Rebar for Plastics – A Novel Approach to Part Optimization with Composite Lattices

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ABSTRACT

Conventional design methodologies are divided between isotropic approaches (metals and randomly oriented discontinuous composites) and laminate-based anisotropic approaches. This bifurcation of methodologies has largely aligned with historical manufacturing processes; however, recent development of hybrid length-scale composites require a novel approach to fully unlock the capabilities of these novel materials. In hybrid length-scale composites, unidirectional tape assemblies are combined with conventional plastic molding processes such as injection molding, compression molding, or thermoforming to create a structural or semi-structural component that is more cost efficient than a pure laminate.

This paper provides an overview of the Rebar for Plastics® design methodology, which leverages various micro-and macro-mechanical concepts to maximize performance and minimize cost in hybrid length-scale composites. Rather than using material properties as a fixed input in part design, stiffness, strength, and toughness can be tuned independently and in parallel with part geometry, based on overall performance targets for the component and the relative ratios of unidirectional tapes and molded plastic in the part. A representative case study will illustrate key optimization concepts associated with hybrid length-scale composites, while also providing a comparison against conventional laminate-based methodologies. This paper will also showcase a woven composite lattice structure created from unidirectional thermoplastic tapes that is suitable for high volume manufacturing.

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1. INTRODUCTION

1.1 Design Degrees of Freedom

Throughout history, material selection has been a critical step in the design of a component; however, material selection does not occur within a vacuum. Rather, material selection is interdependent on manufacturing processes and part geometry, with a material's formability limiting the design degrees of freedom (DoF) available when optimizing the cost, weight, and performance of the final component. As the number of DoFs increases, less material is required to achieve the performance targets as the part can be made thinner in areas with low stress and thicker in areas with high stress. Table 1 summarizes the various design degrees of freedom, key variables and the optimization function or each DoF.

Table 1: Optimization Functions for DoFs 1-4

	Part Thickness	**Material Properties (E, σ)**	**Optimization Function**
1 DoF	Constant	Homogenous	f (Mat_A, t)
2 DoF	Variable w.r.t. part area		f ($Mat_A, t_{1\ldots N}, d_{1\ldots N}$)
3 DoF		Homogenous within Layer	f ($Mat_{A\ldots N}, t_{1\ldots N}, d_{1\ldots N}$)
4 DoF		Heterogenous within Layer	f ($Mat_{A\ldots N}, t_{1\ldots N}, d_{1\ldots N}, s_{1\ldots N}$)

Figure 1 provides an illustration of the design degrees of freedom using a cross-section of several common material configurations. 1 DoF is representative of sheet metal, homogenous organosheet, or sheet-formed thermoplastic materials having constant thickness. 2 DoF is common to injection or compression molded polymers, where part thickness is varied using ribbing and/or step changes in base thickness, while in traditional composite laminates this can be achieved by locating additional reinforcing plies in specific regions. 3 DoF is characterized by varying thickness and material type over the area of the part, which has long been used in composite laminates that combine multiple materials (core materials, different plies with different reinforcing fibers, etc.). More recently, this approach has also been leveraged in hybrid overmolding of organosheet preforms, whereby a base thickness of organosheet is back-injection molded with a melt-compatible thermoplastic compound. While combining multiple materials into the structure enhances performance, the ability to vary material is still limited by 3 DoFs as the different materials remain discrete layers within the resulting structure, with each layer needing to consist of a single material type. This paper presents a design methodology that unlocks a 4th degree of freedom, variability of material type and material spacing within a layer of a structure, enabling the mechanical properties of the resulting component to vary continuously rather than discretely over the entire part. This enables highly-optimized structures, suitable for high rate automotive manufacturing, which exhibit enhanced cost-efficiency over both traditional laminates and existing hybrid overmolding processes. While simulation techniques for this design methodology have been developed, they are beyond the scope of this paper and the reader is advised to read [4].

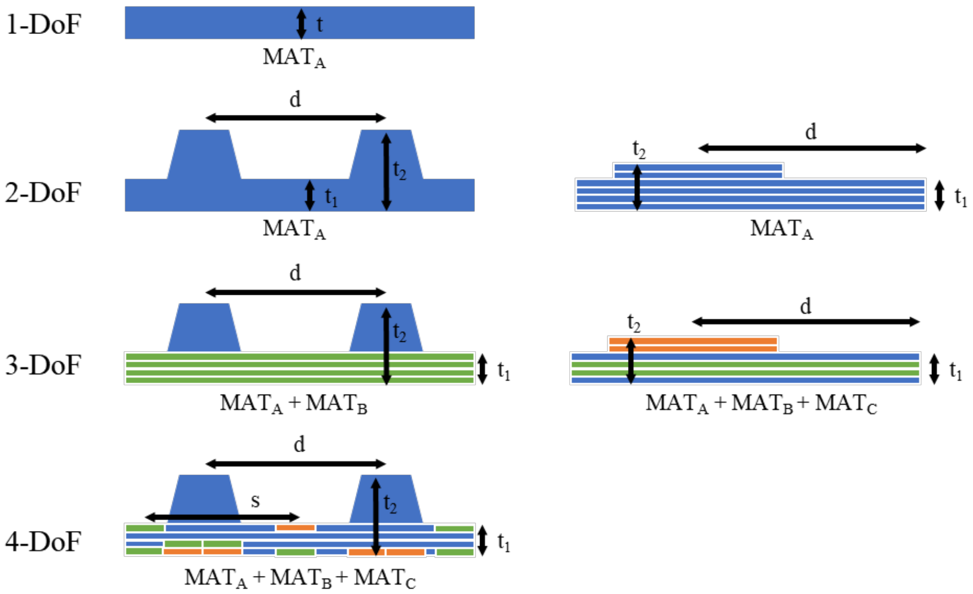

Figure 1: Illustration of design degrees of freedom in increasing order

1.2 Materials Properties and Structural Properties

It is important that we begin by defining some key terms. To start with, we should distinguish between material properties and structural properties as the line between these properties will start to blur once we introduce the concept of homogenized properties in later sections. Material properties are defined as intensive properties, i.e a physical property that does not depend on the amount of the material [2]. By comparison, structural properties are dependent on both the geometry of the structure as well as the constituent materials that make up the structure. Load capacity, for example, describes how much force a structure can withstand before failure; while strength, σ, describes how much stress per unit area a material can withstand before failure. Therefore, for a given cross-section area, A, the load capacity of a structure made of one material can be described as a function of σ and A. While the relationship between material property and structural property tends to be straightforward with uniaxial loading cases, the relationship becomes more complex when looking at bending behavior. Bending stiffness, K, is a structural property that is function of the elastic modulus material property, E, the area moment of inertia, I, and the length of the span, L, such that $K = \frac{EI}{L}$. For a simple rectangular cross-section, $I = \frac{bh^3}{12}$, where b is the width of the cross-section and h is the height. Substituting the definition of I back into the K equation we see that $K = \frac{Ebh^3}{12L}$, which indicates that doubling modulus (by substituting one material for another) would double bending stiffness, while doubling thickness of the original material translates to an eightfold increase in bending stiffness. This relationship is fundamental to why ribs are used in part design today, but this is also critical to understanding the behavior of parts containing a mixture of materials as they are capable of changing the area moment of inertia without changing the thickness of the structure.

The simplest example of this effect can be found in composite beam theory; however, it should be noted that “composite” in this context merely means “a beam constructed from more than one material" rather than a beam constructed explicitly from a fiber reinforced polymer composite. The textbook example of this is that of a wooden beam with a steel plate attached to either one or both the top and bottom of the beam (Figure 2). While the physical cross section of this composite beam remains rectangular, the fact that these two materials exhibit different modulus, E_1 (wood) and E_2 (steel), means that I for the beam needs to be calculated via an alternative approach. This is achieved through the use of the equivalent area method [2], whereby the area of steel in the example above can be replaced with an equivalent area of wood by multiplying the width of the original steel area by n, where $n = \frac{E_2}{E_1}$. As steel has a much higher modulus than wood, this replaces the steel area with a much wider equivalent area of wood, effectively creating a T- or I-beam shape (Figure 2), whose area moment of inertia can be calculated using the parallel axis theorem. Once deformations and stresses are calculated for this equivalent area, the stresses can be converted back into the true steel stresses using n. It is important to note that because of this area equivalence conversion, putting two steel plates on one side of the wooden beam will have smaller effect on the bending performance of the beam than putting one plate each on the top and bottom sides because increasing the area on only one side of the beam shifts the neutral axis of the cross-section towards that side, meaning that the physical centroid of the beam no longer lies on the neutral axis.

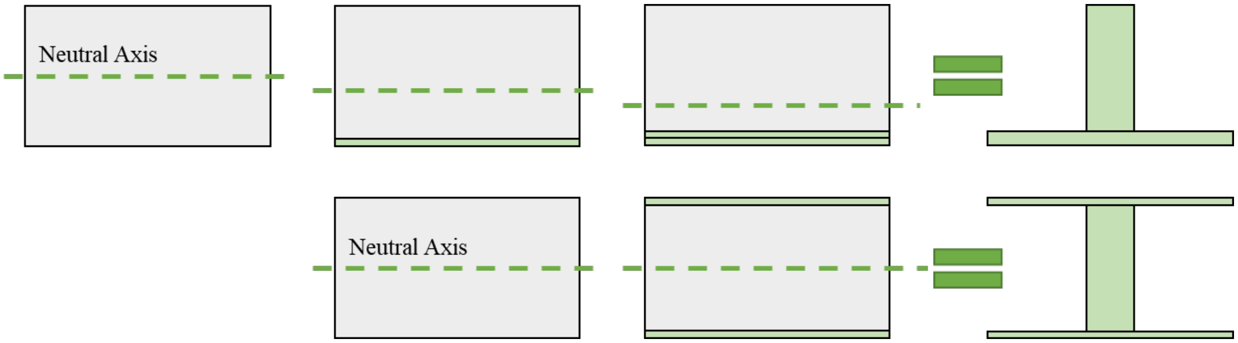

Figure 2: Illustration of composite beam; (Top) Neutral-axis shifting caused by reinforcement of only one side; (Bottom) Constant neutral-axis from symmetrical reinforcement of both sides

1.3 Isotropic and Orthotropic Properties

In the context of design degrees of freedom, it is worth discussing the impact of isotropic and anisotropic material properties. For the purpose of the paper, we will only address the orthotropic special case of anisotropy, as this is most relevant to the types of laminates and unidirectional tapes that are the focus of this discussion. Isotropic materials (metals and most plastics) are those that exhibit no directional dependence with respect to their material properties. In contrast, orthotropic materials (composites) exhibit three axes of symmetry, wherein one axis usually exhibits substantially better material properties than the other two axes. Due to their lack of directional dependence, isotropic materials are limited to, at most, 2 DoFs. While this makes isotropic materials less complex to design for, as the design engineer needs to only pick a material and specify thickness, it also results in significantly overdesigned structures. Orthotropic materials, particularly composite laminates, are more complex to design with as the design engineer must understand the impact of material orientation on the overall structural properties and tailor their design accordingly, though the resulting design is usually a more efficient design than one created using an isotropic material as they can achieve up to 3 DoFs. In order to make it easier to compare mechanical performance between isotropic and orthotropic material solutions, manufacturers of orthotropic materials often provide homogenized material properties for specific reference laminate configurations, effectively treating the structural properties of the entire laminate as a stand in for material properties of the laminate, which eliminates the need for the designer to understand the material properties of individual plies within the laminate.

Combinations of isotropic and orthotropic materials within the same structure have the benefit of "balancing" the more extreme orthotropic property effects, while still leveraging the performance advantages of having one direction with enhanced performance. In many practical designs, the load cases acting on a part can be deconstructed into primary and secondary load paths; therefore, being able to align the best properties in the primary load path without sacrificing too much performance along the secondary enables an efficient design solution. This principle is used in back-injected hybrid overmolding designs; however, this approach has a drawback in that the orthotropic material is used to establish the base thickness of the part, which means that the expensive composite is applied over the entire area of the part even in regions where its high mechanical properties are not being fully utilized.

1.4 Fiber Length-Scale Effects

J.L. Thomason [5-7] 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 3, 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.

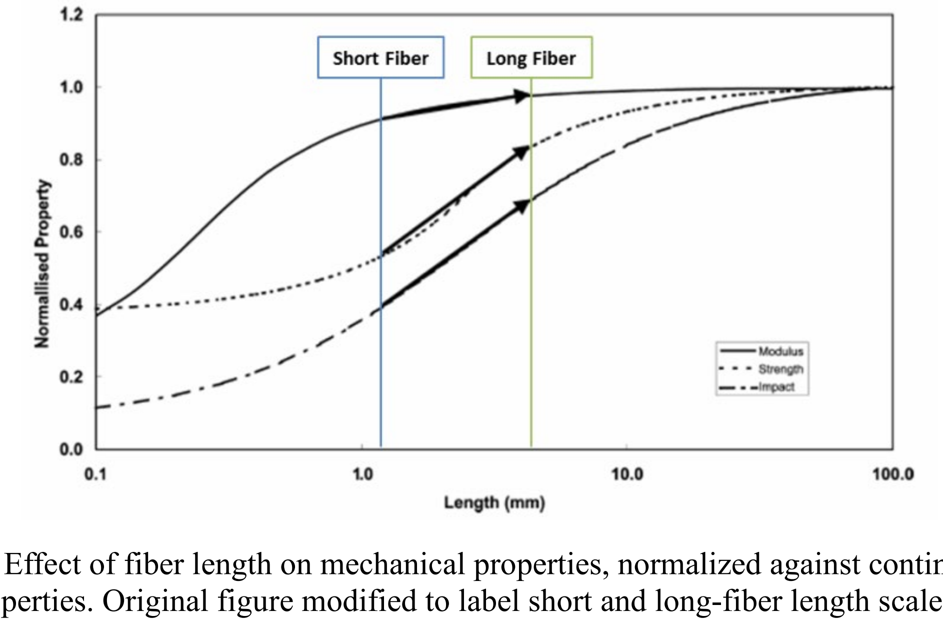

Figure 3: Effect of fiber length on mechanical properties, normalized against continuous-fiber properties. Original figure modified to label short and long-fiber length scales [6]

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, Ec = Vf * Ef + (1 - Vf) * Em. While Thomason shows that this may hold true for flexural modulus, there is a clear plateauing of tensile Young’s modulus around Vf = 0.4 (Figure 4). Furthermore, Thomason also demonstrates that both tensile strength and impact resistance peak around 40–50% fiber weight content (Vf = 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 5). Thomason posits that higher fiber volume fractions have a negative effect on both fiber distribution and residual fiber length after molding.

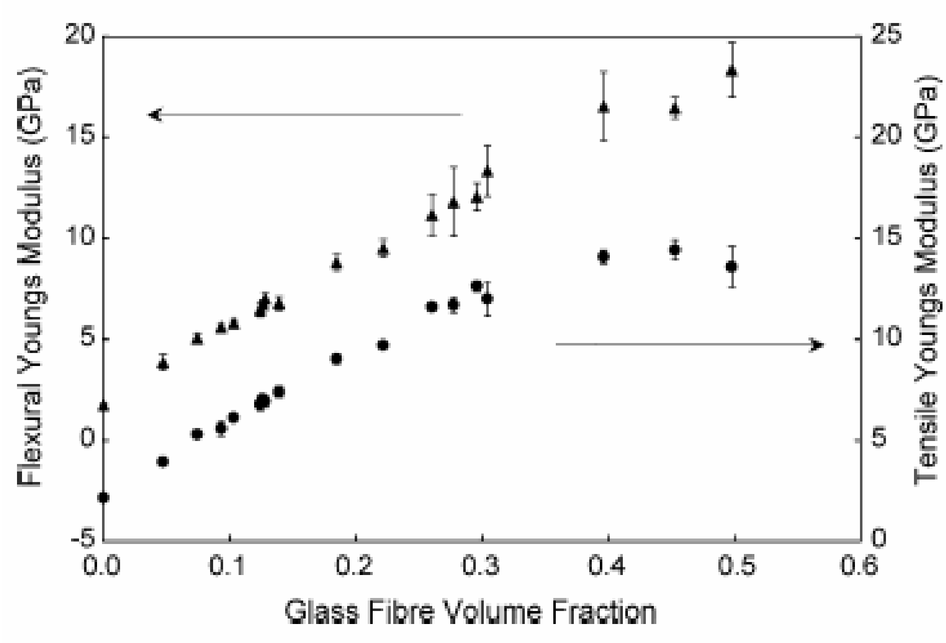

Figure 4: Plot of Young’s modulus vs. fiber volume fraction. Values for flexural (triangle) and tensile (circle) modulus are offset to show deviation [5]

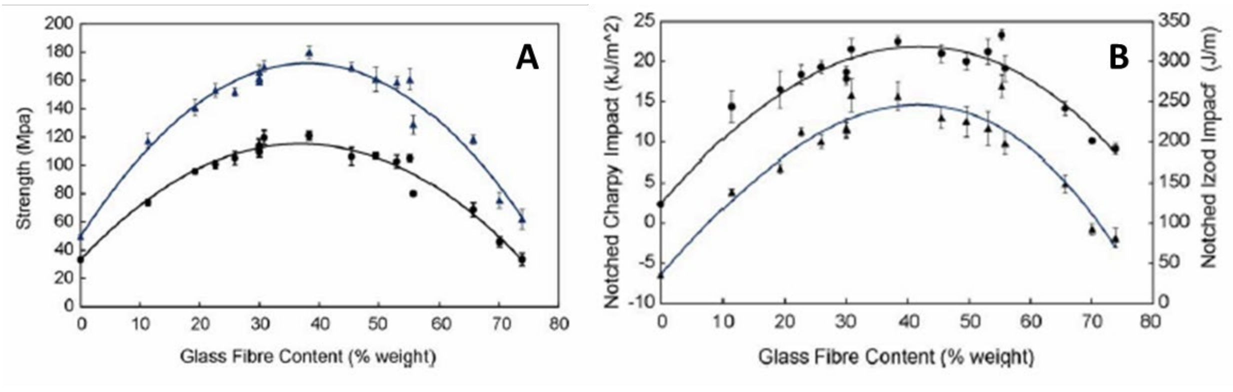

Figure 5: A is a plot of tensile strength (circle) and flexural strength (triangle) vs. fiber weight fraction. B is a plot of Charpy (circle) and Izod (triangle) impact resistance vs. fiber weight fraction. Charpy and Izod data is offset to improve readability [5]

2. THEORY DISCUSSION

2.1 A Brief History of Rebar for Plastics®

The Rebar for Plastics design methodology was the product of research conducted at the Georgia Institute of Technology (Georgia Tech) between 2014 and 2017 and has been subsequently refined after a startup company, WEAV3D Inc., was spun-out from the university in 2017. The researchers were developing a novel composite manufacturing technology that would be suitable for high-rate automotive manufacturing and, as part of a "design from fundamentals" approach, conceptualized a manufacturing and design approach that utilizes a lattice network of woven unidirectional thermoplastic tapes as a structural skeleton within a molded plastic structure, which would later be coined under the phrase "Rebar for Plastics" (Figure 6)

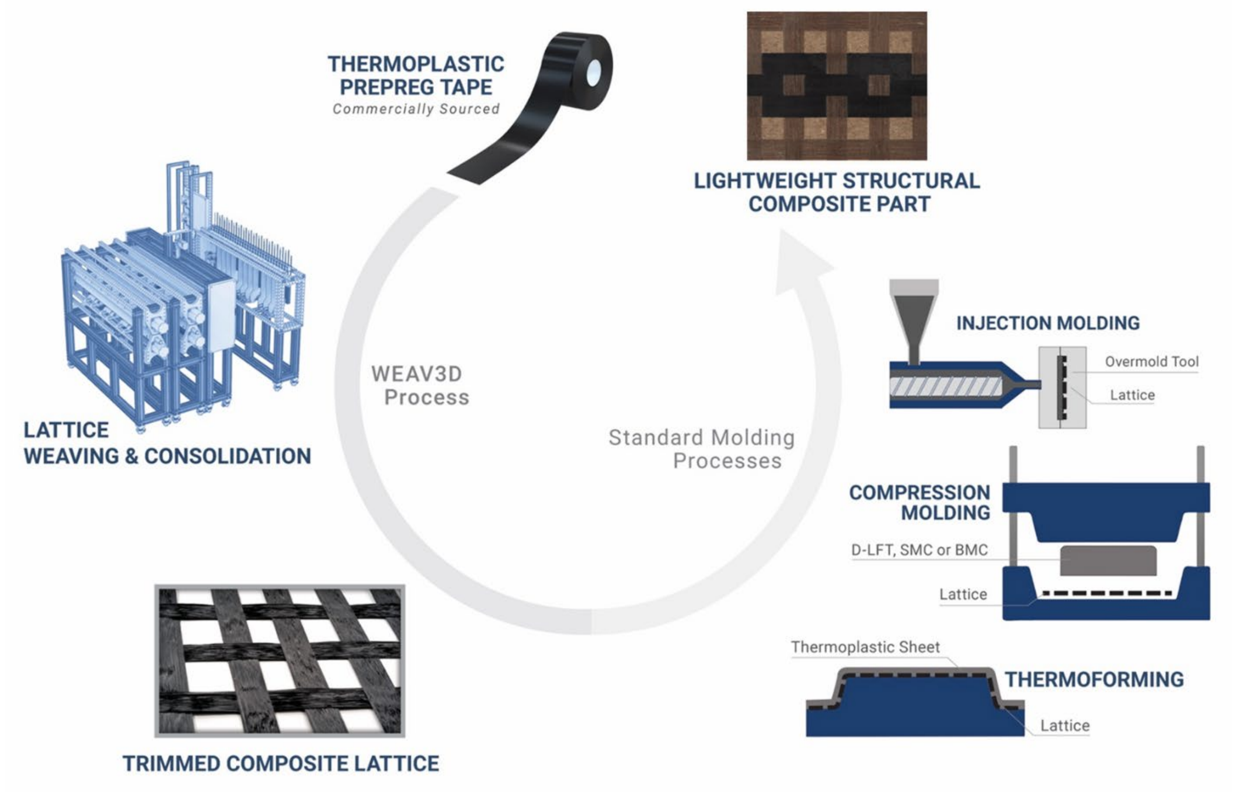

Figure 6: Overview of lattice forming and plastic molding process steps.

Conventional laminate designs rely on the plies to provide both the material properties and the geometry of the resulting structure. In uniaxial tensile loading, this is an efficient configuration as the stress is evenly distributed across the cross-section of the laminate; however, in bending the outer skins of the laminate are subject to maximum normal stresses (Figure 7), while the neutral axis of the laminate is subjected to maximum shear stress, resulting in an uneven distribution of stress over the cross-section of the laminate and therefore an inefficient use of material. Thick cross-sections generally switch from pure laminate construction to sandwich construction, where a core material (such as foam or honeycomb) is located between two laminate skins to improve design efficiency; however, for panel thickness less than 6mm, traditional core materials can become difficult work with and the marginal benefits for using them are limited.

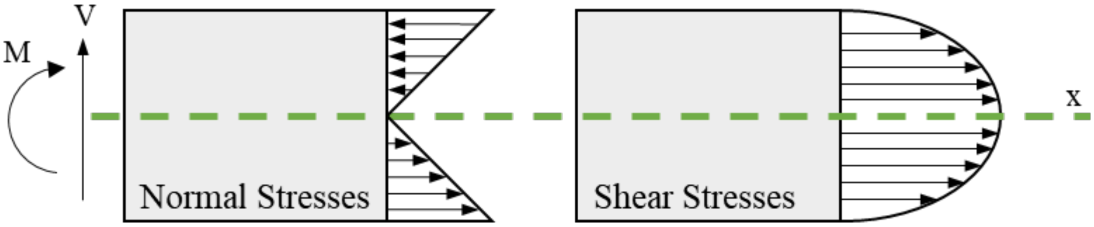

Figure 7: Diagram illustrating the distribution of normal stresses (left) and shear stresses (right) within the rectangular cross-section of a beam in bending

In order to decouple the geometry and material property effects, we conceived of laminating or molding a thermoplastic material onto a thermoplastic composite; however, unlike back-injection hybrid overmolding, we did not want to use a solid laminate stack up to provide the base thickness. Rather, our approach utilizes thin unidirectional tapes (ranging from 0.16 mm to 0.3 mm in thickness, depending on material type and manufacturer), assembled into a lattice structure where the spacing between tapes can be scaled up or down depending on the required structural properties. This lattice is then laminated, compression molded, or injection overmolded with a melt-compatible thermoplastic, which builds-up the thickness of the part and permits the integration of more complex features such as ribs, brackets, or clips. The thermoplastic material can be optionally filled with short or long fiber reinforcements, further adjusting the structural properties. This has the benefit of creating a hybrid length-scale composite, where the fiber volume fraction and fiber length for the filled plastic can be selected to optimize specific performance characteristics (such as strength or stiffness) separately from the lattice itself.

2.2 Four Degrees of Freedom and Metamaterial Behavior

While at the university, the initial focus was on demonstrating this Rebar for Plastics concept using homogenous lattice structures. We define a homogenous lattice structure as one that possesses uniform, repeat spacing between tapes in both the machine (warp) and cross-machine (weft) directions, though the warp and weft spacing do not need to be the same spacing. A homogenous lattice also only possesses a single tape material in each direction (ie. all weft tapes are glass/PP). When homogenous lattices are combined with molded with plastic (the bulk material), the resulting design contains at minimum 3 degrees of freedom (bulk and tape materials, part thickness, tape spacing), though the inclusion of varying thickness over the part area could create a 4th degree of freedom even with a homogenous lattice. Experimentation on homogenous lattice reinforced plastic panels demonstrated that these materials can significantly enhance the performance of the bulk plastic, boosting modulus by 10-25x and strength by 5-10x, depending on the tape type, spacing, and number of layers of lattice. This is a significant enough improvement that lattice-reinforced plastic panels can be considered a viable alternative to structures currently fabricated from sheet steel or aluminum.

While the performance of homogenous structures was excellent, it was also evident that the entire area of the part did not require the same mechanical performance and that reducing the amount of lattice material needed in non-critical regions would translate to significant cost savings, as the unidirectional tapes drive most of the material cost in the design. Work then turned to the optimization of heterogenous lattices. Unlike homogenous lattices, heterogenous lattices can contain regions where the tape material and/or tape spacing varies for the weft and/or warp tapes. In its most simple form, a heterogenous lattice is designed by subdividing the original part into regions of high and low stress and then designing a homogenous lattice within that region. As shown in Figure 8, the homogenous design from each subregion is assembled into single lattice, and tapes that pass from one subregion to another must maintain the same tape type and spacing to enable manufacturability, though tapes that are fully contained within a single subregion can differ from those in neighboring subregions.

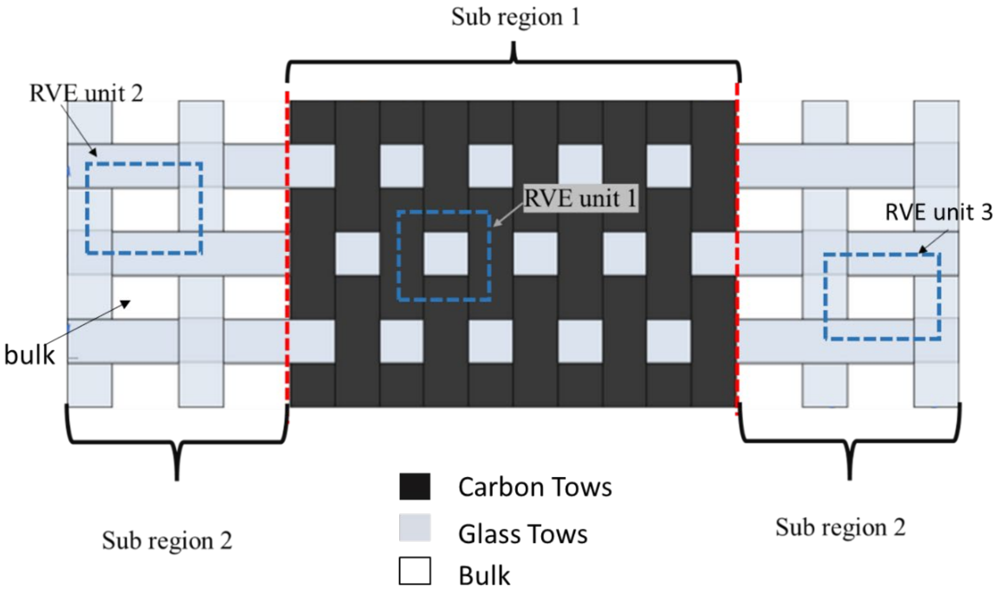

Figure 8: Example of simple heterogenous lattice with two subregions, the representative volume element (RVE) represents the homogenous repeat unit of the subregion. Tows = UD Tapes

This heterogeneity represents the first step into a fully 4 DoF design; however, as long as the regions are large, containing multiple repeat units of the homogenous pattern within them, the part does not exhibit continuous variation of mechanical properties over its surface. Rather, homogenized material properties of the part exhibit discrete step changes at the boundaries of the subregion. By decreasing the region size to around the length scale of the lattice unit cell, it is possible for the panel to exhibit continuous variation of homogenized material properties over its entire surface (or at least the surface where lattice has been applied), creating a true metamaterial, ie. “a synthetic composite material with a structure such that it exhibits properties not usually found in nature” [3]. An example of this is shown in Figure 9, where an automotive component was initially partitioned into two subregions, a bulk only subregion (left and right sides of part) and a lattice reinforced subregion. Within the lattice reinforced subregion, there is a heterogenous lattice structure that consists of one homogenous subregion (with 4 tapes side-by-side) and one continuously variable heterogenous subregion containing 3 tapes that all differ in spacing from one another. Within this continuously variable heterogenous subregion, we can observe metamaterial behavior as the homogenized material properties of the panel will vary depending on exactly where the load is applied relative to the tapes and the proximity of neighboring tapes to one another.

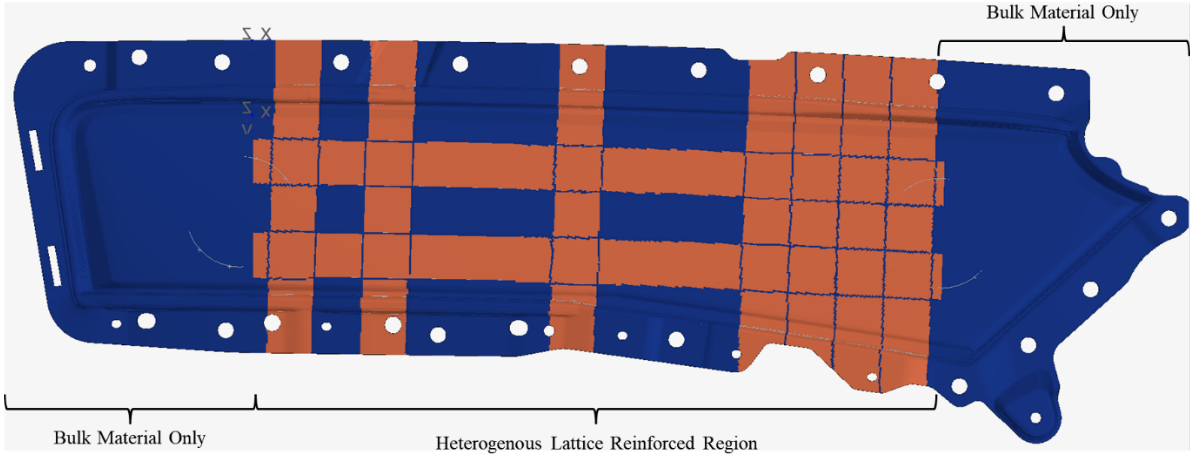

Figure 9: Heterogenous lattice reinforcement of automotive component, blue color represents bulk material, orange represents UD tapes

Leveraging this variability of homogenized material properties over the lattice reinforced area permits extensive optimization of lattice reinforced structures to minimize cost and performance. As illustrated in Figure 9, not every area of the part needs to be lattice reinforced and even in those areas that do require reinforcement, the degree of reinforcement required is dependent on where the load is applied and the distance from the load to fasteners and bonded joints. This enables cost reductions upwards of 70 % relative to a homogenous lattice that is applied over the entire surface of the part.

The continuous nature of the fiber reinforcement in the unidirectional tapes in combination with the substantially higher tensile modulus of these tapes relative to the bulk material also produces a heterogenous stress response when the structure is subjected to deformation. In pure tension, it is obvious that the tapes will strain-control the elongation of the structure and therefore the tapes are subjected to higher stress than the bulk material; however, this behavior also holds true for bending load cases as well. Figure 10 shows the stress plots of three designs, all subjected to the same load case and boundary conditions. On the left, where the panel contains no lattice reinforcement, the stressed region covers a wide area and declines evenly from the maximum in the middle towards the left and right supports. When a homogenous lattice is introduced in the middle image, the amount of stress carried in the bulk declines substantially (in both amount and area), while the amount of stress carried by the tapes of the lattice is 2-3x greater than the maximum stress in the bulk-only design. This increased stress is trivial for the tapes, as it is still less than 25 % of the tape's yield strength. In the third design, two tapes are removed from the homogenous design to produce a heterogenous lattice. Accordingly, stress in both the tapes and bulk material increases from the homogenous case, though the size and intensity of stress in the bulk still remains below the bulk-only base case.

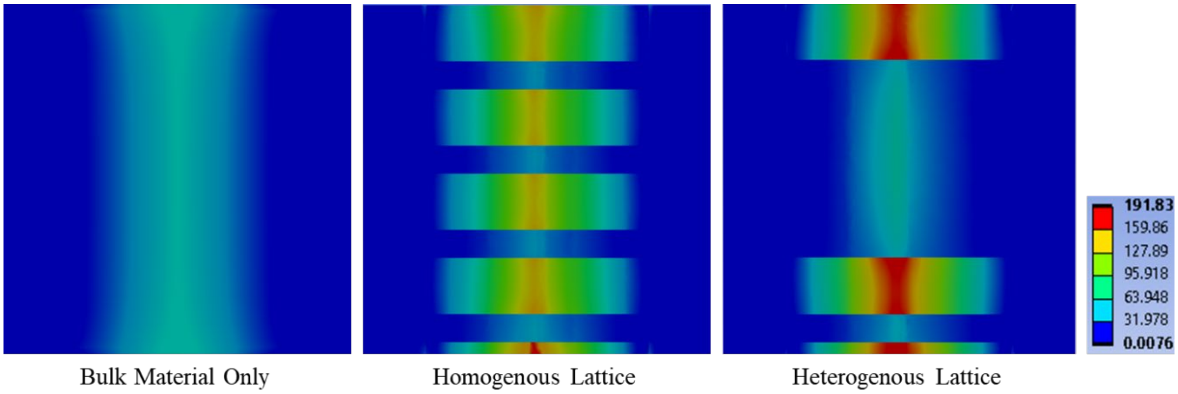

Figure 10: Von Mises stress plot from FEA simulation of 3-point bending with various degrees of lattice reinforcement, perspective is from underside (tensile region) of panel

2.3 Hybrid Length Scale Effects

The DoF 4, hybrid length scale composite that we present in this paper is effectively a “composite of composites”. For example, the bulk material can comprise a 30% short glass polypropylene compound that is then reinforced by a composite lattice consisting of unidirectional carbon fiber polypropylene tapes. Each of these materials has microscale composite properties on their own, but we are now creating a macroscale composite, wherein the bulk material acts as the macro-matrix and the UD tapes as the macro-reinforcement. By tweaking the relative volume fraction of these macro-constituents, such as by increasing or decreasing the part thickness or by increasing or decreasing the lattice density, we will achieve a completely different homogenized material property for the structure. And this is even before we start substituting materials within the macro-constituents.

It is therefore important for us to understand the fundamental micromechanics that influence macro-scale performance so we can determine which variables drive which mechanical properties. For simplicity, we will focus on three properties – stiffness, strength, and toughness and for the purpose of this section, we are assuming that these are homogenized material properties for a given structural design. Based on the literature, these properties can be correlated to the following mechanisms of action:

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

Given that we are dealing with a composite of composites, these mechanisms of action occur on two different length scales – the microscale within each macro-constituent and the macroscale between the macro-matrix and the macro-reinforcement. Modulus behavior of the macro-structure is the easiest to predict, as it is predominately controlled by the microscale properties of each macro-constituent and their relative location within the structure; therefore, they are relatively straightforward to model computationally. Strength and toughness, though, both require an understanding of stress distribution within the structure (as shown in the previous section) and the relative interaction of the macro constituents both before and after failure. As the distribution of stresses between the tapes and bulk material is dependent on the relative volume fraction of each constituent and the difference in modulus between them, it is possible to engineer the part to trigger failure in one constituent phase before the other and, if the goal is to fail the macro-reinforcement phase first, a heterogenous lattice can be designed with 2 or more tape materials to engineer failure in one of the tape materials before the other. This effectively allows the designer to choose between simultaneous and non-simultaneous failure of the constituent phases. In the former case, the material will exhibit high strength, as the stress is more evenly distributed between the materials as a percentage of their yield strength, but it also means that the failure is likely to be brittle, unless the bulk material has very high ductility. In the latter case, the strength of the structure will be reduced, but toughness will increase due to the sequential failure of the materials.

2.4 Manufacturing Effects and Considerations

Due to the reliance on tape spacing and hybrid length scale material interactions to generate the resulting part-level performance, manufacturing processes have a strong impact on the final properties of the structure. The composite lattices produced by the WEAV3D continuous composite forming process are compatible with common plastic molding processes, including thermoforming, compression molding, and injection molding; however, each of these processes has its own benefits and limitations when it comes to implementing the Rebar for Plastic design.

Thermoforming and compression molding of nonwoven mats (such as natural fiber reinforced polypropylene mats) exhibit similar constraints, in that the lattice need to be located onto the base sheet and either laminated (for thermoforming) or tack welded (for compression molded mats) to facilitate a consistent position of the lattice in the final part. The lattice can be applied to one or both sides of the sheet, depending on the mechanical and visual requirements of the part, and during molding the lattice will become embedded flush into the panel surface, displacing or compressing material in the base sheet. If a significant amount of material is displaced, this will cause in-plane flow that can distort the tapes in the lattice leading to a reduction in mechanical performance, so it is important to minimize displacement when matching base sheet thickness against the desired final part thickness. The fact that these sheet materials consist of a constant thickness over their area is not a significant limitation to optimization, as the heterogeneity of the lattice can be used to vary strength and stiffness response over the area.

Injection molding and D-LFT compression molding both unlock thickness variation over the part area, but it is important to understand how this variation, particularly ribbing, can have negative effects on part performance if applied in the wrong area. For bending-dominated load cases, it is critical that the lattice remains the material furthest from the neutral axis within the cross-section, unless the material applied is of very low modulus and high elongation, such as a foam or rubber. If ribs are used in the part, they should not be located on top of a tape as this will have the effect of placing tape near the neutral axis, rendering its effect on bending strength and stiffness nearly zero. If greater bending stiffness is desired for specific regions, and assuming the lattice pattern is held constant, the base thickness of the panel in those regions can be increased to increase the distance between the lattice and the neutral axis, leveraging the thickness cubed effect as discussed previously in Section 1.2.

As most lattice structures are not fully dense, the standard process of using injection pressure to compress a composite laminate against the tool surface (one-step molding) is unreliable. Rather, it is important that any injection or D-LFT mold contain locating and holding features to keep the lattice against the tool surface and prevent wash-out. It is also recommended, especially for complex part shapes or gating that creates high shear along the fill path, that the lattice be preformed to match the contour of the mold. If implemented correctly, this approach of preforming and holding the lattice will prevent plastic from flowing between the lattice and the tool during molding, even in designs where lattice is located on both the core and cavity sides of the mold.

In all processing cases, the hybrid length-scale of the constituents also impacts part warpage. In cases where unfilled or short fiber filled plastic is selected for the bulk plastic, there may be large difference in the coefficient of thermal expansion (CTE) between the bulk plastic and the tapes. If lattice is only applied to one side of the part, the part is likely to warp “away” from the lattice side, as the bulk shrinks by a larger amount on cooling than the lattice does. This warpage effect is most pronounced on large, flat structures, but can also be observed on more complex shapes if not compensated for. That said, if the exact same combination of materials is used to produce a panel with lattice located on both sides of the part, the warpage will be almost zero as the top and bottom planes are equally constrained from shrinking, though considerations may still need to be made for thermal stresses induced in the high CTE material. Small amounts of warpage can also be observed with single-side lattice reinforcement of flat panels produced with a long fiber filled bulk plastic, but even that approaches zero in parts with complex shapes.

While we believe the WEAV3D continuous composite forming process is the most cost-effective way to manufacture the lattice structures we described in this paper, automated tape laying could replicate many of the heterogenous tape spacing and heterogenous tape material arrangements presented here, though without being able to weave the tapes together there would be some loss in handleability and resistance to delamination. For the aerospace industry, where even small amounts of optimization can be worth increased manufacturing cost, references in the literature (REF) have demonstrated that steerable automated fiber placement can generate laminate layups comprising arcs of tows exhibit a variable stiffness effect, and we believe that this technique could be applied to hybrid overmolded structures as well. [1]

3. Case Study

As part of a recent study to validate the Rebar for Plastics design methodology, lattice reinforced plastic panels were compared against traditional organosheet laminate. A total of four lattice reinforced designs were manufactured (Designs A-D, Table 2) with the lattice density and UD tape type (Glass/PP, Carbon/PP, a mixture of both) varying to illustrate the effect of various input properties on the modulus, strength, and toughness of the panels. Lattices for each design were produced using 25.4 mm wide tapes in the WEAV3D process. Panels of each design was fabricated via compression molding of lattice and polymer sheets and after waterjet trimming, the designs were tested in 3-point bending according to ASTMD790 standard, modified to accommodate a 150 mm-wide specimen, and a minimum of 3 specimens were tested for each design.

Table 2: Summary panel designs, all panels 2 mm, with lattice on both sides

	Bulk Material	Lattice Material	Tape Spacing (C-to-C, mm)	Areal Density (g/m^2)
Organosheet	2/2 Twill Laminate – Carbon/PA6			2990
Design A	Unfilled PP – Braskem TI4003F	Glass/PP	25.4	2560
Design B		Carbon/PP	25.4	2190
Design C		Carbon PP	50.8	1985
Design D		Glass/Carbon/PP	25.4 (alternating C and G)	2395

Figure 11 shows the averaged stress-strain curve for each design. It should be noted that Design B was prematurely stopped before reaching ultimate failure due to operator error, so we have provided a dotted line indicating the expected behavior based on prior tests that used an alternative polypropylene grade. The organosheet panel exhibited a flex modulus of 39 GPa and flex strength of 400 MPa, exhibiting sudden, brittle failure at around 1.2 % strain. Designs A, B, and C exhibit an initial peak strength, followed by a progressive failure window of between 0.5-0.7 % strain after peak strength as the tapes on the top side of the panel fail due to compressive buckling. Design D, due to its alternating glass and carbon tapes, exhibits two strength peaks due to non-simultaneous rupture, each around 300 MPa, resulting in a progressive failure window of 1.8 % strain. Referring back to Section 2.3, the size of drop between the flexural yield strength and the residual strength is related to the relative stiffness between the bulk and reinforcement material, with designs containing higher modulus tapes exhibiting a smaller drop, as evidenced by the ≈50 % drop in strength in Design A (glass) vs. the ≈17 % drop in strength for Design C (carbon).

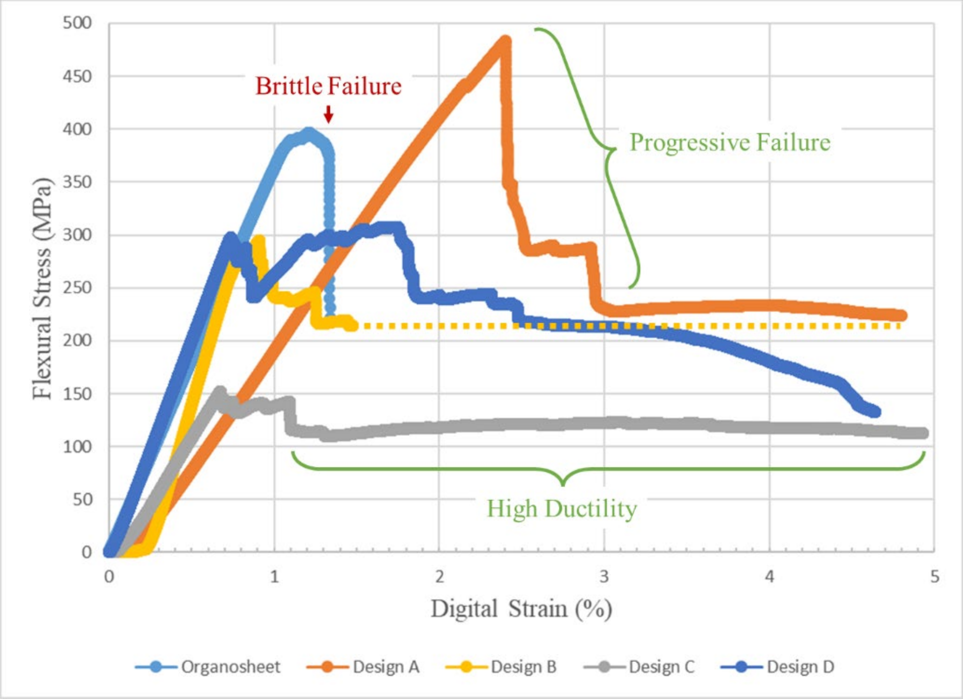

Figure 11: Flexural stress-strain plot for organosheet (baseline) and Designs A-D; brittle failure of organosheet is contrasted with progressive, ductile failure mode of lattice-reinforced panels

Compared to the organosheet baseline, a number of counterintuitive effects can be observed from this data. Design A, based on glass/PP tapes, is both stronger (+25 %) and lighter (-14 %) than the carbon fiber organosheet, while Design B, despite containing less carbon fiber than the organosheet is both stiffer (+ 36%) and lighter (-27 %), albeit at a reduced strength (-26 %). Design C is 22 % lighter than Design A but achieves the same flex modulus, as it utilizes carbon fiber tapes instead of glass fiber tapes, but with a more open center-to-center spacing. Design D was produced after reviewing the A-C test results, with the goal of developing a less expensive version of Design B that more closely matched the modulus of the organosheet. This was achieved to within 0.5 GPa.

All of the tested lattice designs exhibited a high degree of ductility, requiring the test to stop between 4.6 % and 5 % strain when the extensometer reached its limit of travel. After the top-side compressive fracture, the bottom side lattice continues to carry tensile stress, while the polypropylene that was previously in the middle of the panel starts to yield in compression as stress redistributes after initial fracture. The result is very high flexural toughness (area under curve), with Design C achieving a toughness double that of the organosheet, while Design D achieved a toughness more than 3 times that of the organosheet thanks to its good initial modulus, wide, double peaking progressive failure region, and long ductile tail.

Due to the size limitations of most universal testing machines setups, it is difficult to evaluate the heterogenous behavior (either subregion or continuous) on anything less than the part scale. While Designs A-D represent homogenized properties of homogenous lattices (A-C) and material heterogenous (D) lattices, the previously presented Figure 9 illustrates a part containing a truly heterogenous material, where the part level stiffness response varies depending on where the load is applied. Starting from an initial homogenous lattice pattern that was evenly distributed over the lattice reinforced region, iterative FEA optimization was used to increase the density of the lattice in regions that required greater stiffness, while reducing lattice in regions that did not require as much stiffness, resulting in the aforementioned heterogenous pattern. Applying a consistent load at three different locations over the part resulted in different deflection responses in each location.

4. SUMMARY

This paper presented a new design methodology, Rebar for Plastics®, that unlocks a fourth design degree of freedom through the ability to tune material type and material spacing within a layer of a structure. Combining woven composite lattice structures produced using thermoplastic unidirectional tapes with conventional plastic molding processes suitable for high-rate production, this approach enables highly optimized and cost-effective structures with variable stiffness, strength, and toughness properties over the area of a part.

An initial review of fundamental concepts including composite beam theory, homogenization of orthotropic materials, and fiber length scale effects, was provided to help the reader understand the mechanics underpinning the Rebar for Plastics design methodology. Following this was a brief history of the development of this methodology, in response to demand from the automotive industry for cost effective, high-rate composite materials and the design limitations inherent to traditional laminate and sandwich panel structures.

Composite lattice structures were introduced, initially in the form of homogenous lattices and then as region-segmented heterogenous lattices, consisting of varying tape spacing and/or tape material, before the concept of continuous varying heterogenous structures was presented. These continuously variable heterogenous lattices enable metamaterial behavior, wherein the homogenized material properties of the structure can vary continuously over the surface of the part, with the lattice used to concentrate stress away from the bulk plastic to create highly optimized structures. Hybrid length-scale effects based on a “composite of composites” theory of hybrid composites were presented with explanations detailing the relationship of microscale properties to macro-constituent properties and how material selection within the macro-constituents, relative location within the cross section of the macro-reinforcement(s), as well as the relative volume fraction of the macro-matrix to the macro-reinforcement, can be used to tailor the yield strength and toughness behavior of the overall structure. Manufacturing considerations, particularly related to tape distortion, rib locations, and warpage were discussed and recommendations to mitigate negative effects were provided.

A case study involving the design of homogenous and heterogenous lattice-reinforced polypropylene panels was presented to illustrate the differences between conventional organosheet laminates and structures designed with the Rebar for Plastics methodology, in terms of stress-strain behavior and overall mechanical performance. This case study illustrates that lattice-reinforced panels can exceed the performance of carbon fiber organosheets, while utilizing substantially less carbon fiber and providing significant weight savings. The ability to tune strength, stiffness, and toughness using the Rebar for Plastics design methodology was also showcased.

WEAV3D is currently working with several automotive OEM, Tier 1s, and material suppliers to design, fabricate, and test components based on the Rebar for Plastics design methodology presented in this paper. We anticipate publishing the results of these activities within the next 12 months. In parallel, research funded by the National Science Foundation will enable the creation of a database of reference designs that will support ongoing efforts to validate a new, goal-seeking Rebar for Plastics simulation workflow that is currently in development.

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