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DESIGN OPTIMIZATION OF COMBAT VEHICLE DRIVER'S SEAT USING ADDITIVE MANUFACTURING AND COMPRESSION MOLDING

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ABSTRACT

This paper focuses on the application of a novel Additive Molding™ process in the design optimization of a combat vehicle driver's seat structure. Additive Molding™ is a novel manufacturing process that combines three-dimensional design flexibility of additive manufacturing with a high-volume production rate compression molding process. By combining the lightweighting benefits of topology optimization with the high strength and stiffness of tailored continuous carbon fiber reinforcements, the result is an optimized structure that is lighter than both topology-optimized metal additive manufacturing and traditional composites manufacturing. In this work, a combat vehicle driver's seatback structure was optimized to evaluate the weight savings when converting the design from a baseline aluminum seat structure to a carbon fiber / polycarbonate structure. The design was optimized to account for mobility loads and a 95-percentile male soldier, and the result was a reduction in weight from 18 to 3.6 pounds, which was an 80% weight savings. One critical design feature identified in the seatback was the location where the seatbelt loop attached to the seat structure. This novel manufacturing process enabled the optimized design to utilized fibers oriented around the attachment points, which is not possible in traditional composites manufacturing. A subscale bracket was manufactured and experimentally tested to simulate the performance of the carbon fiber / polycarbonate material in the location of the seatbelt loop.

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1. INTRODUCTION

As the Army modernizes the ground vehicle fleet with autonomous capability, active protection systems, and advanced propulsion systems, the packaging space within the vehicles becomes more constrained, and the need for lightweight, optimized structures becomes greater. With the added capabilities of sensor packages and improved lethality, the added weight of these sub-systems must be offset by reducing parasitic weight of non-ballistic structures and structural components in the vehicle. The US Army's Lightweight Combat Vehicle S&T campaign identified design optimization and additive manufacturing as two key enablers in improving the weight to performance efficiency of ground combat vehicles [1], [2]. Gerth and Howell identified four operational considerations where lightweight combat vehicles become advantageous: operational energy usage, air transportability, combat effectiveness, and freedom of movement [3]. Lightweight ground combat vehicles may have improved mobility in combat, thus leading to fewer hits sustained and more favorable outcomes, while also reducing the logistics burden in theater [4]. Today, the case for reducing the weight of ground combat vehicle structures is stronger than ever, however the Army needs materials that can perform in extreme dynamic environments while still remaining relatively low in cost.

Fiber-reinforced thermoplastic composites have been growing in popularity in recent years due to their high toughness, rapids cycle times, inherent recyclability. In the automotive industry, carbon fiber reinforced thermoplastics show potential to reduce weight and improve energy absorption capabilities compared to sheet metal structures [5, 6, 7, 8]. One barrier to implementing thermoplastic composites in ground combat vehicles is the flame, smoke, and toxicity performance of the thermoplastic matrix. In the commercial automotive industry, the flammability considerations [9] are less severe than in military ground vehicles which are subjected to extreme environments, like underbody blast events. With proper material selection, fiber reinforced thermoplastics can be utilized in combat vehicle applications, as was found in a prior effort designing a thermoplastic carbon fiber / polyphenylene sulfide (PPS) crew floor that was found to be over 50% lighter and cost neutral compared to a machined aluminum baseline [10]. Erb et. al. characterized the flame, smoke, and toxicity characteristics of carbon fiber and fiberglass reinforced thermoplastics, including: PPS, polycarbonate (PC), and polyethylene terephthalate (PET) [11]. For larger components or areas in the vehicle at high risk of fire, PPS was the preferred matrix material of choice due to its superior performance in the ASTM D3801 vertical burn test and ASTM D1354 Heat and Visible Smoke test [12, 13], however for smaller components where the risk of fire was lower, PC can be considered to have sufficient performance at a significantly reduced cost compared to PPS. While traditional composite manufacturing methods can be expected to reduce weight by 20-50% compared to traditional metallic designs, there are design limitations, especially related to the ability to leverage topology optimization.

Arris Composites has developed a unique combination of design simulation tools for anisotropic continuously reinforced composite parts and an Additive Molding ™ manufacturing method that combines the production agility of additive manufacturing with the cost benefits and speed of traditional molding technologies.

To use advanced (continuous fiber) composites at high volume, three key factors must be addressed: aligning composite fibers for optimal material performance and minimal material usage, producing optimized structural designs, and employing a low cost / high speed manufacturing process. Arris Composites has addressed these factors with the development of a unique process, Additive Molding™, which combines high performance aligned thermoplastic composite processing methods from aerospace, design latitudes from 3D printing, and existing low cost, high volume production and automation methods. Secondary factors that drive business and technical cases for employing Additive Molding™ for vehicle lightweighting include part consolidation, multi-functional multi-material structures and an efficient recycling / remanufacturing process which employs waste streams as feedstock for a second-generation product

2. METHODS

The objective of this effort was to design a lightweight composite driver's seat for a ground combat vehicle (see Fig. 1) using fiber-reinforced thermoplastic composites and the Additive Molding™ manufacturing process. Due to the severe operating environment of a combat vehicle, the driver's seat would need to be tolerant of extreme dynamic mobility loads (see Fig. 2.), varying thermal loads (from arctic to desert climates), as well as resistance to flammability, smoke generation, and toxicity (FST).

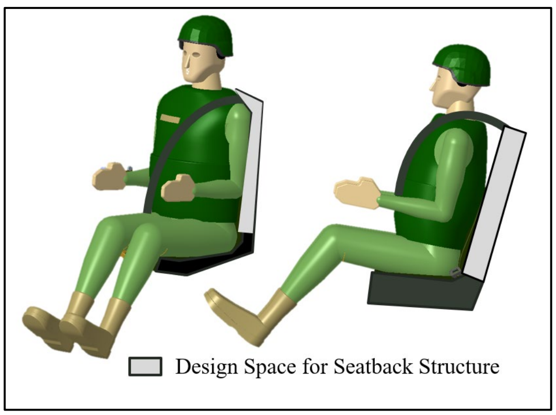

Figure 1: Representation of a 95th-percentile male soldier seated with the allowable design space for the optimized seatback structure defined.

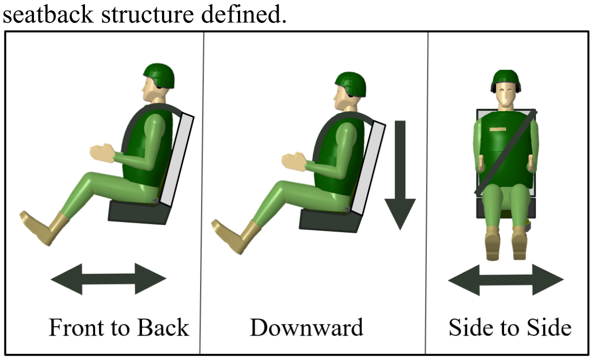

Figure 2: Mobility load cases used for optimizing the design of the driver's seatback structure.

The development effort included optimizing the design of the composite seat structure with tailored fiber orientations, finite element analysis of the mobility load cases, and manufacturing and testing of a sub-scale component.

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 [14], 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 [15], 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 [16-17].

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: [1]

$$C = E_L(x)[T_\sigma(u)]\left[\hat{C}\right][T_\epsilon(u)]$$

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 [2]

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

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 [3]

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

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 [18].

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. Arris Composites, Inc., patented Additive Molding ™ provides a solution to this problem. [19].

2.3. Sub-Scale Manufacturing and Testing

Due to scope constraints, it was agreed with the Army sponsor that a proxy part would be delivered and tested in lieu of a full or partial seatback geometry. The chosen proxy part is a 4-prong bracket (aka quad bracket), developed internally by Arris previously, which is loaded analogously to the seatbelt attachment hole on the seatback component (see Fig. 3). Quad bracket performance was assessed both in simulation and empirically.

The comparison between the simulated and actual performance of the quad bracket informs the simulation accuracy in a representative manner, thereby providing proxy verification of the seatback simulation results.

Specifically, continuous and aligned fibers surrounding a hole at which force is applied are

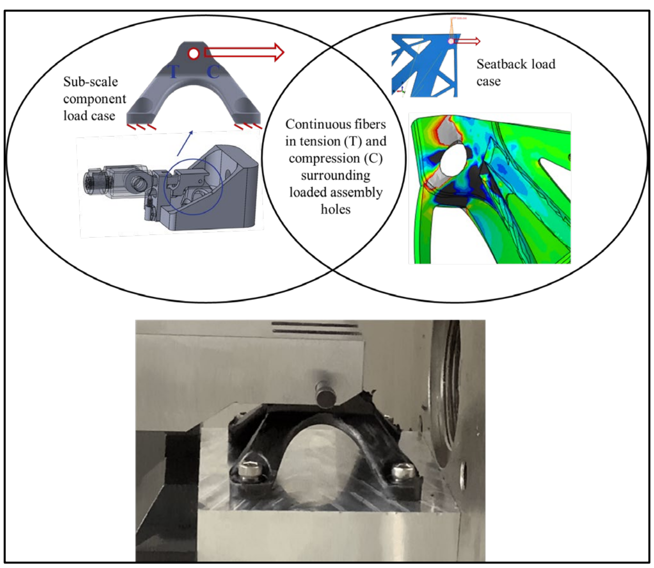

Figure 3: Schematic showing the testing conditions of the sub-scale component used to represent the stress state of the carbon fibers around the seatbelt loop mounting location.

stressed in tension and compression within both the seatback and quad bracket, with stiffness as the resultant assessment criteria. The same simulation method is used for both parts, so accuracy of results is independent of geometry and size.

This verification by proxy is NOT intended to substitute empirical testing of the actual seatback component, but rather to feasibly provide as relevant data as possible to inform simulation accuracy within scope constraints. Results will be relevant and informative but not exhaustive or conclusive

3. RESULTS AND DISCUSSION

Simulation accuracy of the redesigned seatback was gauged through simulation and empirical testing of quad bracket stiffness. Six samples were tested, all manufactured with consistent parameters, and the average measured stiffness compared to the simulation's predicted stiffness. The primary assessment criteria for testing of the quad bracket part was consistency across samples (i.e. precision), while comparison between empirical and simulated results (i.e. accuracy) was secondary. Precision being the primary criteria evaluates Arris' capability to consistently product complex parts having continuous fiber alignment, while accuracy being the secondary criteria informs factor of safety specification. Without precision, factor of safety accuracy would thus be inconsistent.

Figure 4 depicts the quad bracket force vs. displacement trend predicted by simulation (SIM, dashed line), as well as the measured force vs. displacement trends of the six samples (TQB3-8, solid lines). For the tested sample set, the average measured stiffness was 4094.84 N/mm, with a standard deviation of 366.73 N/mm and coefficient of variation (CV) of 8.96%. The simulation predicted stiffness was 5820.17 N/mm. The percent

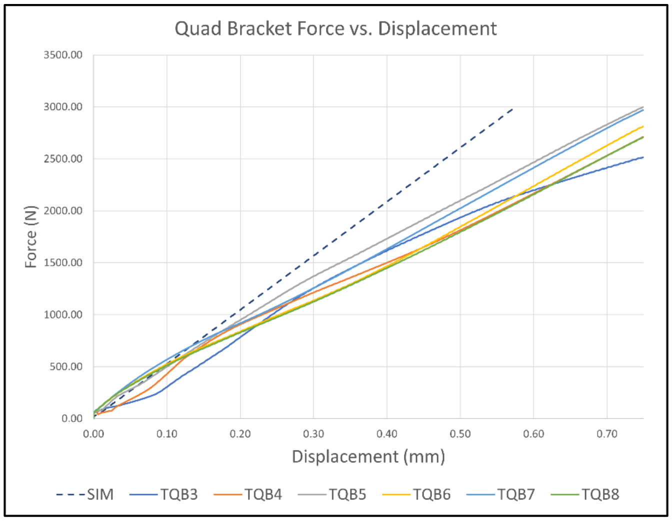

Figure 4: Graph showing the quad bracket force vs. displacement trend predicted by simulation (SIM, dashed line), as well as the measured force vs. displacement trends of the six samples (TQB3-8, solid lines).

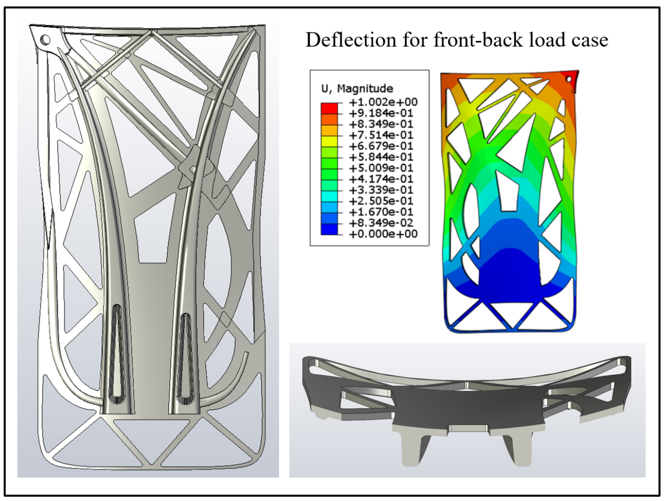

Figure 5: Final optimized seatback design

error between theoretical and actual stiffness was therefore 29.65%.

In general statistics, a CV < 10% is considered acceptable precision. A CV > 6% is to be expected in standard mechanical testing of composites, and this expectation increases for complex geometries such as the quad bracket. [20]. The measured stiffness CV of 8.96% thus satisfies the primary precision criteria.

The percent error between theoretical and actual stiffness of 29.65% is attributable to two primary sources. First, the simulation of the quad bracket did not model the entire test fixture assembly, but rather only the bracket with rigid boundary conditions. Elastic deformation of both the fixture and loading adapter during testing thus contributed to the lesser measured stiffness compared to predicted. Second, fiber discontinuities in the model are estimations. While fibers in both the model and samples are largely continuous within high stress regions, discontinuities are nonetheless present in other regions. Improving the modeling of such fiber discontinuities is currently an active area of R&D for Arris. Given the satisfactory CV and percent error being within safety factor specification, the secondary criterion of accuracy is acceptably met.

4. CONCLUSIONS

This paper focused on the application of a novel Additive Molding™ process in the design optimization of a combat vehicle driver's seat structure. The design was optimized to account for mobility loads and a 95-percentile male soldier, and the result was a reduction in weight from 18 to 3.6 pounds, which was an 80% weight savings. One critical design feature identified in the seatback was the location where the seatbelt loop attached to the seat structure. This novel manufacturing process enabled the optimized design to utilized fibers oriented around the attachment points, which is not possible in traditional composites manufacturing (see Fig. 5).

A subscale bracket was manufactured and experimentally tested to simulate the performance of the carbon fiber / polycarbonate material in the location of the seatbelt loop, and the results showed that the tailored fibers wrapped around the bolt location successfully reinforced the hole and effectively carried the simulated seatbelt-loop load.

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