THE CONVERGENCE OF COMPOSITES AND TOPOLOGY OPTIMIZATION, USHERING IN THE NEXT ERA OF AIRCRAFT LIGHTWEIGHT STRUCTURES

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ABSTRACT

Although advanced composite material outperforms metal on material data sheets, actual composite structures often fail to provide a significant improvement. In part, this is due to the application of design approaches that were originally meant for metallic constructions. As a result, advanced composite structures end up having a redundant layup, with a quasi-isotropic stacking sequence that eliminates anisotropy, instead of leveraging it, so called black aluminum. Today's approach to take better advantage of continuous carbon fiber's mechanical properties, fibers are aligned based on the anticipated loading conditions. This can be achieved using hand layup or automated tape layup (ATL) / automated fiber placement (AFP) techniques. Though this provides a significant improvement over the "black aluminum" approach, it still falls short of realizing the full potential of continuous fiber anisotropy. Since carbon fibers perform best in tension, the part itself should be redesigned to take advantage of this effect. Though this exercise may seem intuitive for simple parts, in the aerospace industry these coupled design activities easily become non-intuitive due to the complex loading conditions the aircraft structures are subjected to.

Arris Composites has developed a new process, additive molding™, capable of manufacturing complex geometries, using continuous fiber. This paper presents optimizing topology and fiber orientation for an aerospace bracket, having complex 3D load cases. These optimized structures are shown to outperform current composite structures as well as structures machined and 3D printed from metal, making them ideal for next generation aerospace brackets and joining structures.

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1. INTRODUCTION

The A350XWB and B787 programs are the first large-scale commercial programs to develop composite-intensive aircraft with a composition of about 80% composite materials by volume [1]. Reports on the costly investment of these clean-sheet designs [2] suggest that next-generation aircraft structures will likely be based upon derivatives of these models. Yet light weighting challenges still abound within these programs and the upcoming ones. Particularly, for brackets whose function is to transfer load from one mechanical interface to another. These aerospace applications still lack a complete advanced composites solution. While commercial support of simulation tools is currently emerging for metallic additive manufacturing processes, advanced composites manufacturing processes still lack such support. For instance, most leading vendors of finite element analysis packages have recently added topology optimization features for isotropic materials, yet topology optimization for fiber-reinforced composite structures is still not supported.

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On the academic front, several research papers have already focused on topology optimization of continuous fiber-reinforced composites [3-4] and the academic community appears to have settled on a few benchmark problems, like the three-point flex problem, so-called the Messerschmitt-Bölkow-Blohm (MBB) beam. However, these problems are simplified for purposes of benchmarking. Thus, the challenge of applying topology optimization and finite element analysis techniques to aerospace composite structures remains.

This paper aims to explore the potential benefits of applying a simultaneous topology and fiber orientation optimization toolset to 3D aerospace composite structures. Although care to experimentally verifiable performance measures has been given, the exploration is numerical in nature. The remainder of this paper is structured as follows. Section 2 presents the methodology used to apply this toolset during the design process. The results of applying the methodology of Section 2 on two case studies are presented and discussed in Section 3. Finally, Section 4 overviews the benefits and limitations of using a toolset based on topology optimization and finite element analysis techniques.

2. METHODOLOGY

Computer-driven optimization requires a parametric model of the product under design. These parameters can represent geometry like the thickness of a plate under sizing optimization, or material properties like free material optimization [5], where the stiffness coefficients are under design. Moreover, these parameters can be lumped like the layer orientation of uni-directional (UD) composite laminates or spatially distributed. For instance, topology optimization, as formulated by Bendsoe and Sigmund [6], parameterizes the shape of a structural component by assigning a fictitious density to all the points of the design space and labeling them as being part of the component or not. Thus, topology optimization is a spatially distributed parameterization of geometry. Subsection 2.1 presents the design parameterization used by Arris Composites toolset. The probability of significantly improving the performance of the design increases with more parameters. However, the computational cost and non-convexity increases as well. Non-convexity is simply defined in this paper as the number of local optima that arise and where the optimizer might get stuck.

Once the design is parameterized, the design variables are to be optimized based on key performance criteria. These criteria are mathematically formulated in terms of objective functions and constraints in what Subsection 2.2 calls an optimization problem statement.

2.1 Design parameterization

To formulate a topology optimization problem, one must define a volumetric space where the simulation is allowed to add or remove material, and onto which load and boundary conditions are applied. This design space is then discretized into finite elements to make the problem amenable to finite element analysis. Moreover, these finite elements are used to spatially discretize the so-called density field into variables that describe the presence of material in a given element. A density value of 0 denotes a void (i.e., material is removed), while the value of 1 denotes the presence of material in that finite element. Each finite element is also parameterized with a vector, u that describes the orientation of the fiber at the centroid of such finite element [3-4].

The parameterization of the stiffness matrix as a function of the design variables x and u is accomplished by using a stiffness matrix, computed as:

$$C = E_L(x)[T_\sigma(u)]\big[\hat{C}\big][T_\epsilon(u)] \qquad [1]$$

where, E_L is the Young modulus along the direction of the fiber,

$[T_\sigma]$ and $[T_\epsilon]$ are the stress and strain coordinate transformation matrices, and

$\hat{C}$ is a normalized transversely isotropic stiffness matrix given by

$$C^{-1} = \begin{bmatrix} 1 & -v_{LT} & -v_{LT} & & & \\ -v_{LT} & \frac{E_L}{E_T} & -\frac{E_L v_{TT}}{E_T} & & \ddots & \\ -v_{LT} & -\frac{E_L v_{TT}}{E_T} & \frac{E_L}{E_T} & & & \\ & & & \frac{2(1+v_{TT})E_L}{E_T} & 0 & 0 \\ & \ddots & & 0 & \frac{E_L}{G_{LT}} & 0 \\ & & & 0 & 0 & \frac{E_L}{G_{LT}} \end{bmatrix} \qquad [2]$$

Where $E_L, E_T, v_{LT}, v_{TT},\ G_{LT}$ are the engineering constants of a transversely isotropic material, and their subscripts L and T denote the fiber direction and the plane of isotropy perpendicular to it, respectively.

2.2 Optimization problem statement

The challenge of light-weighting a load bearing structure made with continuous carbon fiber composite can be formulated as a multi-objective minimization problem

$$\begin{aligned} &\min_{\boldsymbol{x},\boldsymbol{u}} (\boldsymbol{U}(\boldsymbol{x}), \boldsymbol{r}(\boldsymbol{u})) \\ &\boldsymbol{subject} \quad \frac{\boldsymbol{V}}{\boldsymbol{V_0}} \leq \boldsymbol{\eta} \\ &\qquad\qquad \boldsymbol{0 \leq x \leq 1} \end{aligned} \qquad [3]$$

Where $\boldsymbol{U}$ denotes the strain energy and measures global stiffness

$\boldsymbol{r}$ denotes a vector of failure indices, one per each finite element, and measures local strength.

The light-weighting criteria is formulated as a constraint to achieve a target volume fraction, η. Finally, the densities are bounded to values between 0 and 1 [7].

A traditional approach to solving this problem is to sequentially design the topology using a proxy isotropic material and thereafter optimize the fiber orientation for the previously optimized shape. This approach, called hereafter sequential design, decouples each design activity and provides a flexible toolbox to design from functional requirements or with legacy structural shapes. However, it does not account for the anisotropy of the reinforcement during the shape definition stage, resulting in not leveraging the full design latitude of design for functional requirements.

Taking advantage of the anisotropy of the reinforcement requires solving the topology and fiber orientation simultaneously. Moreover, the solution to this optimization problem shall be implemented in such a way that both a sequential or simultaneous approach is available to the user. The solution to this problem must use computer resources efficiently to scale up to many parameters. Finally, it also requires a manufacturing process capable of aligning the fibers along the complex shapes that may result thereof.

3. RESULTS

This section presents the results of applying the Arris Composites toolset to a couple case studies. Section 3.1 studies the design of a three-point bending beam, so called MBB beam, with the purpose of verifying the Arris Composites toolset against state-of-the-art topology optimization results. Section 3.2, on the other hand, serves as a demonstrator of the light weighting benefits that can be obtained on aerospace bracket design. Finally, Section 3.3 discusses the experimental results from the comparative testing, done by Northrop Grumman, between a titanium baseline T-bracket and an Additive Molded Aligned T800/PEEK composite bracket.

3.1 MBB Beam

The classic MBB problem is a simply supported 2D beam, subjected to a vertical point load at mid-length. As shown by Andreassen et al. [7], the optimal shape after performing an isotropic topology optimization on the MBB beam is a Warren-type truss, where the bar arrangement shows equilateral triangle patterns. Figure 1 verifies that the same topology is obtained when applying the herein proposed methodology with an isotropic material. However, Figure 2 shows that when using a simultaneous approach, the optimized shape converges to a topology reminiscent of a Bowstring-type truss. A Bowstring truss connects the top curved chord with the bottom horizontal chord with diagonal struts.

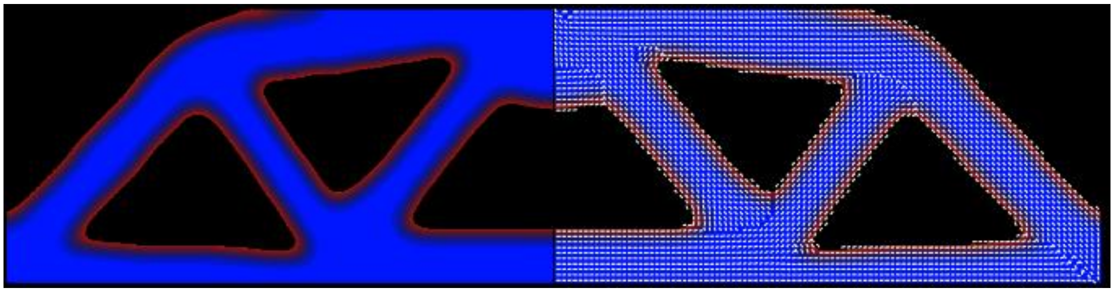

Figure 1. Optimized shape of an isotropically optimized MBB beam. The left side shows a solid view of the shape, while the right side plots the a-posteriori aligned fiber orientations.

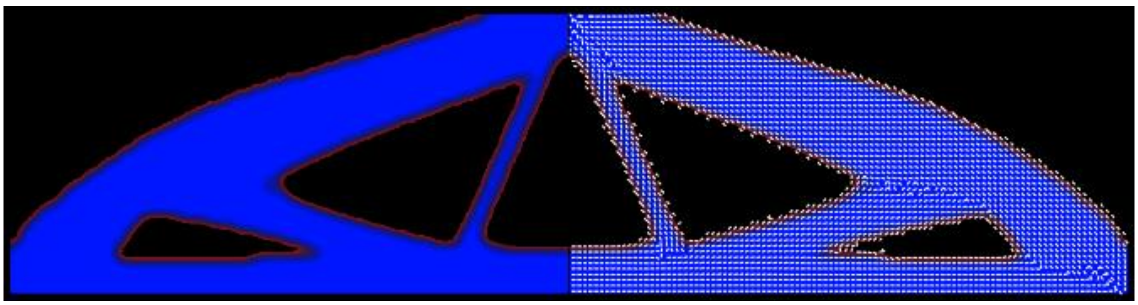

Figure 2. Optimized shape of a simultaneously optimized MBB beam. The left side shows a solid view of the shape, while the right side plots the aligned fiber orientations.

Figure 3 shows the convergence history of both optimizations by plotting the variation of the objective function, normalized with respect to the initial value, as the number of iterations increases. Compared to the isotropic optimization run, the simultaneous optimization converges to a smaller value of the objective function, suggesting improved stiffness for the same weight reduction.

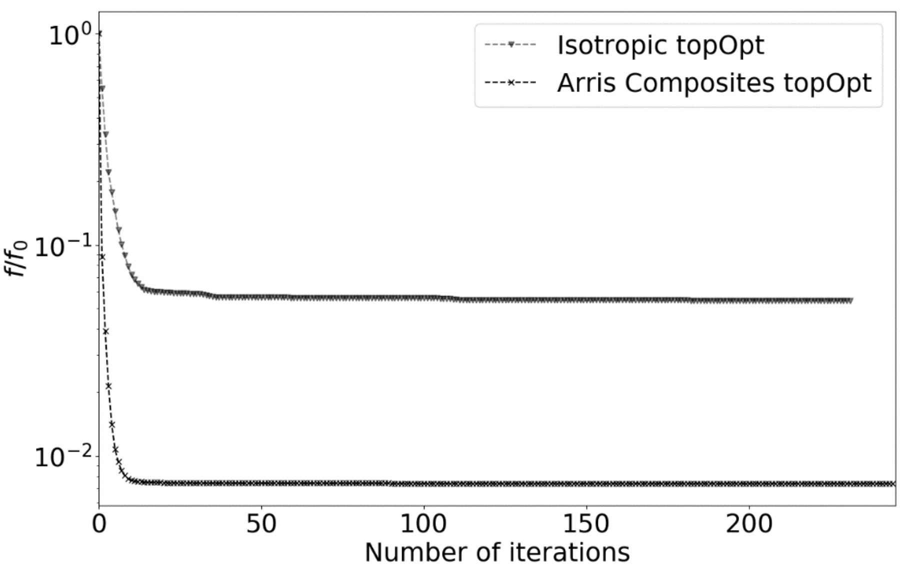

Figure 3. Convergence history of the normalized objective function for both MBB optimizations.

3.2 Aerospace bracket

The aerospace bracket under study is shown in Figure 4. The bracket has 5 mechanical interfaces. The top bolt hole is connected to a tie rod which applies a horizontal force (contained in the midplane and parallel to the plane of the bottom face), while the remaining four bolt holes are mounted onto an infinitely rigid plate. The finite element model applies the horizontal force using rigid body constraints on the inner face of the bolt hole, and fixes all degrees of freedom of the remaining four bottom holes.

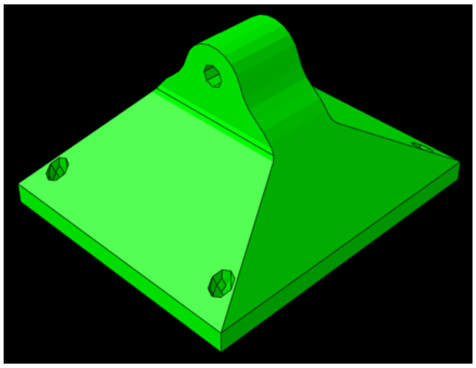

Figure 4. Design space of an aerospace bracket.

Figure 5 shows the resulting shape after running an isotropic topology optimization for 100 iterations with a light weighting target of 70% weight reduction. The isotropic material was the common aluminum alloy 6061-T6. On the other hand, the optimized shape obtained after running 100 iterations a simultaneous optimization, with the same light weighting target, is shown in Figure 6. The thermoplastic T800/PEEK material was used for the simultaneous optimization. Note Figure 6 also shows the fiber orientation vector plot.

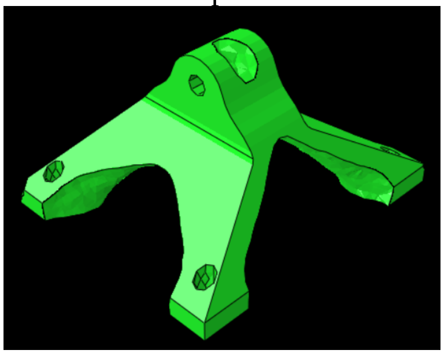

Figure 5. Resulting aerospace bracket design after an isotropic optimization.

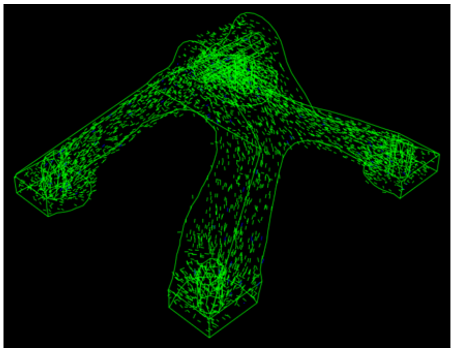

Figure 6. Resulting aerospace bracket design after a simultaneous optimization.

Both shapes connect the fixed interfaces with the top loaded bolt hole using uniaxial members. However, while the isotropically optimized bracket exhibits a webbing between the two lateral legs, the simultaneous optimization prefers to shift the anisotropic material along the axis of each leg.

Figure 7 shows the convergence history of both optimizations by plotting the variation of the objective function, normalized with respect to the initial value, as the number of iterations increase. Compared to the isotropic optimization run, the simultaneous optimization converges to a smaller value of the objective function, suggesting improved stiffness for the same weight reduction.

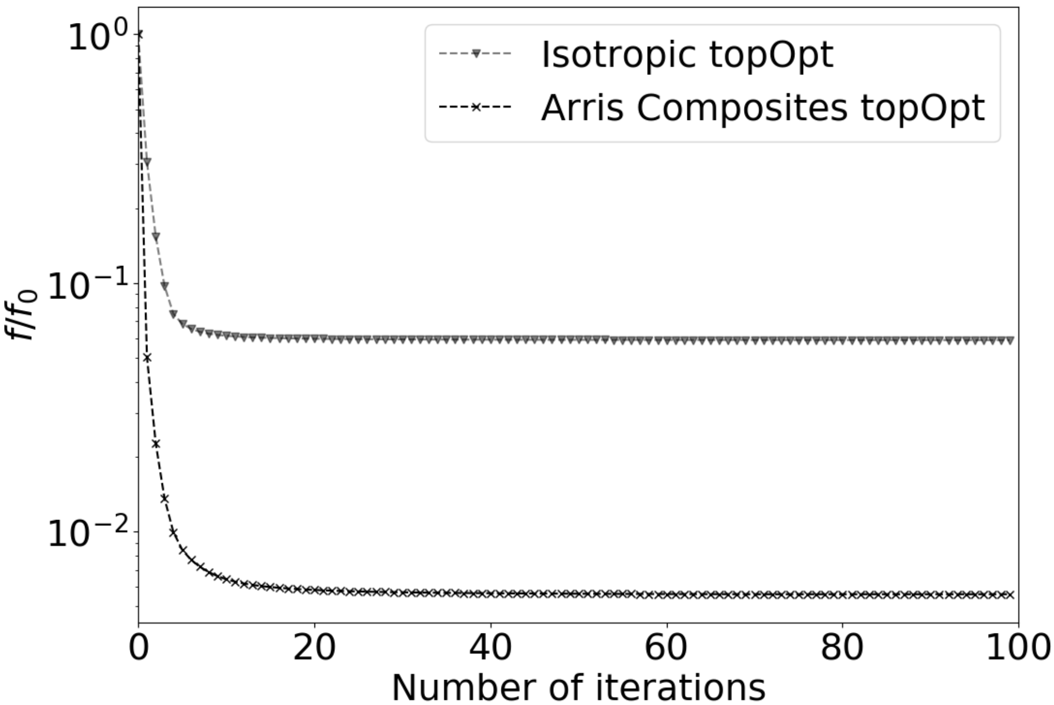

Figure 7. Convergence history of the normalized objective function for both bracket optimizations.

To more accurately compare these designs in terms of stiffness, a post-optimality analysis was performed and the displacement of the centerline of the top bolt hole was used as the measurement of stiffness. This measurement is more amenable to correlation with experimental data. Figure 8 shows the tip displacement and weight, normalized with respect to the displacement and weight of the baseline design of Figure 4, for four configurations:

1. the isotropically optimized design shows a reduction in stiffness of 35.67% when the weight is reduced by 70.00%;

2. if the same isotropically optimized (QI) shape where to be made with a non-continuous carbon fiber composite that has randomly oriented chopped fibers, and thus can be modeled

as quasi-isotropic in 3D, the weight reduces by 81.52% but the stiffness also suffers a large reduction of 72.37%. Thus, having a very light yet very flexible bracket.

3. Aligning fibers along the uni-directional members of the isotropically optimized shape shows a significant numerical increase of stiffness retention. The stiffness is now reduced by only 19.25%. Since the material has not been changed, but optimally placed, the weight reduction is roughly the same as 81.52%.

4. However, using the simultaneous optimization approach the design weight is also reduced by 81.52% but the stiffness with 96.67% retention remains practically the same as the original aluminum baseline. And compared to a sequential approach of case 3 is 16.10% stiffer.

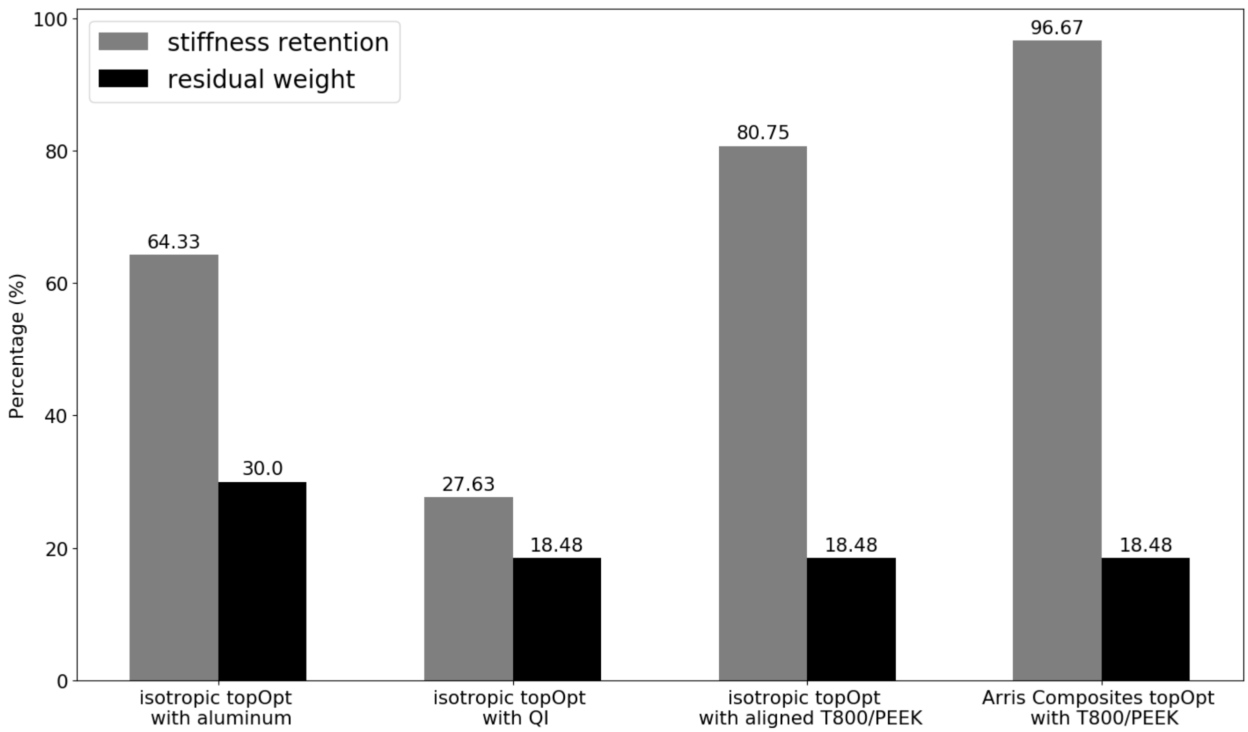

Figure 8. Stiffness and weight reduction of 3 light weighted design configurations as compared to the baseline design of Figure 4.

3.3 Comparative Testing by Northrop Grumman of Titanium Baseline T- Bracket to Additive Molded Aligned T800/PEEK Composite Bracket

Northrop Grumman [8] performed a comparative mechanical destructive testing of its typical baseline titanium T-Plate bracket to the additive molded aligned T800 Carbon Fiber/PEEK bracket design supplied by Arris. From the Figure 9 comparative Force vs. Deflection curves, the additive molded 4-prong T800/PEEK bracket failed at ~93% of the force at which the titanium bracket failed but revealed similar stiffness as shown by the similar slopes of their respective Force vs. Deflection curves. More important, the composite bracket weighed only 16 grams in comparison to the 56 grams for the optimized titanium bracket; an approximate 71% weight reduction. The results are summarized in Figure 10.

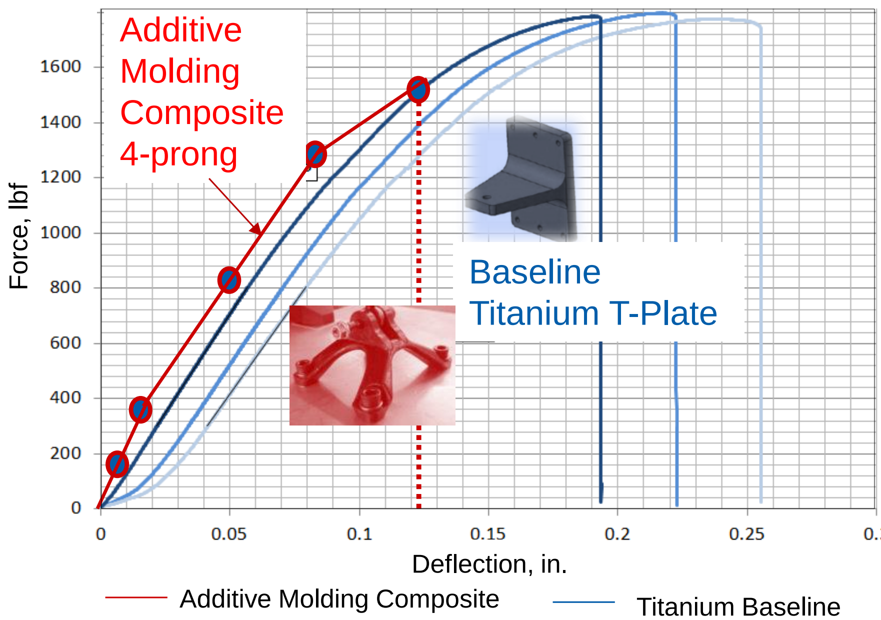

Figure 9. Comparative Force vs. Deflection Curves between Baseline Titanium T-Plate Bracket under bending and the Additive Molded Composite 4-Prong T800/PEEK Arris Bracket under tension.

		Weight	Comments
Baseline 3D Printed Titanium T-Bracket		76 gms	Part that is Not Optimized for Weight Savings
Optimized 3D Printed Titanium 6-Prong Bracket		56 gms	30% Lighter Weight vs. Baseline 3D Printed Titanium
Additive Molded Continuous Carbon Fiber Composite 4-Prong Bracket		16 gms	71% Lighter Compared to Optimized 3D Printed Titanium

Figure 10. Comparative Weight Between Titanium and Additive Molded Composite Brackets

4. CONCLUSIONS

A design parameterization based on discretizing the design space with finite elements was proposed in Section 2.1. This design parameterization was applied on 2D MBB and 3D aerospace bracket case studies, in Section 3, by using the Arris Composites toolset.

Numerical results suggest that using a simultaneous optimization approach not only provides a T800/PEEK bracket design that is lighter than an isotropically optimized titanium, but also can be just as stiff as the original overweight titanium baseline. Experimental results further confirmed these numerically predicted benefits.

5. ACKNOWLEDGEMENT

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