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Re-design of an Aircraft Bracket Using Topology Optimization Technique

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Abstract *- The project's objective is to explore the possibility of using Aluminium Alloy to optimize an existing aircraft bracket using the Topology optimization technique. Topology optimization is performed using Altair Inspire software. Topology optimization is carried out with single draw shape control based on five-volume retentions each. 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 performed. Finally, one model based on manufacturing feasibility is selected, and a smoothing operation is carried out using Polynurbs fit. SolidWorks is used to re-design the bracket by taking optimized topology design as a reference. The re-designed and original bracket prototype is printed in ABS plastic using the Fused Deposition Modeling (FDM) technique. The re-designed model is compared with the original bracket. The re-designed model has a weight reduction of 39.18% and a significant stress reduction of 15.7%, 28.2%, 39.5%, and 28.2% in vertical, horizontal, oblique, and torsional load cases, respectively. By performing, topology optimization combined with re-design, 6.3% and 5.4% lower Displacement is observed in vertical and oblique load cases, respectively, when compared with conventional geometry*

Keywords - *Topology Optimization, Aircraft bracket, Shape control, Aluminium 7075, Weight reduction, design, and Non-design space.*

I. INTRODUCTION

Topology optimization is one of the most promising technologies that has been recently developed in computer-aided design. This new type of technology completely changes how products are made. It gives multiple solutions for accomplishing a specific goal according to the designer's criteria. The topology optimization exercise removes material from all locations where it is unnecessary to support the specific loads or satisfy specific boundary conditions. Topology optimization has a wide range of aerospace applications, mechanical, biochemical, and civil engineering [1]. Topology optimization is revolutionizing and improving efficiency in many fields, from racings cars to industrial machinery equipment to aerospace engineering design. Traditional structural simulations allow engineers to check if a design will support the required loads. Topology optimization enhances this process by generating a new material layout within a package space using the loads as an input. Topology optimization aims to find the optimal distribution of material inside a prescribed design domain for a given amount of material. Its ability to reduce the material used and further redistribute it to achieve an optimal structure capable of sustaining applied loads within available boundary conditions [2]. Density-based topology optimization is the best method for the distribution of material within a prescribed domain. It does so by discretizing the design domain and optimizing density variables associated with each element within the discretization. It is a systematic tool to produce a strong part with less waste of material [3]. The topology optimization process carves material away from design spaces, creating the lightest structure capable of withstanding the model's forces. This approach is ideal for maximizing the stiffness of components while trying to achieve the desired mass target. In this work, Altair Inspire is used to carry out Topology optimization. Inspire is a powerful software for performing topology optimization, enabling simulation-driven design to produce lightweight designs with improved strength and manufacturability. The topology optimization solver used by Inspire is the same as that in Optistruct [4]. It enables users to create and investigate structurally, efficient concepts quickly and easily.

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 impacts fuel usage and emission levels [5]. The original bracket is made in Titanium alloy Ti6Al4V. The bracket weighs 2050 grams and has a volume of 463 cm^3. Fewer raw materials are used in a smaller part reducing the energy usage and emissions in mining and manufacture. This is particularly pertinent as titanium production consumes high levels of energy [6]. A recent cradle-to-grave life cycle analysis (LCA) by Norgate et al. [7] showed Titanium to have a 361 MJ/kg gross energy requirement, more than 15 times that of steel. Persistent rogue elements can make alloys of Titanium difficult to recycle [8]. In 2012, a well-known airline flew 109,346,509 revenue passengers on a total of 1,361,558 trips at the cost of $6.12B in fuel. These values indicate an average fuel cost of $4500 per trip or $56 per passenger. If the average passenger weighs 200-lb, including luggage, then the fuel cost is $0.28 per pound per trip. Thus, if one pound could be stripped from all of its aircraft, the airline would save just over $380,000 per year. Scaling this number to include all aircraft worldwide, the savings increases to more than $9.5M per year (> 3M gallons) [9]. The results demonstrate that the GW method is effective and efficient in solving this problem [10].

Research Objective

The project's objective is to demonstrate the importance of Topology optimization technique and explore the possibility of using Aluminium Alloy to optimize an existing aircraft bracket using this technique. This optimization will reduce the mass of the bracket while maintaining strength to weight ratio. Based upon the results of Topological optimization, the bracket is re-designed and verified for structural stability.

II. METHODOLOGY

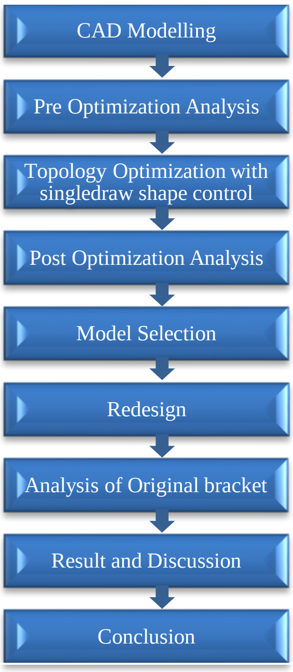


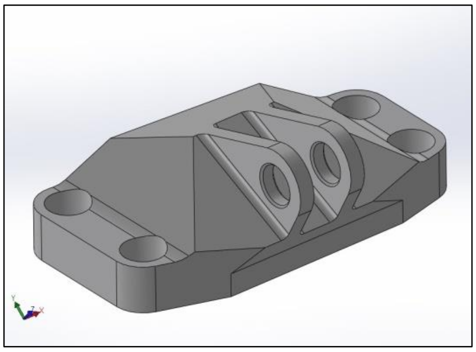
Fig. 1 Methodology

First, the CAD design is modeled 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. After confirming the feasibility of optimization, Topology optimization is performed. The topology optimization process begins with the gross model. The Gross model has information about design and non-design regions. Using the Partition tool, the design domain is divided into design and non–design regions by selecting interfaces where the bolts would be in contact and Clevis arm. Design spaces are such areas that are considered for optimization, whereas the non-design space is fixed regions in which boundary conditions are applied. To execute a topology optimization, objective functions must be established. For all topology optimizations carried out, the objective function is defined as maximizing stiffness. The maximization of the component's stiffness is a critical objective function that results in more rigid components after the optimization.

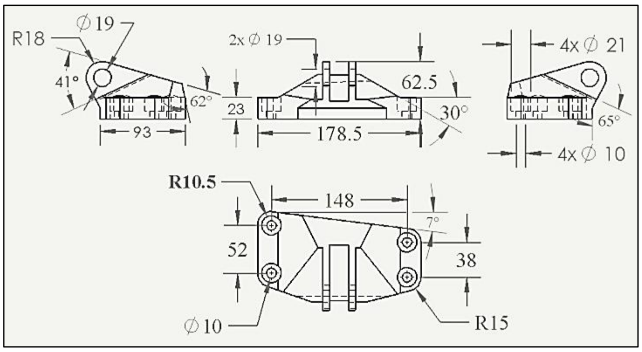
Topology optimization is carried out with single draw shape control based on five-volume retentions each. Mass targets are used to specify the amount of material to keep. The mass target can be defined either as a percentage of the total volume of the design space or the entire model's total mass. Volume is specified as 20%, 30% 40%, 50% and 60% of the total design space volume. Single draw shape control and symmetry constrain are applied to the design space. Single draw shape control can reduce the need for supports by eliminating overhanging surfaces. It tries to extrude material in a particular direction. The direction of the single draw is selected as +ve z-direction, and the direction of the symmetry plane is perpendicular to the bracket from the center of two clevis arms. Post optimization analysis of each optimized geometry is performed. The analysis of the results is made with an emphasis on the Displacement, Von mises stress, and Factor of safety. The minimum Factor of safety should be 1.5 for an Aircraft part to be airworthy following Federal Aviation Regulation (FAR 25). The final model is selected based on manufacturing feasibility. Smoothing operation is performed on the final selected model using Polynurbs fit, which accurately and efficiently represents curved surfaces. It is easier to export the optimization results directly in the CAD for the re-design phase. Following the smoothing operation stage, it is converted to a mathematical CAD representation. This stage is done manually by 'tracing' the optimized geometry. SolidWorks is used to re-design the bracket by taking topology optimized design as a reference followed by an FEA analysis. Finally, the re-designed model is compared with the original bracket. The Prototype of the re-designed and original bracket is printed in ABS plastic using the Fused Deposition Modeling (FDM) technique.

A. CAD Modelling

A CAD design of the bracket was modeled in SolidWorks 2013, as shown in 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 an element size of 2.9 mm.



(a)



(b)

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

B. Loads and boundary conditions

The part is subjected to the 4 individual load conditions, with the specified loads being applied to 19 mm diameter clevis hole at interface 1 while interfaces 2-5 are fixed as shown in table 1. For all load cases, the bolts' interfaces would be in contact with the bracket (the four holes) are restrained in all directions.

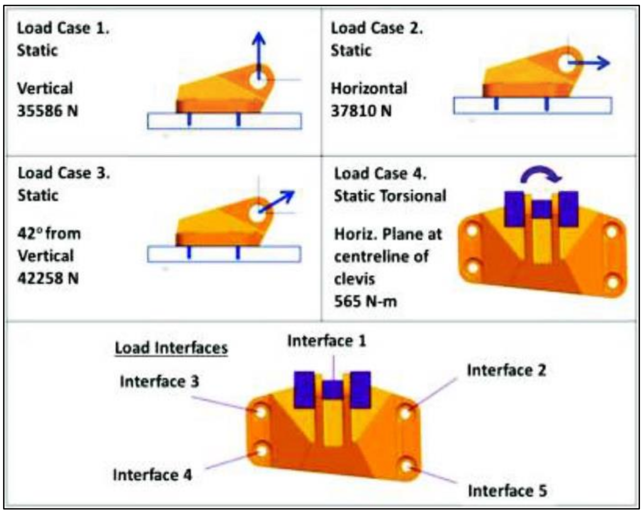


Fig. 3 Loading conditions

- For load condition-1, a concentrated force of 35586 N is applied in the Z-direction. The force is restrained in all degrees of freedom except for the Z-direction to ensure the load is applied along the fixed path.

Table 1. Load Cases

DIRECTION	FORCE
Vertical + 4 Fixed supports	35586 N
Horizontal + 4 Fixed supports	37810 N
42 from vertical + 4 Fixed supports	42258 N
Torsional + 4 Fixed supports	565 N-m

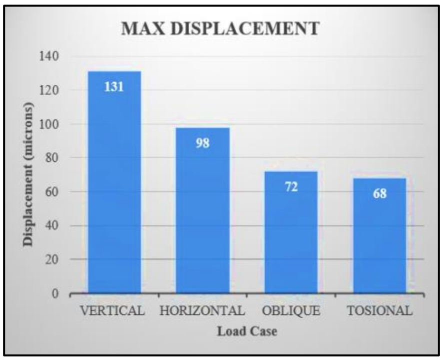
- For load condition-2, a concentrated force of 37810 N is applied in the negative Y-direction. Due to the Cartesian coordinate system's orientation, the concentrated force is equal to -37810 N. Similar to in Load Condition 1, and the force is restrained in all degrees of freedom except for the Y-direction.
- For load condition-3, a concentrated force of 42258 N is applied along with a line 42 degrees from the vertical. This angled force is decomposed into orthogonal y & z components, -31404 N and 28276 N, respectively. For this load case, the force is restrained in all degrees of freedom except in the Y and Z directions.
- Finally, for load condition-4, a 565 N-m (564924 N-mm) moment is applied to the clevis's centreline. The moment is restrained in all degrees of freedom except for the rotational degree of freedom about the X-axis.

C. Material Selection

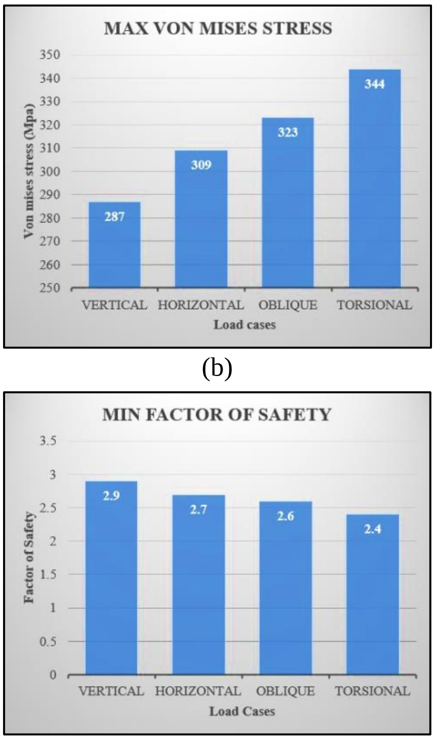
Aluminum 7075 is one the strongest Aluminium alloys, with zinc as the primary alloying element. It has a high yield strength of more than 500 Mpa, and its low density makes the material a fit for applications such as aircraft parts or parts subject to heavy wear. Aluminum 7075 is often used in the aerospace industry due to its well-balanced set of properties. It has excellent mechanical properties and exhibits good corrosion, high strength, toughness, and good fatigue resistance. It is used in highly stressed structural applications. Low weight and high-stress resistance allow for weight savings over Titanium. Thus, Aluminium 7075 is the preferred choice because of its excellent strength-to-weight ratio.

D. Analysis of Original Titanium Bracket

The original bracket is made in Titanium Ti-6Al-4V. The simulated volume of the component is 463 cm^3 and it weighs 2050 grams. An analysis of the results is made with an emphasis on the Displacement, Von mises stress, and Factor of safety. These three parameters are compared to the final re-designed bracket results. The X-Axis represents four individual load cases, and Y-Axis represents maximum Displacement, maximum von mises stress, and minimum Factor of safety. It shows very low Displacement, although stresses are a little higher. The minimum Factor of safety for each load case is above 2.4.



(a)



(b)

(c)

Fig. 4 (a) Maximum Displacement, (b) Maximum Von Mises Stress and (c) Minimum Factor of Safety of each load case

E. Pre-Optimization Analysis

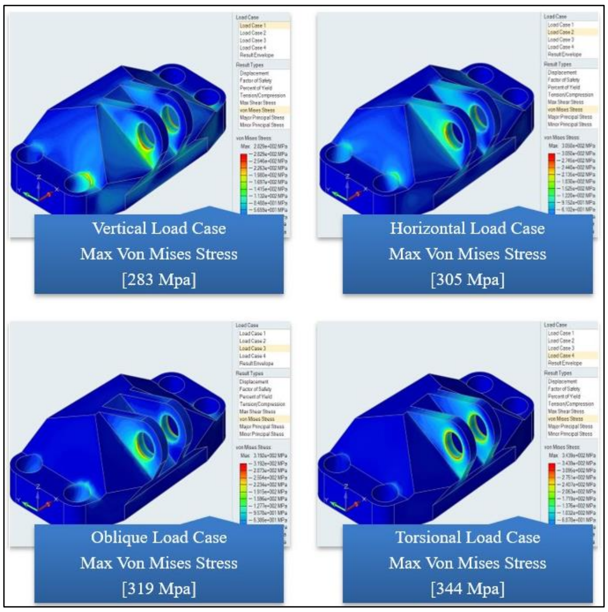
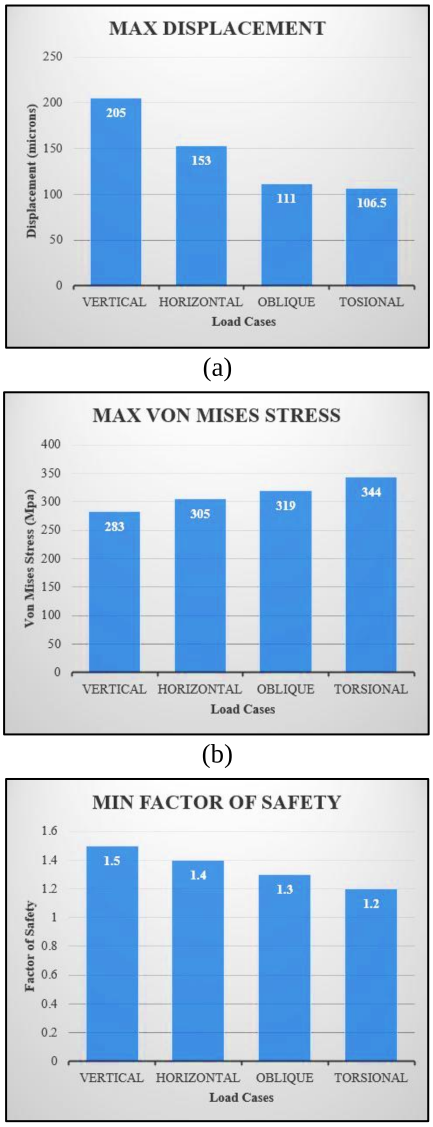


Fig. 5 Max Von Mises Stress of each load case

Altair Inspire is used for Pre-Optimization analysis of the Aircraft bracket considering Aluminium 7075. The change of material from Titanium Ti-6Al-4V to Aluminium 7075-T6 is proposed. Pre-Optimization is performed to verify the feasibility of using Aluminium 7075 as an alternative to Ti6Al4V for optimization. The bracket weighs 1294 grams as a result of the material change.



(a)

(b)

(c)

Fig. 6 (a), (b), (c) Pre-Optimization Analysis Results

Altair Inspire is used for Pre-Optimization analysis of the Aircraft bracket considering Aluminium 7075. The change of material from Titanium Ti-6Al-4V to Aluminium 7075-T6 is proposed. Pre-Optimization is performed to verify the feasibility of using Aluminium 7075 as an alternative to Ti6Al4V for optimization. The bracket weighs 1294 grams as a result of the material change.

As expected, the original piece's analysis showed higher Displacement and Von Mises stress only on the areas near the upper holes, since all the loads are applied from these points, as shown in Fig. 5. The peak stresses correspond to contact stresses between the pin and the clevis arm. The rest of the piece shows lower displacements and Von Mises stress, suggesting that the bracket is oversized. The areas where stresses are low can be removed as it does not contribute much in load distribution. Thus, keeping the required material and therefore, we can optimize the bracket's mass. Many stress concentrations and relatively unstressed material indicate inefficient use of the material in part. It is also very likely that material could be removed from the part with a negligible effect on the part's performance; this is effectively a waste of material [11].

The Displacement has increased as a result of a material change. The min Factor of safety in horizontal, oblique, and torsional load cases is 1.4, 1.3, and 1.2, which is below the required safety factor of 1.5 for a part to be airworthy, according to Federal Aviation Regulations (FAR 25). From the contours in Fig. 5, it can be seen that the bulk of the bracket is relatively unstressed, with most of the stress concentration in the clevis. This would indicate that there is likely a significant improvement that can be made when topology optimization methods are employed. Therefore, this pre-optimization analysis suggests that it is possible to optimize the bracket with Aluminium 7075.

III. TOPOLOGY OPTIMIZATION

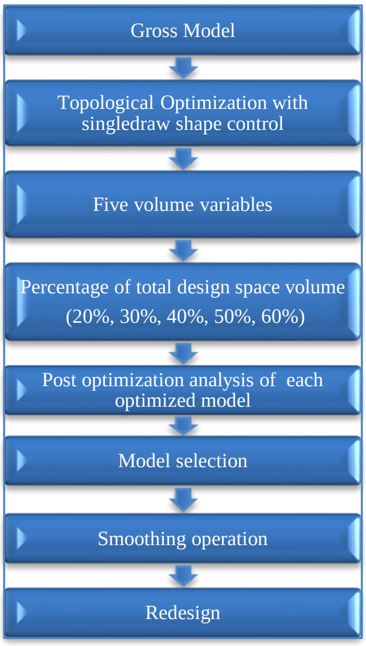


Fig. 7 Topology Optimization Methodology

A. Gross Model

The design process starts from the gross model; this model does not describe the part's shape but contains just the information of the boundary dimension that the part can occupy and the interface that cannot be modified [12]. The first step of the topology optimization is to define the design and non-design space [13]. Design space is a volume in which the topology optimization algorithm decides where the material is needed to fulfill the part's structural requirements [1]. Non-design spaces are such areas that are not supposed to be altered as these regions are subjected to load cases. Using the Partition tool, the bracket is segmented into design and non-design spaces, as shown in Fig. 8. Design space is represented by burgundy color and the non-design space with greyish color. The clevis arm and interfaces where the bolts would be in contact are designated as non-design spaces as the entire inner surface is subjected to a load case. After designing the gross model, boundary constraints, material properties, and loads have to be imposed on the part [12].

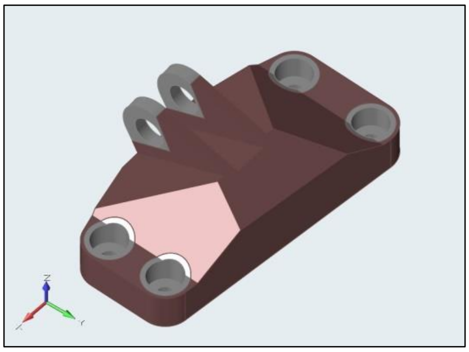


Fig. 8 Design and Non-design space in the gross mode

B. Topology Optimization Run

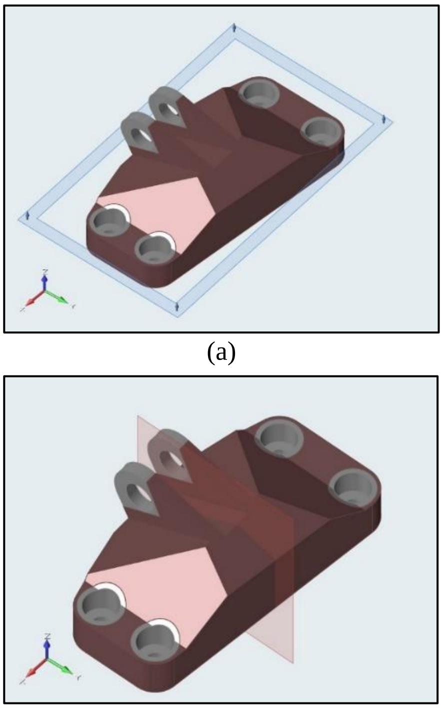
By considering the boundary conditions called out in the section' Loads and boundary conditions', topology optimization is performed in iterations using Altair Inspire software 2019.1. At each iteration, the design is revised based on the inputs obtained by optimization. The design at each iteration is subjected to analysis to check for the structural stability, which is compared to pre-optimization results. This topological optimization aims to maximize stiffness while minimizing mass with low manufacturing cost and using a minimum thickness constrain of 9 mm and a minimum safety factor of 1.5, following the Federal Aviation Regulation (FAR 25). There are four basic components of topology optimization.

1. The first component of topology optimization is selecting the optimization type and definition of design and non-design regions. The type of optimization is selected as topology. For all of the optimizations carried out in this work, the design space is the entire bracket (excluding the loading pin, clevis arm, and bolt regions), selected as non-design space mentioned in the gross model.
2. The second component of topology optimization is to define the objective function. For all topology optimizations carried out, the objective function is defined as maximizing the bracket's stiffness. It's a critical objective function that results in more rigid components after the optimization [14].
3. The third component is to define shape control. The single draw shape control is applied to the design space. A single draw direction is a type of manufacturing constraint for a part to be manufactured by casting or machining. Five topology optimization iterations with single draw shape control are performed along with symmetry constrain and analyzed to build an optimized design.
4. The fourth component is to define optimization constraints. When running topology optimization and maximize stiffness as an objective, mass targets are used to specify the amount of material to keep. The mass target is defined as a percentage of the total volume of the design space. Volume is selected as a mass target constraint. Five volume targets are

selected. The volume is 20%, 30%, 40%, 50%, and 60% percentage of the total design space volume. The total weight of the bracket is 1294g, and the original part volume of design space is 433cm^3.

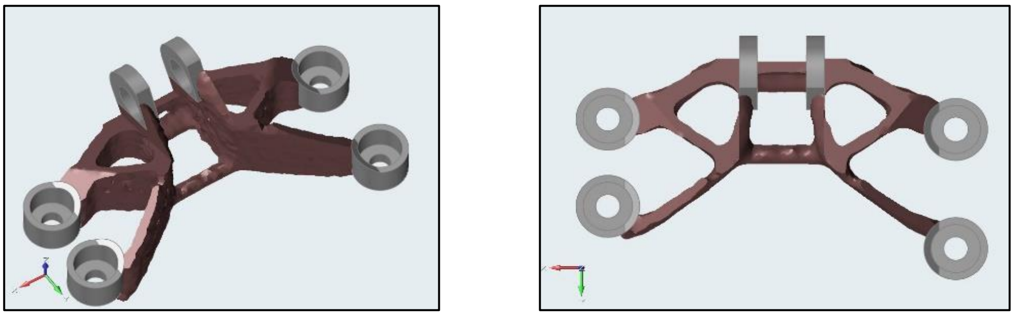
C. Topology optimization with Single Draw shape control

Five topology optimization iterations are performed based on Singledraw shape control. Volume is selected as mass targets. The volume is 20%, 30%, 40%, 50%, and 60% percentage of the total design space volume. Single draw shape control and symmetry constrain are applied to the design space. A single Draw direction is a type of manufacturing constraint which tries to extrude material in a particular direction for a part to be manufactured by casting or machining. The symmetry constraint generates symmetric shapes, even under asymmetric conditions, by defining symmetry planes in the design space. The direction of the single draw is selected as +ve z-direction, i.e., from bottom to top. The symmetry plane's direction is selected perpendicular to the bracket from the center of the two clevis arms, as shown in Fig. 9. 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 in Fig. 10. 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 the same boundary conditions described in the section' Loads and boundary conditions'.

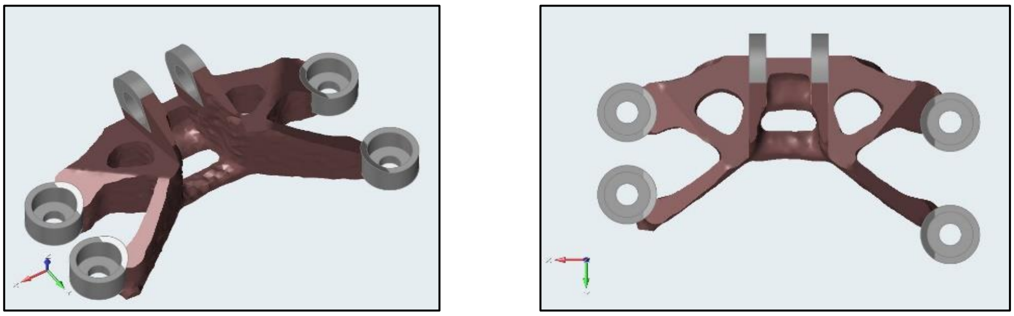

(a)

(b)

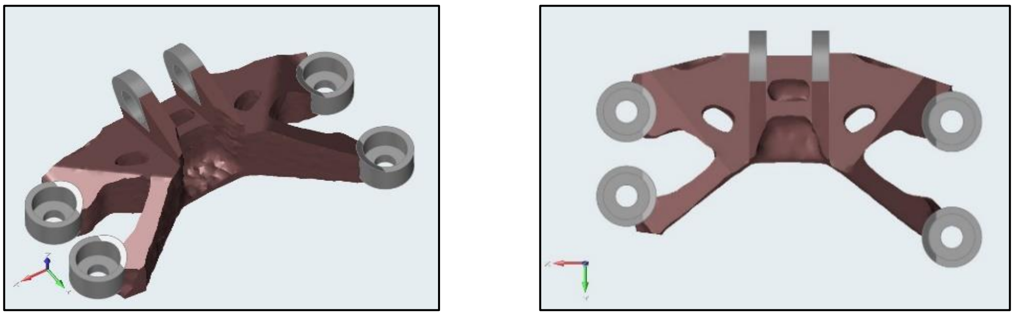
Fig 9 (a) Singledraw shape control and (b) Symmetry plane


(a) Optimized geometry for 20% volume retention

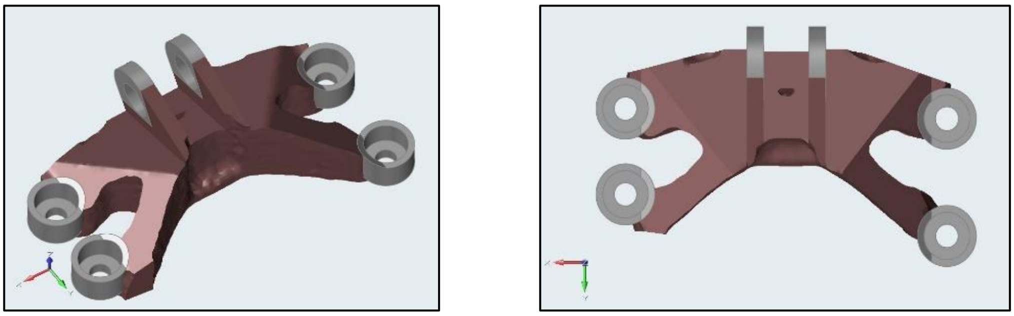
Top View


(b) Optimized geometry for 30% volume retention

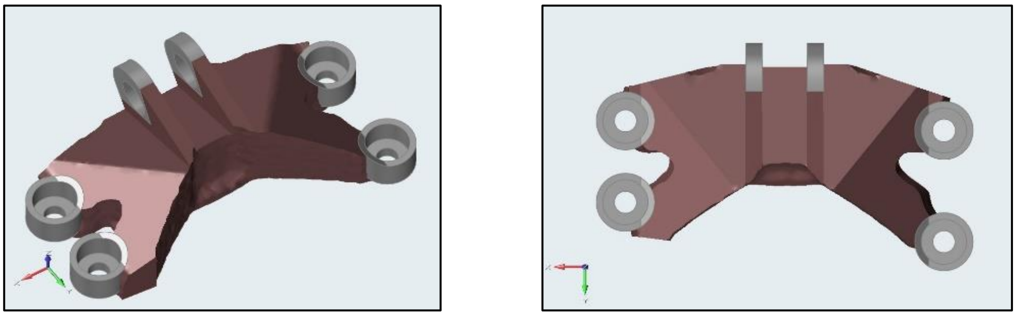
Top View



(c) Optimized geometry for 40% volume retention Top View



(d) Optimized geometry for 50% volume retention Top View

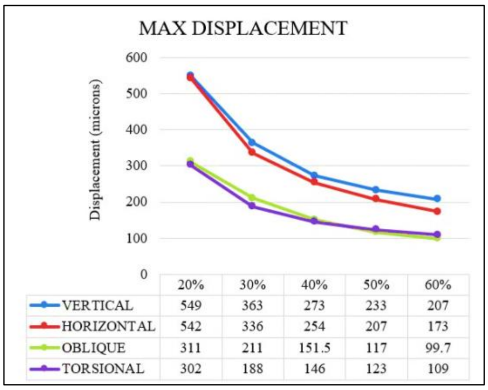


(e) Optimized geometry for 60% volume retention Top View

Fig. 10 Topology optimized geometries based on singledraw shape control for a (a) 20%, (b) 30%, (c) 40%, (d) 50% and (e) 60% volume retentions

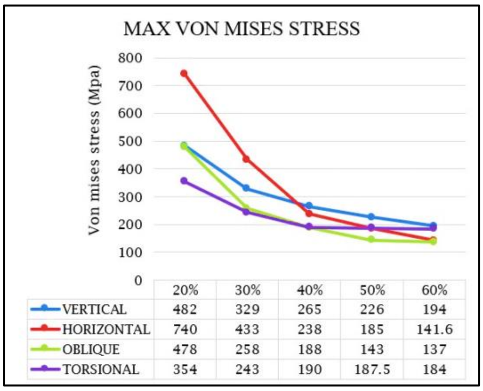
D. Post Optimization Analysis of all five optimized models based on shape control

As the analysis of all five optimized models is performed, it is very important to compare topology optimization results and the various structural parameters for each iteration. To confirm the structural stability, post-optimization analysis is carried out. A comparison chart of all the topology optimization is used to determine the system's best design solution. The results are summarized in Graphs. The X-axis represents 4 load cases, and Y-axis represents the min factor of safety, max Displacement, and max von mises stress.



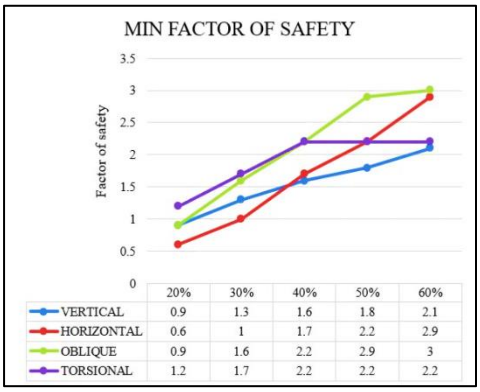
	20%	30%	40%	50%	60%
VERTICAL	549	363	273	233	207
HORIZONTAL	542	336	254	207	173
OBLIQUE	311	211	151.5	117	99.7
TORSIONAL	302	188	146	123	109

(a)



	20%	30%	40%	50%	60%
VERTICAL	482	329	265	226	194
HORIZONTAL	740	433	238	185	141.6
OBLIQUE	478	258	188	143	137
TORSIONAL	354	243	190	187.5	184

(b)



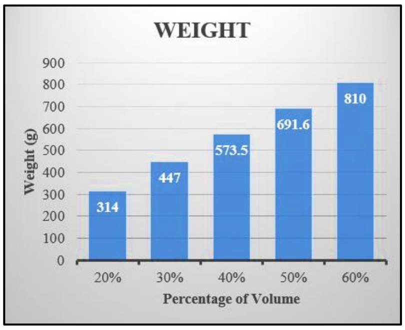
	20%	30%	40%	50%	60%
VERTICAL	0.9	1.3	1.6	1.8	2.1
HORIZONTAL	0.6	1	1.7	2.2	2.9
OBLIQUE	0.9	1.6	2.2	2.9	3
TORSIONAL	1.2	1.7	2.2	2.2	2.2

(c)

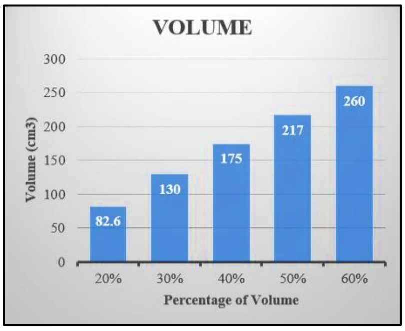
Fig. 11 (a), (b), (c) Post Optimization Analysis Results of all five optimized models

A minimum factor of safety should be 1.5, following the Federal Aviation Regulation (FAR 25). The topology optimized geometry based on single draw shape control for a 20% volume retention and 30% volume retention is rejected. It does not satisfy the min Safety factor of 1.5 as specified by Federal Aviation Regulation. The remaining 3 optimized models are compared based on Displacement, von mises stress, and weight.

From the above graphs, it can be seen that as the percentage of total design space volume of optimized models increases, Displacement and stress decreases with an increase in safety factor. The weight of the bracket also increases as a result. The optimized model with 40% volume retention has higher Displacement and stresses than the optimized model of 50% volume retention. Thus, it is not preferred. An optimized model with 50% volume retention has a little higher Displacement and stresses than an optimized model with 60% volume retention but is 119 grams lighter. Therefore, with the best balance among the Displacement, von mises stress, volume, and weight is the optimized bracket with a 50% volume retention of single draw shape control. Thus, an optimized bracket with a 50% volume retention is selected based on optimal results and weight.



(a)

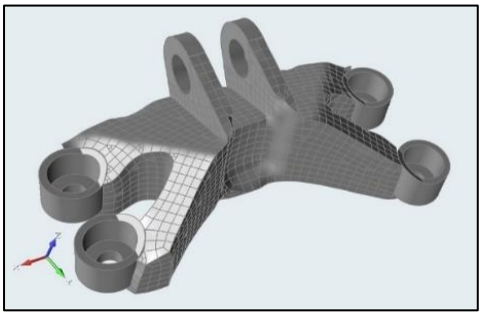


(b)

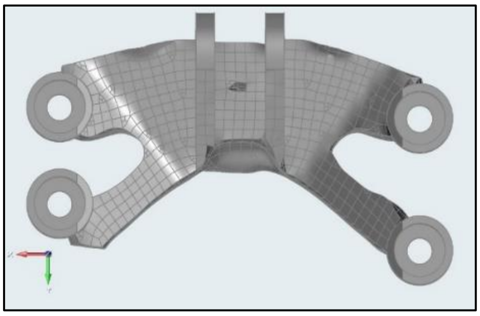
Fig. 12 (a) Weight and (b) Volume of all five optimized models

E. Smoothing Operation

Following the topology optimization stage, it is important to smooth the topology to reduce the element boundaries [15]. The final geometry resulting from the optimization algorithms is rough, in the sense that it is based on the initial tetrahedral finite element mesh. Inspire generates topology designs in a tessellated format, which may not be manufacturable. To make the topology design manufacturable, post-processing is usually required to identify, smooth, and parameterize the structural boundary [16]. Smoothing is the process of converting an optimized 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. Optimized shapes obtained in Inspire can only be exported in STL format (.stl) to other CAD software.



(a)



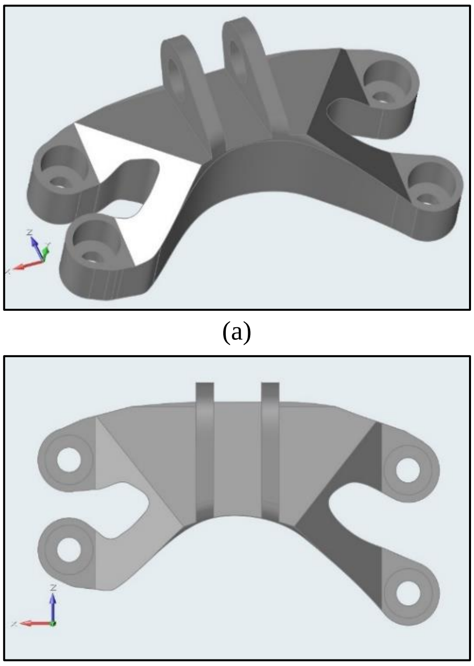
(b)

Fig. 13 (a) Smoothed geometry and (b) Top view

The algorithm used to smooth and trigger the surface is OS-Smooth by Altair. It is directly implemented inside the Inspire interface so that it is easier to export the optimization results directly in the CAD for the re-design phase. The optimized smoothed geometry, as shown in Fig. 13, is imported to SolidWorks 2013 for re-design.

F. Redesigned Model

Following the smoothing operation stage, it is needed to convert the smoothed geometry into a mathematical CAD representation. This stage is done manually by 'tracing' the optimized result. SolidWorks 2013 is used for re-designing the bracket by taking the optimized topology model as a reference. The simulated volume of the component is 281cm^3 and the weight is 787 grams. The result is a fully parameterized design.



(a)

(b)

Fig. 14 (a) Re-designed model and (b) Top view

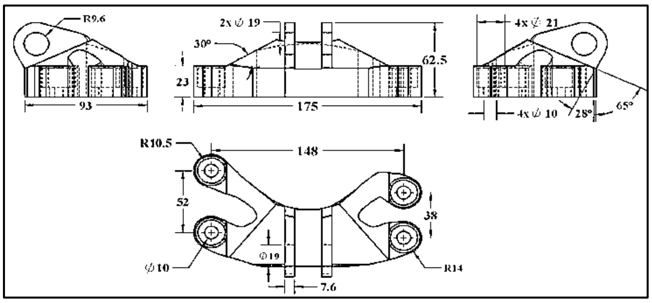
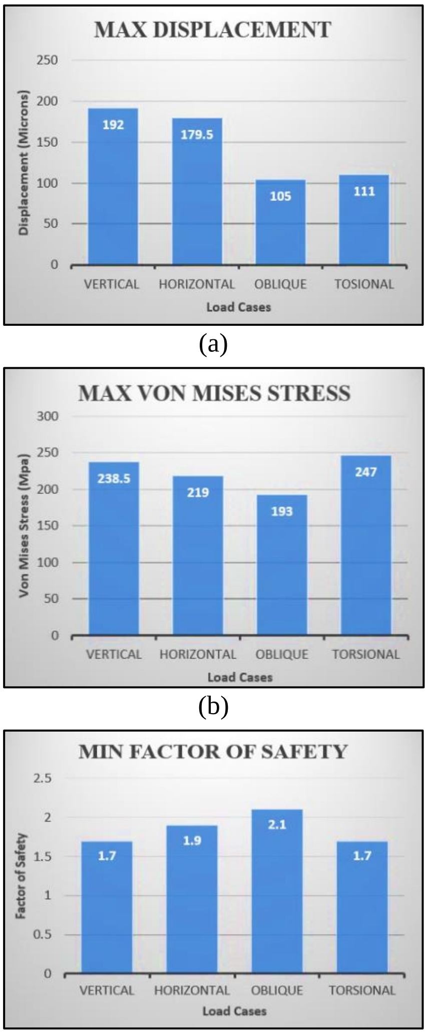


Fig. 15 Part drawing of the re-designed model

G. Analysis of Redesigned model

The re-designed model, as shown in Fig. 14, is then analyzed by applying the same boundary conditions as described in c' loads and boundary conditions'. The minimum Factor of safety of the final re-designed bracket is above the 1.5 mark for all load cases, which is satisfactory.



(a)

(b)

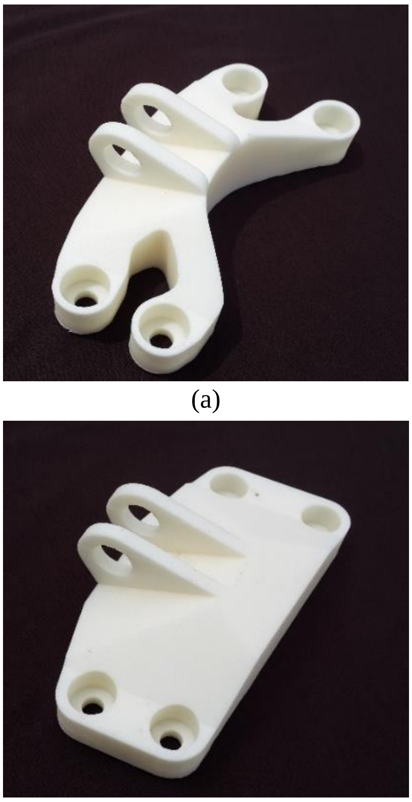
(c)

Fig. 16 (a) Maximum Displacement, (b) Maximum Von Mises Stress and (c) Minimum Factor of Safety of each load case

H. Prototype of Redesigned model and Original model

The Prototype of the re-designed and original model is printed in ABS plastic using the Fused Deposition

Modeling (FDM) technique. The Prototype is fabricated in Pramaan 300 printer. The infill percentage is set to 25%, and the minimum layer height is set to 0.2mm. The weight of the re-designed and original model in ABS is 135 and 193 grams, respectively. The support is only required in the clevis hole. The Printing took 10 and 11 hours for the re-designed and original model, respectively.



(a)

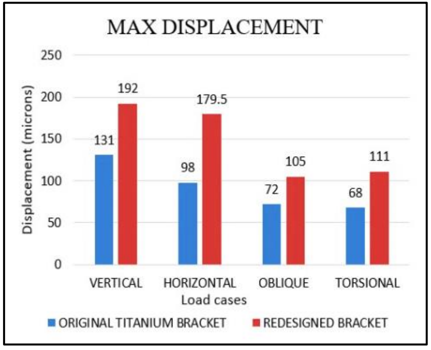
(b)

Fig. 17 Prototype of (a) Re-designed bracket and (b) Original bracket

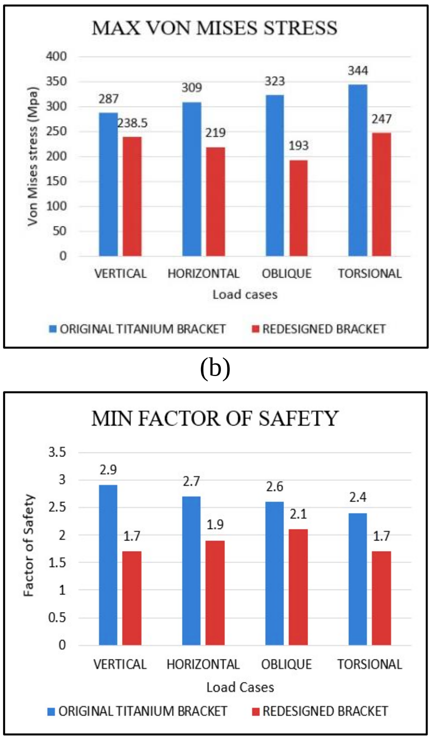
IV. RESULT AND DISCUSSION

A. Original Titanium bracket in comparison with Re-designed bracket

The original titanium bracket is compared with the optimized re-designed model. The minimum Factor of safety of the optimized re-designed bracket satisfies the 1.5 marks for all load cases. There is significant weight and stress reduction in the optimized re-designed bracket, although there is little increase in Displacement.



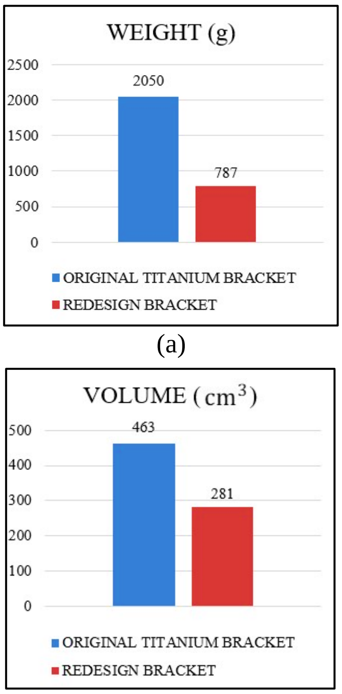
(a)



(b)

(c)

Fig. 18 (a), (b), (c) Comparison of original titanium bracket and re-designed bracket



(a)

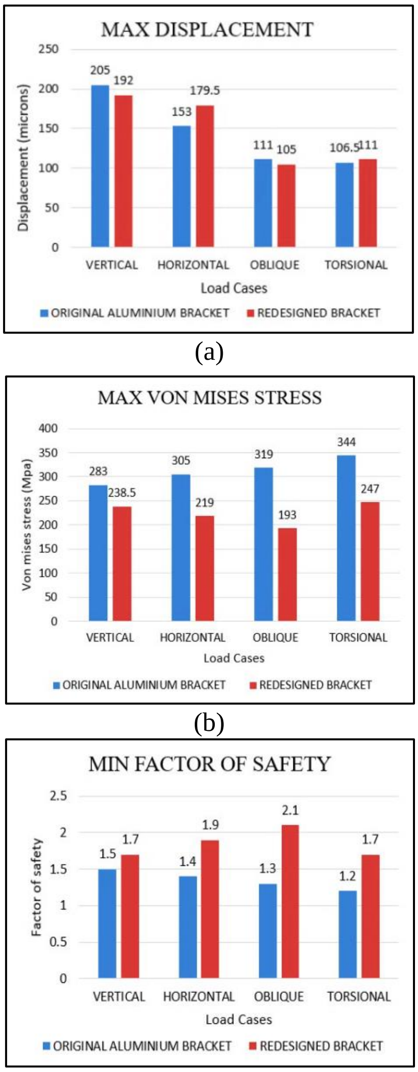
(b)

Fig. 19 (a) Weight and (b) Volume Comparison

There is significant stress reduction in the re-designed model, i.e., 17%, 29%, 40.2%, and 28.2% in vertical, horizontal, oblique, and torsional load cases. The volume of the re-designed bracket is a reduction from 463 to 281 cm^3 i.e. 39.3% reduction. The optimized re-designed model has a weight reduction of 1263g, which is 61.6% weight saving than the original titanium bracket.

B. Original Aluminium bracket in comparison with Re-designed bracket

Original Aluminium bracket (Pre-optimization) is compared with the re-designed model. The optimized re-designed model has greatly improved the bracket by reducing Displacement and stress while maintaining a Factor of safety above 1.5. Previously minimum Factor of safety for horizontal, oblique, and torsional load cases was below 1.5, which was not satisfactory, following the Federal Aviation Regulation (FAR 25). Still, after optimization and re-design, the Factor of safety has increased above 1.5.

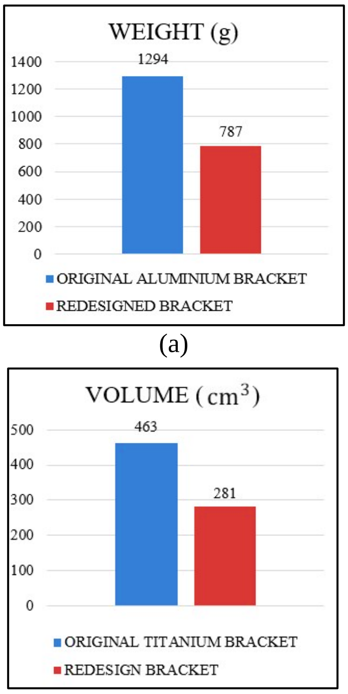


(a)

(b)

(c)

Fig. 20 (a), (b), (c) Comparison of original titanium bracket and re-designed bracket



(a)

(b)

Fig. 21 (a) Weight and (b) Volume Comparison

There are significant weight and stress reduction in the optimized re-designed model. It has a 6.3% and 5.4% lower displacement in vertical and oblique load cases. In comparison, horizontal and torsional load case has an increase in Displacement by 17.3% and 4.2%, which has a negligible impact on parts. The optimized re-designed model has 15.7%, 28.2%, 39.5%, and 28.2% stress reduction in vertical, horizontal, oblique, and torsional load cases. It has a volume reduction of 39.3% while the weight is reduced to 787g from 1294g, which is 507g, which is 39.18% weight saving.

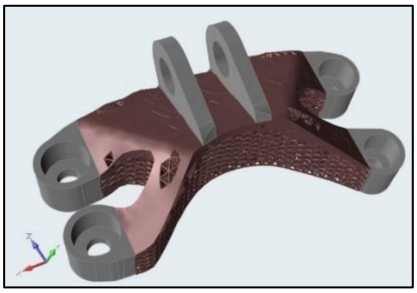
V. CONCLUSION

A. Conclusions

In comparison with conventional design, the advantages of topology optimization are demonstrated in the project. The re-design model results from a Topology optimization process with a weight reduction of 39.18% compared to the original bracket. The re-designed model has a stress reduction of 15.7%, 28.2%, 39.5%, and 28.2% in vertical, horizontal, oblique, and torsional load cases. It has a 6.3% and 5.4% lower displacement in vertical and oblique load cases. The successful reduction of weight, stress levels, and Displacement concerning the design space and the applied forces is achieved. This paper exemplified the potential of topology optimization as an emerging technology that will revolutionize many industries.

B. Future Scope

For future research, topology optimization combined with lattice is emphasized. It could be interesting to proceed with lattice incorporation into the final (re-designed) model while improving its stiffness to weight ratio. This uses the same principle of topology optimization. However, instead of adding or removing material, this technology uses lattice beams to fill in the structure. A lattice structure is an architecture formed by an array of unit cells' spatial arrangement with edges and faces [17]. Lattice optimization is an AM-specific shape control. It is a continuation of topology optimization, which assigns intermediary regions with a lattice [18]. Thus, it is a combination of lattice and topology optimization design. It is essentially a traditional topology optimization where solid elements are replaced with lattice beams. Lattice optimization can also be simulated for different percentages, which may further reduce material. Example of 50% and 100% lattice fill of the optimized topology model as shown in Fig. 22.


(a)

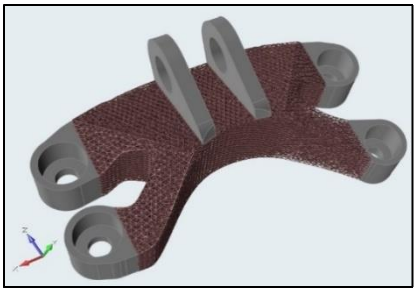

(b)

Fig. 22 (a) 50% and (b) 100% Lattice fill

This technology's limitation is that the optimal design can only be achieved by Additive Manufacturing technology, which can create this lattice structure and is not possible by conventional methods. This type of optimization is still under development and will replace topologically optimized solid parts with lattice structures.

REFERENCES

[1] Orme, M., Madera, I., Gschweitl, M., & Ferrari, M. (2018). Topology optimization for additive manufacturing as an enabler for lightweight flight hardware. Designs, 2(4) 51.

[2] Lim, S. T., & Wong, T. T. (2018, November). Unleash the potential of additive manufacturing with topology optimization. In AIP Conference Proceedings. 2035(1) 040007. AIP Publishing LLC.

[3] Rozvany, G. I. A critical review of established methods of structural topology optimization. Structural and multidisciplinary optimization, 37(3) (2009) 217-237.

[4] Reddy K, S. N., Ferguson, I., Frecker, M., Simpson, T. W., & Dickman, C. J. Topology optimization software for additive manufacturing: A review of current capabilities and a real-world example. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 50107 (2016) V02AT03A029. American Society of Mechanical Engineers.

[5] Morgan, H. D., Levatti, H. U., Sienz, J., Gil, A. J., & Bould, D. C. GE Jet engine bracket challenge: a case study in sustainable design. Sustainable Design and Manufacturing. (2014) 95-107.

[6] Seong, S., Younossi, O., & Goldsmith, B. W. Titanium: industrial base, price trends, and technology initiatives. Rand Corporation (2009).

[7] Norgate, T. E., Jahanshahi, S., & Rankin, W. J. Assessing the environmental impact of metal production processes. Journal of Cleaner Production, 15(8-9) (2007) 838-848.

[8] Lu, X., Hiraki, T., Nakajima, K., Takeda, O., Matsuabe, K., Zhu, H. M., ... & Nagasaka, T. Thermodynamic analysis of separation of alloying elements in the recycling of end-of-life titanium products. Separation and purification technology, 89 (2012) 135-141.

[9] Carter, W. T., Erno, D. J., Abbott, D. H., Bruck, C. E., Wilson, G. H., Wolfe, J. B., ... & Stevens, R. G. The GE aircraft engine bracket challenge: an experiment in crowdsourcing for mechanical design concepts. In Solid Freeform Fabrication Symposium (2014) 1402-1411.

[10] Kavita, Rakesh Saxena, Lalit Ranakoti, Ashish Bedwal. Topological Optimization using Guide Weight Method. SSRG International Journal of Mechanical Engineering 2(7) (2015) 18-22.

[11] Tomlin, M., & Meyer, J. Topology optimization of an additive layer manufactured (ALM) aerospace part. In Proceeding of the 7th Altair CAE technology conference. (2011) 1-9.

[12] Ferro, C., Grassi, R., Seclì, C., & Maggiore, P. Additive manufacturing offers new opportunities in UAV research. Procedia CIRP, 41, 1004-1010 (2016).

[13] Patil, A. V., Kumar, R. C., & Patel, R. Topology Optimization of a Lower Barrel in Nose Landing Gear. International Research Journal of Engineering and Technology (IRJET). 6(6) (2019) 1493.

[14] Junk, S., Klerch, B., Nasdala, L., & Hochberg, U. Topology optimization for additive manufacturing using a component of a humanoid robot. Procedia CIRP. 70 (2018) 102-107.

[15] Brackett, D., Ashcroft, I., & Hague, R. Topology optimization for additive manufacturing. In Proceedings of the solid freeform fabrication symposium, Austin, TX. 1 (2011) 348-362.

[16] Vipul Matariya, Hiren Patel, Topological Optimization of Automobile Rotor Disk Brake, SSRG International Journal of Mechanical Engineering 6.4 (2019) 23-27.

[17] Walton, D., & Moztarzadeh, H. Design and development of an additive manufactured component by topology optimization. Procedia CIRP, 60 (2017) 205-210.

[18] Tao, W., & Leu, M. C. (2016, August). Design of lattice structure for additive manufacturing. In 2016 International Symposium on Flexible Automation (ISFA) 325-332. IEEE.

[19] Liu, J., & Ma, Y. A survey of manufacturing-oriented topology optimization methods. Advances in Engineering Software, 100 (2016) 161-175