Investigating the Relationship between Fiber Length, Volume Fraction, and Mechanical Properties of Fiber-Reinforced Plastics

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Introduction

Within the current reinforced plastic manufacturing paradigm, a paradox exists; filled[1] and long-fiber-reinforced plastics[2] are cheap, but lack the mechanical properties needed to displace structural metals, while continuous-fiber reinforced plastics[3] ("CFRP") possess exemplary mechanical properties but cost too much to compete with inexpensive stamped steel. A revolutionary approach is needed to enable vehicle designers to bridge this gap and restart the growth of plastics in automotive structures.

The evolution of materials and manufacturing processes in the automotive industry is driven by customer expectations and regulatory requirements but limited by cost-sensitivity and a demand for high production volumes. Since the 1970s, OEMs have sought to reduce vehicle weight and cost by replacing traditional materials, such as glass and steel, with plastic materials. This growth was initially fueled by the adoption of filled and long-fiber-reinforced plastics to displace metals in non-structural applications; however, growth has largely stalled in recent years as plastic materials saturated non-structural applications. The next frontier for reinforced plastics are structural components, such as the body-in-white and vehicle frame. Unfortunately, filled plastics and long-fiber-reinforced plastics lack the strength and impact resistance required for these applications. CFRPs have the potential to address these performance issues but must still overcome unique challenges to attain wide-spread adoption. Most CFRP manufacturing processes, such as hand layup, automated tape/fiber placement, and resin transfer molding, were initially developed for use in the aerospace industry. The automotive industry has struggled to adapt aerospace-grade composite manufacturing processes, leaving the industry unable to meet cost targets and production volumes.

This whitepaper begins with a review of published literature covering the effect of fiber length and volume fraction on the mechanical properties of fiber reinforced plastics. Next, it demonstrates how to optimize composite performance and cost using a mixture of volume fractions and fiber lengths in a single part. Finally, this paper presents a case-study for the use of WEAV3D composite lattice preforms to create low-cost structural components through the use of hybrid length scale fiber-reinforced plastics.

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[1] Filled plastics are defined as particulate-reinforced plastics where the particulate is less than 1mm in size.

[2] Long-fiber-reinforced plastics are defined as fiber-reinforced plastics with fiber lengths of 1-10mm.

[3] Continuous-fiber-reinforced plastics are defined as fiber-reinforced plastics where the fiber length is equal to or greater than the length of the loaded region of the part (often the full length of the part). Unidirectional and woven composites both contain continuous-fiber-reinforcement.

Literature Review

J.L. Thomason (Ref 1-6) has published extensively on the topic of short and long glass-fiber-reinforced polypropylene and polyamide plastics. His research has focused on characterizing the effects of fiber length and fiber volume fraction on the tensile modulus, tensile strength, and impact resistance of these materials. As indicated in Figure 1, the critical fiber lengths for tensile strength, tensile modulus, and impact resistance differ significantly, which limits the utility of short and long-fiber-reinforced plastics to applications where impact resistance and tensile strength are not required.

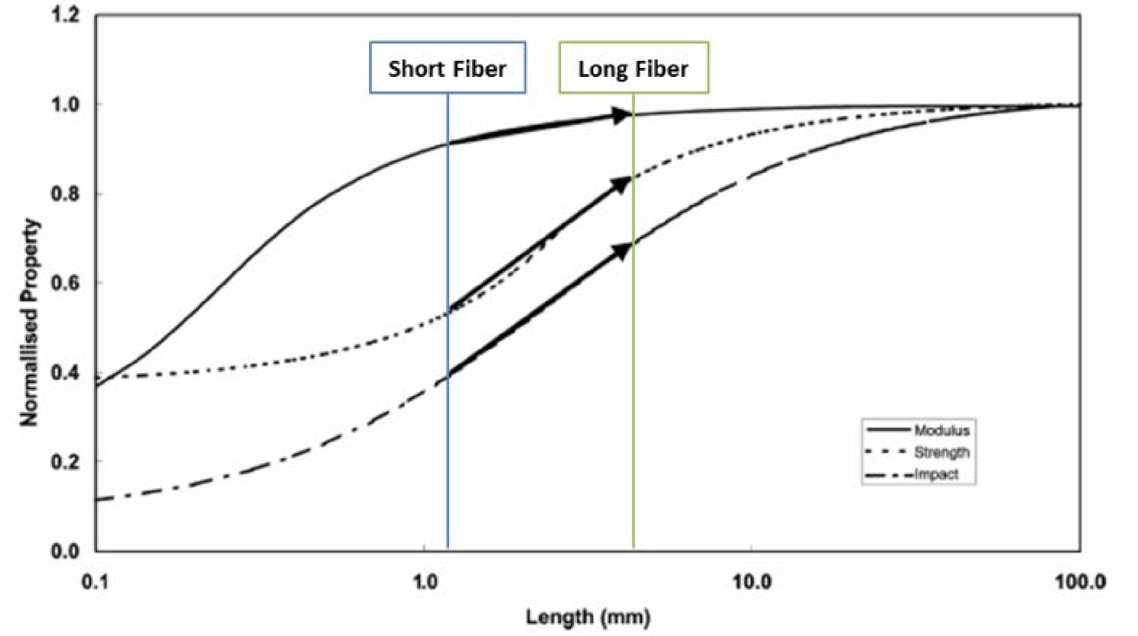

Figure 1: Effect of fiber length on mechanical properties, normalized against continuous-fiber properties. Original figure modified to label short and long-fiber length scales. (Thomason, 2002)

Thomason's findings on the effects of fiber volume fraction in long-fiber-reinforced plastics are particularly interesting. The conventional assumption for most composite designers is that composite modulus will follow the rule of mixtures approximation ($E_c = V_f * E_f + (1 - V_f) * E_m$)[4]. While Thomason shows that this may hold true for flexural modulus, there is a visible plateauing of the tensile Young's modulus around V_f = 0.4 (Figure 2). Furthermore, Thomason also demonstrates that both tensile strength and impact resistance peak around 40–50% fiber weight content (V_f = 0.2–0.3). In fact, at the highest weight fractions, strength and impact resistance were almost the same as the unfilled polypropylene material (Figure 3). Thomason posits that higher fiber volume fractions have a negative effect on both the residual fiber length after molding, as well as the even distribution of fibers in the matrix.

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[4] E_c = elastic modulus of composite, V_f = volume fraction of reinforcement fiber, E_f = elastic modulus of reinforcement fiber, E_m = elastic modulus of plastic (matrix).

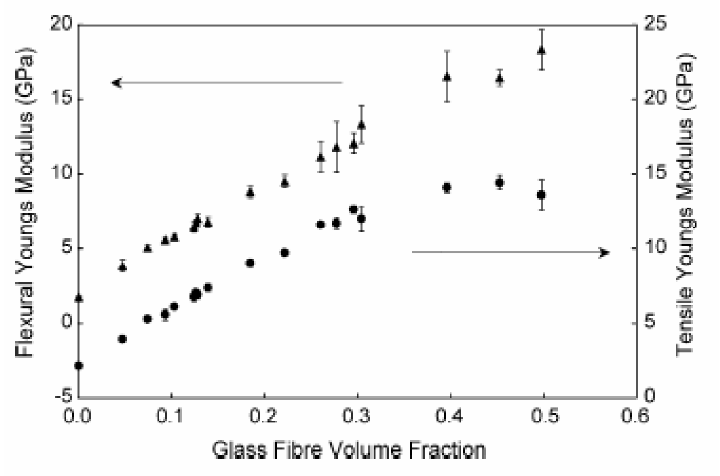


Figure 2: Plot of Young's modulus vs. fiber volume fraction. Values for flexural (triangle) and tensile (circle) modulus are offset to show deviation. (Thomason, 2005)

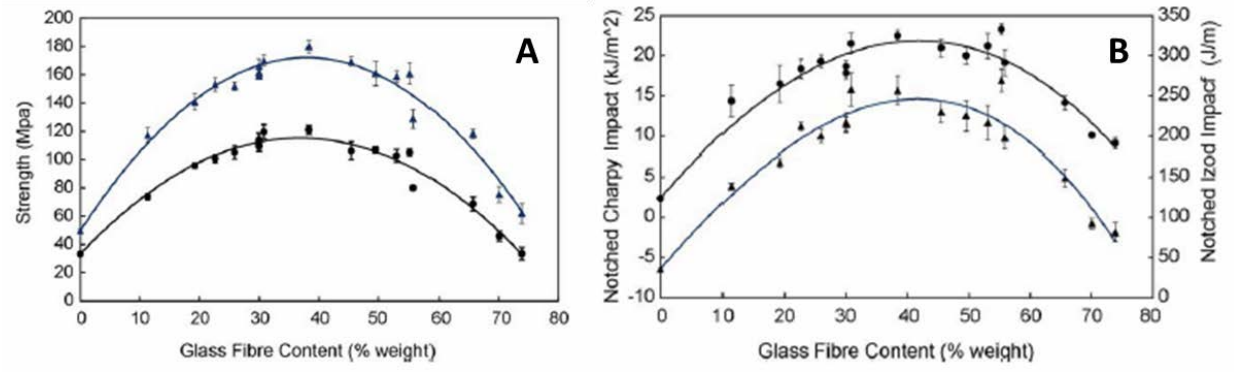
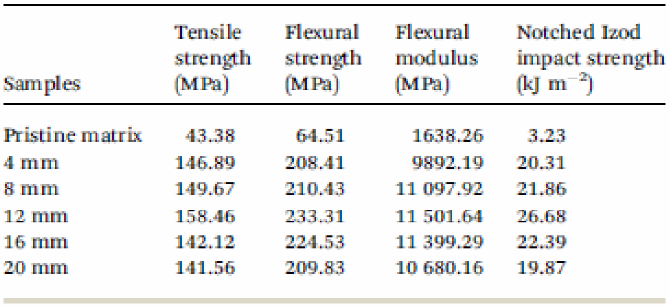


Figure 3: A is a plot of tensile strength (circle) and flexural strength (triangle) vs. fiber weight fraction. B is a plot of Charpy (circle) and Izod (triangle) impact resistance vs. fiber weight fraction. Charpy and Izod data is offset to more clearly show the data. (Thomason, 2005)

Zhang et al. conducted similar studies evaluating the effect of fiber length on the properties of long glass fiber/poly(butylene terephthalate) plastics reinforced at a fiber volume fraction of 40%. The study processed a number long-fiber-reinforced plastic samples using glass fiber pellets with initial fiber lengths ranging from 4mm to 20mm. Significant fiber breakage was observed during processing, with the 4mm fiber reduced to an average length of 2.48mm and the 20mm fibers reduced to an average length of 4.17mm. It was also observed that composites made using longer initial fibers suffered from poor distribution of the fibers in the matrix, which in turn degraded the mechanical properties of the fiber-reinforced plastic (Table 1).

Table 1: Mechanical properties of pristine matrix and LGF/PBT composite (Zhang et al., 2017)



Samples	Tensile strength (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Notched Izod impact strength (kJ m^{-2})
Pristine matrix	43.38	64.51	1638.26	3.23
4 mm	146.89	208.41	9892.19	20.31
8 mm	149.67	210.43	11 097.92	21.86
12 mm	158.46	233.31	11 501.64	26.68
16 mm	142.12	224.53	11 399.29	22.39
20 mm	141.56	209.83	10 680.16	19.87

Design Theory of Fiber Reinforced Plastics

Unlike metallic parts, the strength, stiffness, and toughness (failure energy) of fiber-reinforced plastics are not closely linked, which presents both a blessing and a curse. The properties of fiber-reinforced plastics (continuous-fiber-reinforced plastics in particular) have a reputation for being difficult to model; yet if one is able to overcome this challenge, these materials enable an astounding degree of optimization potential. Based on the prior literature review, we can correlate modulus, strength, and toughness to three different mechanisms of action:

1. Modulus: load transfer and load distribution between plastic matrix and reinforcement fiber
2. Strength: failure mode (plastic failure, fiber failure, interface failure)
3. Toughness: fracture mechanics (failure propagation, deflection, or arrest)

As a general statement, modulus is largely driven by fiber volume fraction, fiber elastic modulus, and fiber alignment. Moreover, modulus is independent of fiber length once critical length is achieved (around 1mm). When a load is applied to a reinforced plastic, it is unequally distributed between the plastic matrix and the reinforcement fiber. The degree of load carried by each component is based on the fiber volume fraction and the ratio of moduli between the plastic matrix and the reinforcement fiber. The higher the modulus of the reinforcement fiber, the more load is carried by the fiber relative to the plastic matrix. This contributes to a higher overall modulus of the reinforced plastic. For fibers with different longitudinal and transverse moduli[5] (such as carbon fiber), aligning the fibers yield high part stiffness in the direction of the alignment and lower stiffness in other direction. Random orientation will provide a middling level of stiffness in every direction.

The strength of fiber reinforced plastics is more difficult to predict, as it relies on understanding the failure mode of a specific combination of plastic matrix and reinforcement fiber. This failure mode depends on the ductility[6] of the matrix and reinforcement, as well as the strength of the interface between the two materials. Most reinforcement fibers are brittle and most plastic matrix materials are ductile, so we will focus our discussion on this particular combination, rather than all possible combinations. For this combination, the failure mode will either be interface failure or reinforcement fiber failure. Interface failure is defined as an adhesion failure between the matrix plastic and the reinforcement fiber. This failure mode is most common when low surface-energy plastics (polystyrene, polyethylene, polypropylene, or PTFE) are combined with fibers that have not been treated to increase adhesion. In this failure mode, the plastic separates from the fiber, which disrupts the load transfer between the matrix and the reinforcement. This in turn forces the plastic matrix to carry more of the load, leading to deformation of the plastic matrix, resulting in additional interfacial failures. This cycle repeats until the plastic matrix itself fails. This failure mode can be mitigated by selecting compatible plastics and fibers, and also by increasing the fiber volume fraction

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[5] Longitudinal refers to along the length of the fiber, while transverse is perpendicular to the length.

[6] Ductility is determined by strain-to-failure. Materials with strains of less than 3% are considered brittle, while higher strains are considered ductile.

above V_{crit} (Figure 4). For CFRP materials, strength can be increased by increasing fiber volume fraction; however, Thomason has shown that this relationship does not hold true for long-fiber-reinforced plastics. The strength of long-fiber-reinforced plastics peak at V_f = 0.2–0.3, which means that it is impossible to simultaneously achieve high-strength and high-stiffness in a long-fiber-reinforced plastic.

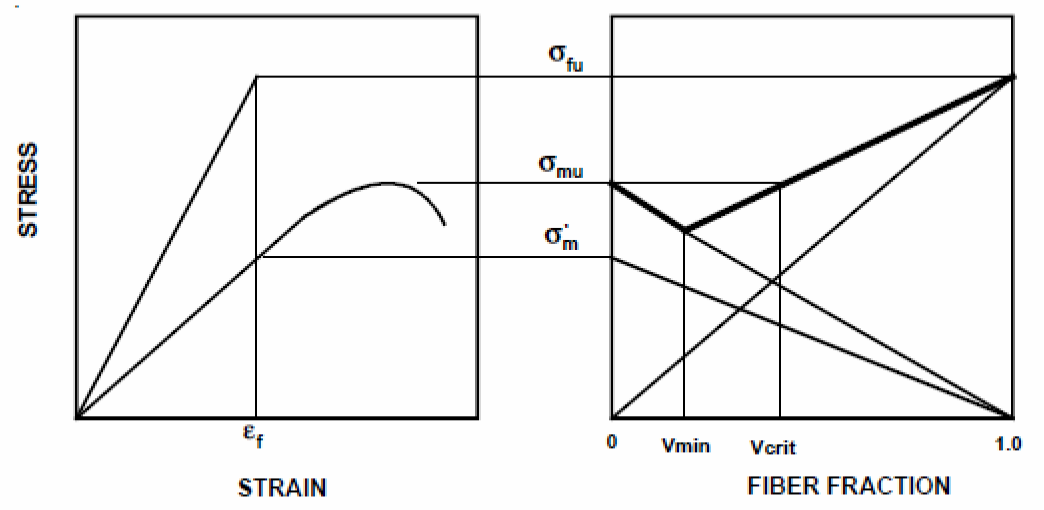

Figure 4: (Left) Stress-strain curve for reinforcement fiber and plastic matrix. (Right) Relationship between fiber volume fraction (V_f) and strength of CFRP, developed from figure on the left

The most likely failure mode for CFRPs above V_{crit} is reinforcement fiber failure. In this failure mode, one or more fibers break under the load (either due to variation in tensile strength of the fibers or complex loading[7]). Once the fiber breaks, the load that it was carrying must be distributed to the remaining fibers in the reinforced plastic, potentially leading to a sequence of fiber breakage as the effective load on each fiber increases despite the applied load remaining constant.

Finally, toughness is determined by the fracture mechanics, which describe how a failure propagates once it occurs. Brittle materials fail suddenly, while ductile materials fail more slowly. This allows ductile materials to absorb more energy during the failure. The independence of toughness from the modulus and strength of a material is best illustrated by comparing a glass bottle against a plastic bottle. A glass bottle has high modulus and strength; however, it shatters if dropped on the ground. Alternatively, a plastic bottle can be easily deformed by squeezing, but will not break if thrown at the ground with great force. The material is able to deform in order to absorb energy before recovering. Toughness, measured as energy absorbed per volumetric unit, is critical to understanding the impact behavior of a material. This is because impacts tend to trigger localized failure at the point of contact, which can then propagate a fracture throughout the material.

The ductile nature of the plastic matrix provides a good baseline toughness for fiber-reinforced plastics; however, careful optimization is needed to maximize toughness. The addition of reinforcement fibers to the plastic matrix initially increases the toughness of the material as the fibers are able to arrest or deflect crack propagation in the plastic matrix. Using continuous fibers also increases the toughness of the material by eliminating the number of stress concentrations caused by the tips of the discontinuous fibers and forces cracks to follow a longer path when deflected. At high volume fractions, the brittle nature of the reinforcement fiber starts to offset the benefits gained from crack deflection. The failure strength of the fiber reinforced plastic is well above the failure strength of the plastic matrix and approaches the failure strength of the reinforcement fiber itself. When one fiber fails, the rest

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[7] Complex loads differ from simple loads in that the magnitude of the stress in the part varies with location. Bending and torsion are both examples of complex loads, while mono-direction tension and compression are examples of simple loads.

follow in rapid succession, leaving no fibers to arrest the crack propagation. This relationship inhibits the ability to design long-fiber-reinforced plastics with high toughness and high modulus.

Breaking the Paradox: Hybrid Length Scale Fiber-Reinforced Plastics

Conventional wisdom holds that since long-fiber-reinforced plastics are unable to simultaneously offer high stiffness, high strength, and high impact resistance, the only solution is to use continuous-fiber-reinforced plastics for structural components, despite their high cost and manufacturing challenges. We reject this position and propose an alternative. One that combines the performance benefits of CFRPs with the low cost and ease of production associated with long-fiber-reinforced plastics: hybrid length scale fiber-reinforced plastics.

In the hybrid length scale approach, a low density, woven lattice of continuous-fiber-reinforced plastic is overmolded with long-fiber-reinforced plastic to form a finished structure (Figure 5). The volume fraction of the lattice ranges from 0.6–0.7, while the volume fraction of the long-fiber-reinforced plastic can be selected to maximize strength and toughness (V_f = 0.2–0.4, resulting in an overall volume fraction in the range of 0.4–0.6, depending on the density of lattice. The overall volume fraction provides a specific stiffness that is comparable to steel and aluminum, and an absolute flexural strength that is greater or equal to steel. The CFRP lattice structure also increases the overall toughness of the structure by interrupting fracture propagation between the long-fiber reinforced plastic that fills the lattice openings. Part properties can be further enhanced by selecting a high-performance fiber for the lattice (such as carbon fiber) and a less expensive material for the long-fiber-reinforced plastic (such as glass). This reduces the overall cost of the part, while still ensuring high performance. The hybrid length scale approach will enable designers to achieve the modulus, strength, and impact resistance properties needed for structural components, at a cost that is much lower than traditional composite materials.

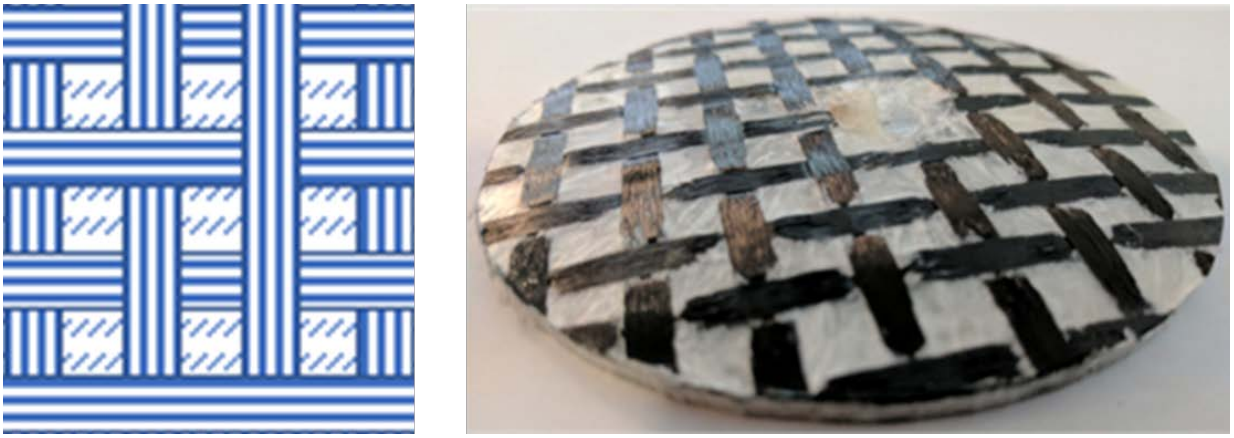

Figure 5: (Left) Diagram of hybrid length scale fiber-reinforced plastic structure. (Right) Injection molded plaque containing a WEAV3D woven, continuous-fiber-reinforced lattice structure

WEAV3D Inc. has developed a manufacturing process to produce multi-layer low-density lattice structures at high volumes and low cost. Using an internally developed composite modelling tool, a case study was conducted to predict the cost and weight of a WEAV3D fiber-reinforced plastic door panel optimized to match the stiffness of a steel door panel. Due to the higher absolute strength of composite materials, and the innate toughness of fiber-reinforced plastics, we project the strength and toughness of the WEAV3D fiber-reinforced plastic door panels to meet or exceed the strength and toughness of the steel baseline. Design specification, cost, and weight calculations for steel and aluminum door panels are pulled from "Assessing the Costs and Benefits of Effective Lightweighting Technologies," published by the Center for Automotive Research in July 2015.

Several traditional composites were selected for benchmarking comparison as part of this case study, including autoclave cure prepreg hand layup, snap cure resin transfer molding (RTM) and thermoplastic automated fiber placement (AFP). Hand lay-up and resin transfer molding assuming carbon fiber/epoxy materials, AFP assumes carbon/nylon 6 material. The WEAV3D design used in this comparison is a carbon/nylon 6 lattice combined with a chopped glass/nylon6 injection overmolded material. The traditional processes can generate a part that is 12 pounds lighter than the steel baseline, while our process will produce a part that is 10.74 pounds lighter. For reference, an aluminum design is only 8.7 pounds lighter that that the steel solution.

The industry roadmap target to composite adoption in composites is $2.50 per pound saved. As shown in Figure 6, the WEAV3D composite solution can achieve this target; while even the least expensive traditional composite design can only achieve $4.47 per pound saved. Other composite forming processes, such as hand lay-up or automated tape laying have a weight premium as high as $18.84 per pound saved. Furthermore, most traditional methods struggle to produce volumes above 50,000 parts per year, even at 2 shifts per day. The WEAV3D manufacturing process was optimized for the automotive industry and is expected to achieve a minimum production volume of 200,000 parts per year.

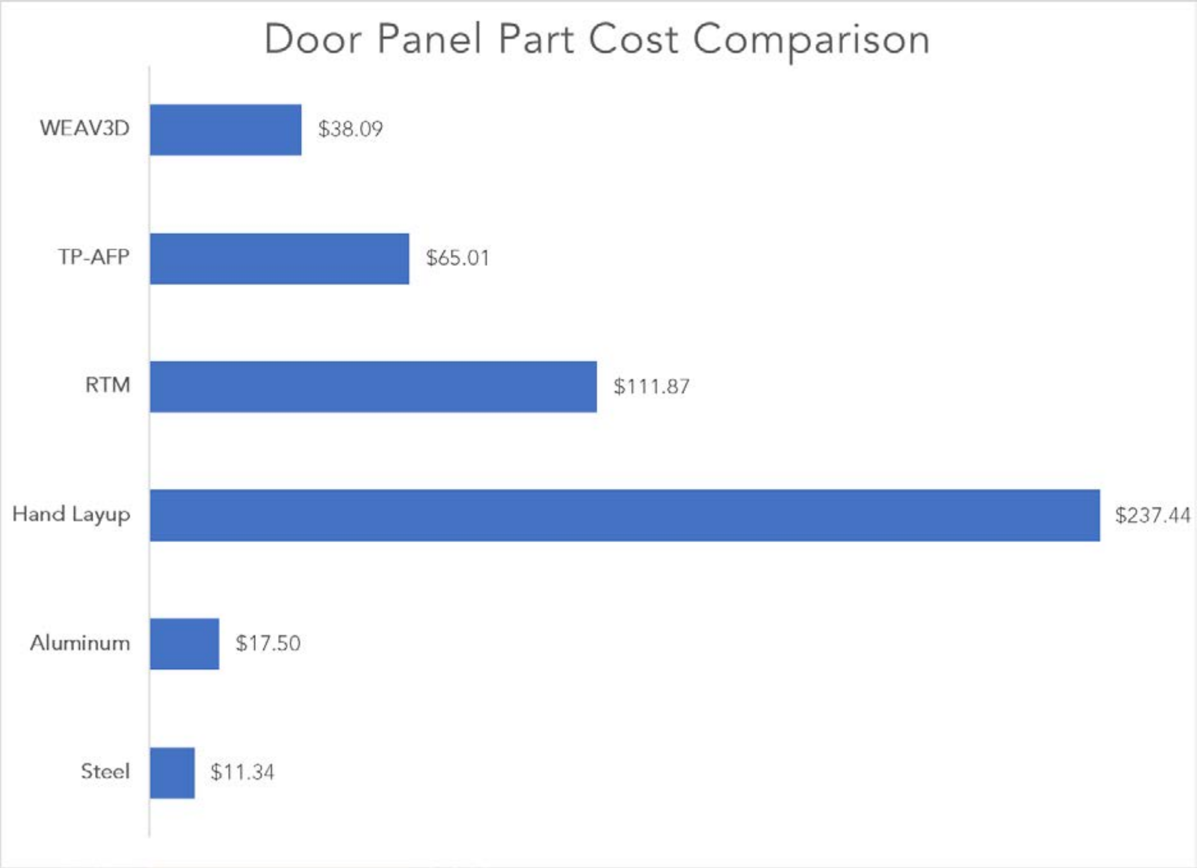

Figure 6: Chart comparing the cost of vehicle door outer panels. Baseline steel panel mass is 16.5 pounds, aluminum panel mass is 7.8 pounds, traditional composite mass is as low as 4.5 pounds, and the WEAV3D panel mass is 5.76 pounds. All panels are designed for stiffness equivalance.

About WEAV3D Inc.

WEAV3D Inc. is a manufacturing technology company focused on developing and commercializing revolutionary fiber-reinforced plastic manufacturing processes and processing equipment. WEAV3D Inc. is currently commercializing a patent-pending continuous manufacturing process capable of forming low-density continuous-fiber-reinforced lattice structures. This manufacturing process will reduce the cost of producing composite structures and enable high-volume production of structural components.

WEAV3D Inc. is seeking innovative partners interested in developing new product offerings for the automotive market using WEAV3D lattice preforms. For more information about partnering opportunities please contact us at info@weav3d.com.

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