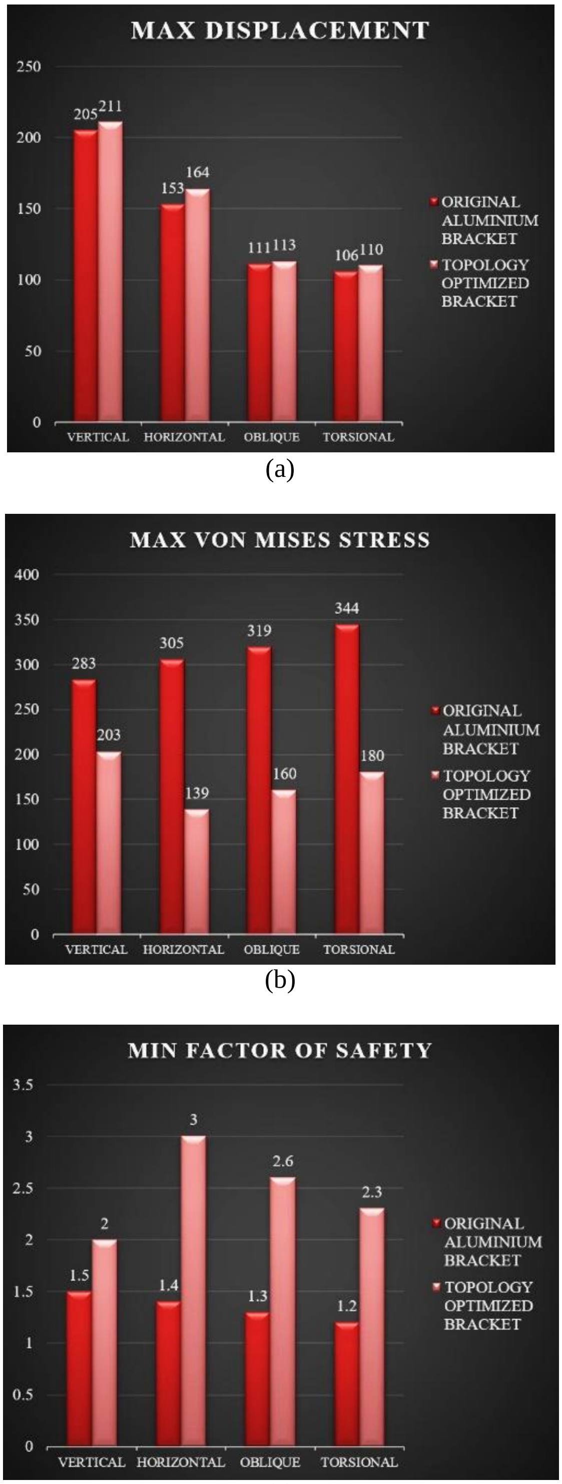
(b)

Figure 16. (a) Smoothed geometry and (b) Top view

IV. RESULT AND DISCUSSION

4.1 Original bracket in comparison with Topology optimized bracket

Original bracket is compared with the Topology optimized bracket. The optimized model substantially enhanced the bracket by reducing stresses while retaining a safety factor above 1.5.Previously, the minimum safety factor for horizontal, oblique and torsional load cases was less than 1.5, which was not satisfactory in compliance with the Federal Aviation Regulation (FAR 25), but after optimization, the safety factor has increased above 1.5 mark.

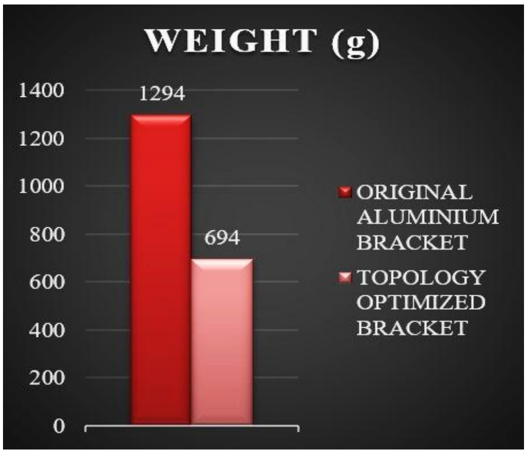


(a)

(b)

(c)

Figure 17. (a), (b), (c) Comparison of original bracket and Topology optimizedbracket



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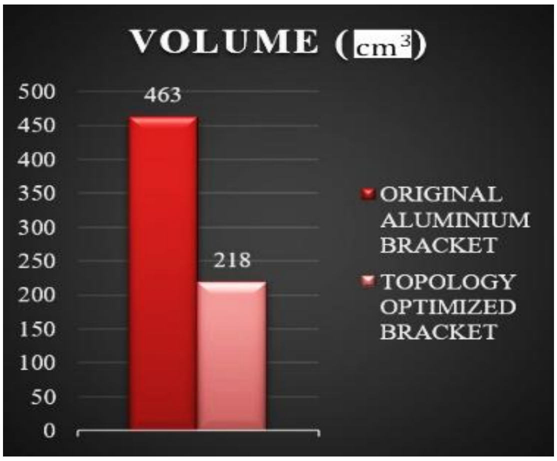

(b)

Figure 18. (a) Weight and (b) Volume Comparison

There is asubstantial reduction in weight and stressesof the Topology optimized model. The Topology optimized model has 28%, 54.4%, 49.8% and 47.7% stress reduction in vertical, horizontal, oblique and torsional load cases respectively. It has a volume reduction of 52.9% while the weight is reduced to 694g from 1294g that is reduction of 600g which is 46% weight saving.

V. CONCLUSION

5.1 Conclusions

The advantages of topology optimization are seen in this work compared to traditional design. The optimized model is the product of a Topology optimization process with a weight reduction of 46% relative to the original bracket. The Topology optimized model has a stress reduction of 28%, 54.4%, 49.84% and 47.67% respectively in vertical, horizontal, oblique and torsional load cases. Successful reductions in weight and stress levels are accomplished with regard to the design space and the applied forces.

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