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PNNL-39208

Low-Cost Highly Recyclable Structural Composites Utilizing Vitrimers and Natural Fibers (Basalt) Manufactured via a Novel Pultrusion Method for High-Volume Applications

April 2026

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U.S. DEPARTMENT of ENERGY

Prepared for the U.S. Department of Energy
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LightMAT

Lightweight Materials Consortium

Final Technical Report

Low-Cost Highly Recyclable Structural Composites Utilizing Vitrimers and Natural Fibers (Basalt) Manufactured via a Novel Pultrusion Method for High-Volume Applications

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Background: The automotive industry has been focused on developing lightweight materials that are cost effective, meet performance, recyclability, and sustainability targets. However, while material costs are a significant component of the piece cost of composite parts, manufacturing costs are often as significant or even more. In addition, even though thermoset composites often do offer a viable lightweight substitute to metals, they are typically manufactured using costly tooling, floor equipment and manufacturing setup whose costs are exponential with the part size. Furthermore, thermoset resins typically offer extremely limited recyclability and repairability options for manufacturers and end users. Providing a new option for industry to consider, in which manufacturing costs are significantly lowered by using a pultrusion line, along with utilizing vitrimer systems in a pultrusion process will open the possibility of manufacturing large parts (with geometric shapes that are amiable to pultrusion) which can be repairable in the field and recyclable. Vitrimers resins can produce composites that are lightweight, and depending on the particular vehicle component, they can offer as high as 40% weight reduction compared to steel. Furthermore, the use of basalt fibers is very attractive to industry due to several factors: significantly lower embodied energy compared to carbon fibers (~10% of CF); their precursor is 100% natural (volcanic rock); mechanical properties similar to glass fibers; extremely attractive thermal properties (withstand 1000^{o}C+); and exhibiting some attractive NVH properties (acoustic insulation and sound deadening). All are of high level of relevance and interest to industry.

There are several technical barriers which historically have contributed to the prevention of high penetration of such technology within the automotive industry. The barriers can be summarized as follows:

(1) Vitrimers are relatively new, and they have been explored only within the last 10-12 years or so. Typically, new material systems take a long time to penetrate high-volume automotive production due to the progressive maturity of the knowledgebase (mechanical characteristics, performance, manufacturing, cost, supply chain maturity, …etc.). Developing this knowledgebase will help mitigate this barrier.

(2) Pultrusion of polymeric composites is a mature manufacturing method in several other industries but not in the automotive industry. However, its relatively low-cost, especially since cost of tooling does not increase exponentially with the size of the part, makes it very attractive for automotive explorations especially for lightweight structural composites made with vitrimers. This has not yet been explored in the automotive industry. This project will explore using vitrimers as a potentially viable automotive material for pultrusion.

(3) Reinforcing vitrimer resins with a natural fiber like basalt is challenging from the pultrusion perspective, because such an abrasive fiber system may require special considerations for manufacturing composite components. This has not been explored yet for automotive applications, and this project will explore that further.

(4) The use of vitrimer-basalt composites provides a high level of recyclability especially since vitrimers are > 95% recyclable, and basalts are 100% natural material. Furthermore, such a composite system is highly repairable, and it is individual components exhibits low embodied energy (for example, embodied energy for basalt fibers is about 20MJ/kg while for carbon fiber is at least 200MJ/kg—10 times that of basalt). However, the total embodied energy of the combination of vitrimer, basalt, and a pultrusion process has not been explored. Lack of such important knowledge mitigates it deployment int automotive applications. This project will quantify this attribute, and provide two models, one to estimate material and manufacturing costs (for a demonstrator vehicle part), and a model to estimate the total embodied energy.

Project Objectives: The project’s overall goal is to explore and demonstrate as proof-of-concept that a highly recyclable and repairable composite material system, that is reinforced with natural fibers, can be used to produce lightweight structural components using a low-cost manufacturing process for high-volume automotive applications. More specifically, the project’s objectives will focus on vitrimer resins (which are a hybrid polymeric system of thermoplastics and thermosets) reinforced with basalt fibers and manufactured using pultrusion technologies. Pultrusion, as a method, is well-known to be one of the lowest-cost manufacturing processes for high-volume applications. However, to date, the validity and viability of such attractive objectives have not been demonstrated in support of the automotive industry.

Approach: The project’s approach will be divided into 3 tasks.

Task 1: System Identification: This effort involves selecting the vitrimer resin, basalt fiber, and pultrusion processing parameters to map a technology landscape that maximizes the likelihood of a positive, high-impact outcome. In parallel, a target vehicle component is defined, and its key geometric attributes and performance requirements are established.

Task 2: System Design: This task focuses on component design using the inputs developed in Task 1. As a proof of concept, the approach will be demonstrated using an existing tool and a simple cross-sectional geometry (e.g., round, square, or rectangular).

Task 3: System Verification & Models: This task will include a laboratory-scale demonstration of post-damage repair capability in the composite following damage initiation. In addition, mass reduction estimates, informed by the design parameters, will be developed to quantify the maximum achievable weight savings of this technology. Finally, a cost model will be established that captures both material and manufacturing costs, along with the associated cost-saving potential.

Results and Discussion:

Composite Development and Testing

VITRIMAX T100 vitrimer resin (Mallinda Inc.), consisting of an epoxy resin and imine hardener, was used to fabricate fiber-reinforced composites via pultrusion. The hardener was preheated to 80 °C and mixed with the epoxy at a 1.5:1 ratio, with additives (tert-butyl, styrene, and imidazole) introduced to reduce viscosity and extend working time. Composites were produced using both silane-sized unidirectional fiberglass and flax fiber mats to demonstrate process feasibility. Pultrusion was carried out using a heated steel die with controlled temperature zones, resulting in 3 mm thick panels with varying fiber loadings (60% fiberglass and 30% flax). Samples were subsequently cut and prepared for mechanical and thermal characterization.

Pultruded vitrimer composites based on Vitrimax T100 exhibit fiber-dependent tensile performance, with glass fiber composites achieving high stiffness and strength (41.68 GPa, 570 MPa) due to efficient stress transfer and strong interfacial bonding, while flax fiber composites show lower properties (13.72 GPa, 105 MPa) limited by their intrinsic morphology and weaker fiber–matrix interactions, as shown in Figure 1a. The dynamic bond exchange in the vitrimer matrix enhances interfacial stress distribution and deformation stability in both systems, though glass fibers enable abrupt, fiber-dominated failure, whereas flax fibers promote gradual, energy-dissipative failure through interfacial debonding and fiber pull-out. As shown in Figure 1b, glass fiber–reinforced Vitrimax composites exhibit superior flexural performance (164.36 MPa strength, 22.15 GPa modulus) due to high fiber stiffness, continuous alignment, and strong interfacial bonding enabled by dynamic vitrimer network rearrangement, resulting in efficient load transfer and brittle, fiber-dominated failure. In contrast, flax fiber composites show lower flexural properties (91.84 MPa, 12.60 GPa) and a more compliant, progressive failure mode driven by microstructural variability, weaker interfacial bonding, and limited dynamic exchange at the fiber–matrix interface despite improved matrix wet-out.

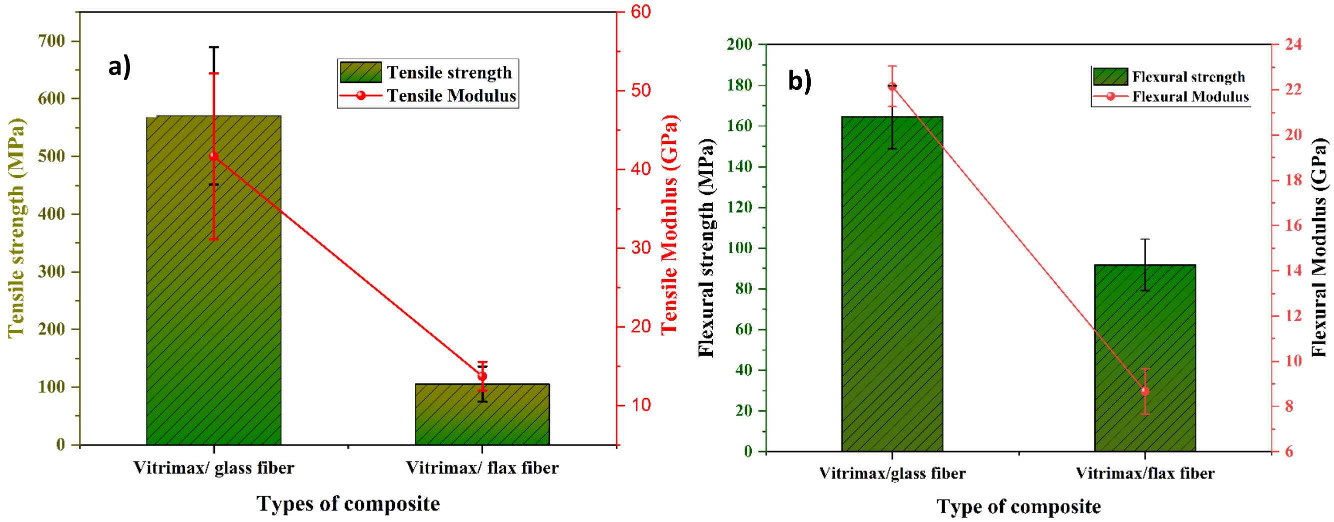

Figure 1. a) Tensile and b) flexural properties of Vitrimax composite reinforced with glass and flax fiber.

Repairability Demonstration

Fracture-tested Vitrimax composites were repaired by hot-pressing in a steel mold at 150 °C and 500 psi for 15 minutes—above the topology freezing temperature to activate bond exchange—under conditions selected to minimize dimensional distortion and reflect practical repair scenarios, after which the samples were re-tested for flexural properties. The results (Figure 2) indicate that recycling of Vitrimax/flax composites preserves or slightly improves stiffness due to enhanced resin redistribution and fiber alignment, but repeated cycles lead to fiber degradation, reduced strength, and catastrophic failure after the second cycle, limiting recyclability. In contrast, Vitrimax/glass composites show substantial gains in flexural strength and modulus through two recycling cycles due to improved consolidation and interfacial bonding, with performance declining only in the third cycle as accumulated fiber and interfacial damage begins to dominate.

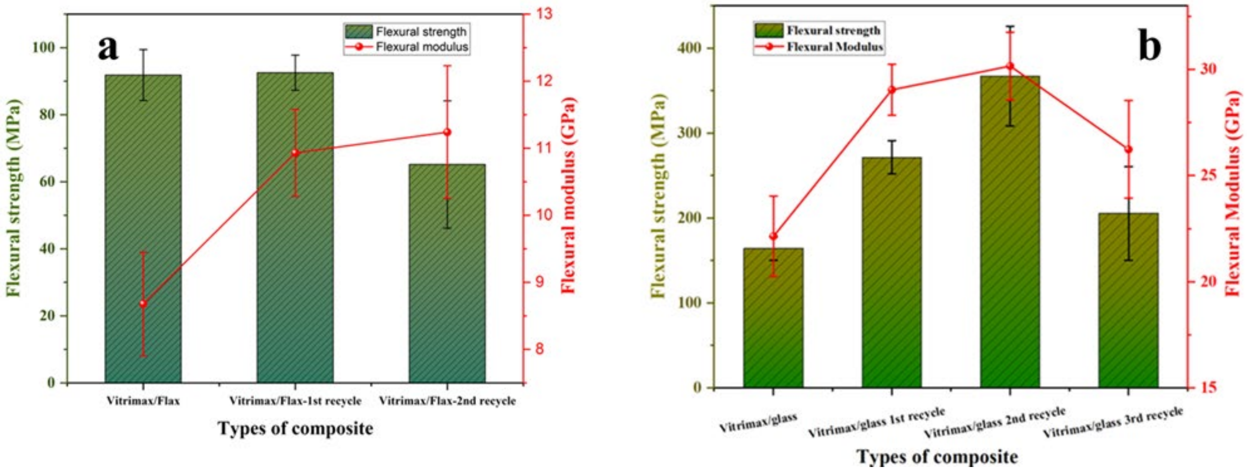

Figure 2. Flexural properties of a) Vitrimax/flax fiber composites and b) Vitrimax/gass fiber composites.

<u>Component Design and Construction</u>

Fiber-reinforced Vitrimax composites with 60% glass fiber and 30% flax fiber were fabricated via industrial pultrusion by PulFlex Technologies using a heated steel die with controlled temperature zones and a resin system prepared by mixing imine hardener and epoxy at a 1.5:1 ratio. The process employed a 3 mm thick die and a defined heating profile, after which cured panels were cut and machined into specimens for mechanical and thermal characterization. Tubular pultrusion of the Vitrimax/flax system (as shown in Figure 3) was hindered by insufficient cure within the die, leading to low green strength, deformation, and eventual process instability, while attempts to increase dwell time caused premature crosslinking and die sticking. These issues stem from slow vitrimer cure kinetics, poor thermal conductivity of flax fibers, and geometric heat transfer limitations, indicating the need for optimized die heating, extended cure zones, or preheating strategies.

Figure 3. Pultruded square tube using Vitrimax and flax/glass fiber.

Finite Element Simulation

Finite element analysis compared steel (SS304) and vitrimer-based composites for truck running boards under two design criteria: equal strength and equal stiffness. In the equal-strength case (Tabe 1), composites required slightly greater thickness but achieved similar safety factors with ~70–75% mass reduction, despite higher deflections than steel. In the equal-stiffness case (Table 2), increased composite thickness led to significantly lower stresses and comparable deflection to steel while still reducing mass by ~50%. Overall, vitrimer composites demonstrated strong potential as lightweight alternatives to steel, particularly where weight savings and structural efficiency are critical.

Table 1. Case A - Equal-strength configuration results.

Material	Thickness (mm)	Worst-Case Max Stress (MPa)	Safety Factor	Mass (kg)
SS304	3.25	~215	1.0	7.07
Glass/Vitrimer	3.70	~163	1.0	1.85
Flax/Vitrimer	5.00	~90	1.0	1.90

Table 2. Case B – Equal-stiffness configuration results.

Material	Thickness (mm)	Worst-Case Max Stress (MPa)	Safety Factor	Mass (kg)
SS304	3.25	~215	1.0–6.2	7.07
Glass/Vitrimer	6.76	~40–50	3.3–20.2	3.38
Flax/Vitrimer	9.23	~24–40	3.4–21.3	3.50

Cost Analysis

A simplified cost analysis was conducted to estimate the manufacturing cost of pultruded flax/Vitrimax vitrimer composites for a 2-kg automotive running board. Bulk procurement data for Vitrimax resin and natural fibers are proprietary; therefore, retail pricing and publicly available literature values were used.

Three production scales were evaluated: (1) single-unit laboratory fabrication, (2) 1,000 units/year, and (3) 10,000 units/year. These cases illustrate the effect of equipment utilization, per-run waste, and labor distribution on normalized part cost. Actual industrial-scale composites would be significantly lower than the values reported here due to improved economies of scale, reduced startup waste, and discounted bulk resin pricing.

The running board dimensions used in this analysis are 1830 mm × 150 mm × 5 mm, resulting in a mass of approximately 2 kg. The laminate is pultruded using six plies of ampliTex™ 5043 flax fabric (35% fiber volume fraction per ply) and Vitrimax resin. Using flax density (1.47 g/cc) and vitrimer resin density (1.15 g/cc), the resulting composite contains approximately: 0.4 kg flax fiber (20 wt.%) and 1.6 kg Vitrimax resin (80 wt.%). Retail material prices and open-literature estimates used are summarized in Table 3. The Vitrimax VHM two-part vitrimer system was priced using the 10-kg kit cost, corresponding to $126/kg. Flax pricing was derived from Bcomp fabric cost converted to mass-normalized equivalent. Acetone was included for cleaning and line flushing.

Table 1. Material cost assumptions

Material	Price used in model
Vitrimax vitrimer resin (Mallinda)	$30/kg
Flax (ampliTex 5043)	$28/kg
Acetone	$1.10/kg
Electricity	$0.12/kWh

Figure 4 illustrates the normalized cost per kilogram of composite for each scenario. The trend shows rapid cost reduction with increasing production rate, driven by distributed startup waste, improved equipment utilization, and reduced labor burden.

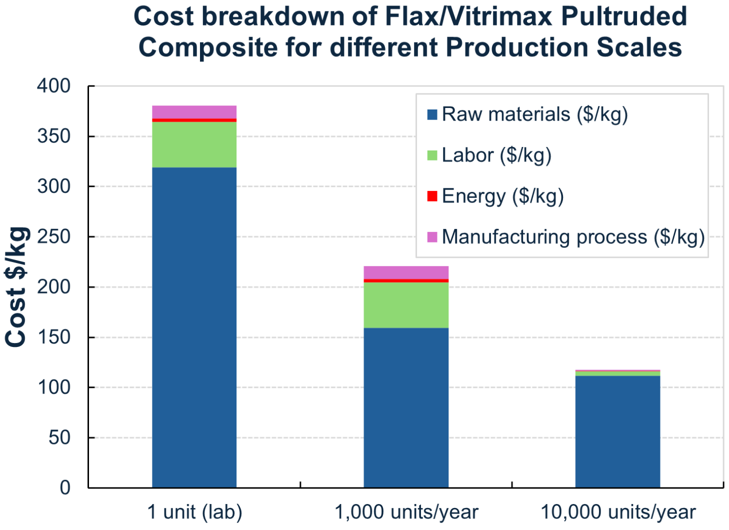

Figure 4. Normalized cost breakdown of pultruded flax/Vitrimax composite at three different production scales.

The cost analysis demonstrates that laboratory-scale pultrusion of flax/Vitrimax composites is strongly dominated by retail resin pricing and per-run waste. Scaling production from one part to 10,000 parts per year reduces the cost from approximately $380/kg to $118/kg, primarily through improved machine utilization and lower waste allocation. Although retail vitrimer resin prices significantly elevate costs in this study, bulk-procurement scenarios and optimized pultrusion operations would further reduce part cost in an industrial environment. These results support the potential viability of natural-flax fiber vitrimer composites for lightweight structural components given continued process development and scale-appropriate material pricing.

Potential Impacts: The demonstrated performance of Vitrimax/flax composites highlights their strong potential to transform lightweight structural design by combining high mechanical efficiency with intrinsic repairability and recyclability. Compared to conventional thermoset systems, the vitrimer network enables extended service life through damage recovery and multiple reprocessing cycles, directly addressing end-of-life challenges associated with fiber-reinforced polymers. The significant mass reductions observed in finite element simulations (50–75% relative to SS304) position these materials as viable candidates for transportation applications where weight savings translate to improved energy efficiency and reduced emissions. Additionally, the ability to tailor performance through fiber selection—high-performance glass fibers or flax fibers—provides a flexible pathway to balance mechanical requirements, cost, and environmental impact.

From a manufacturing standpoint, the successful pultrusion of flat laminates demonstrates compatibility with established industrial processes, supporting near-term scalability. However, the challenges observed in tubular pultrusion of flax/vitrimer systems underscore the need for improved process design, particularly in managing cure kinetics, thermal gradients, and fiber-specific heat transfer limitations. Addressing these issues will be critical for expanding vitrimer composites into more complex geometries and structural profiles.

Future Work: Future work should focus on several key areas. First, optimization of cure schedules and die design—potentially through integrated thermal modeling and in-line sensing—will be essential to enable stable processing of closed-section profiles. Second, interfacial engineering strategies (e.g., fiber surface treatments or compatibilizers) are needed to enhance bonding and dynamic exchange efficiency, particularly for natural fibers. Third, long-term durability studies, including fatigue, environmental aging, and multi-cycle repair/recycling performance, will be necessary to validate real-world reliability. Finally, economic viability will benefit from scale-up studies incorporating bulk resin procurement, continuous operation, and reduced waste, alongside life cycle assessments to quantify sustainability advantages.

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