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Editorial

Editorial for the Special Issue on Advanced Fiber-Reinforced Polymer Composites

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Fiber-reinforced polymer (FRP) composites are ubiquitous structural materials owing to their high specific strength, impact resistance, and scalable manufacturing. Unlike other structural materials, FRP composites can be engineered and optimized to fulfill specific engineering purposes with their tailored mechanical behavior. More recently, researchers have developed methods to integrate non-structural functions in the composites. The new functionalities include energy harvesting, [1,2] force sensing, [3,4] damage detection, [5,6], ballistic impact resistance, [7,8] electromagnetic shielding, [9,10] UV resistance, [11,12], and so forth. In advanced composite materials, the reinforcing fibers can be selected from various synthetic or natural fibers in the form of short fibers, continuous tows, or woven fabrics. The polymer matrix can be a thermoset or thermoplastic with different thermal and mechanical properties. FRP composites have gained even more popularity in the recent years due to the progress in additive manufacturing. With the increasing demand and user experience, there is a major demand for new materials, fabrication methods, characterization techniques, and design frameworks. This Special Issue focuses on advanced composites with tailored mechanical properties and integrated functional properties. We present an overview of the studies published here.

To promote sustainable composite materials, Saleem et al. [13] studied natural fibers as a reinforcement in polymer composites. In this study, efforts were made to improve the structural integrity of bast (flax + kenaf) and basalt hybrid FRP composites. For the polypropylene matrix, the tensile strength and flexural strength of the composite with tailored coating was increased by 39% and 44%, respectively, when compared to epoxy-based basalt composites [13]. In a separate study, Fehri et al. conducted experimental and simulation studies on the damage process in flax fiber-reinforced polymer composites under buckling load [14]. They performed continuous buckling on specimens while monitoring damage propagation via an acoustic emission system. They concluded that for natural fiber composites the mechanical properties can be improved by controlling the process parameters (such as the pressure which affects the compaction of the material) to minimize porosity and enhance the adhesion between the fiber and the matrix [14]. Another bottleneck for these composites is processing them with specific geometries. The article by Al-Obaidi et al. [15] introduced induction heating to bond basalt FRP laminates. To achieve this, they used a method termed inductive contact joining (ICJ) and compared the results with two common joining mechanisms (nut and bolt, and two-piece hollow riveting). It is expected that ICJ will become a favorable processing method for fiber-reinforced thermoplastics because during this process the fibers were not damaged and the strength of the base material was maintained [15]. Cellulose-based composites are another class of biobased materials that are environmentally friendly and can be incorporated into a material system at different scales. For instance, cellulose nanocrystals (CNC) can be used as a functional coating. In an article by Xu et al. [16], atom transfer radical polymerization (ATRP) was utilized to attach azobenzene monomer brushes to CNC to be

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used in polymer nanocomposites [16]. This surface modification allowed for the application of CNC in hydrophobic polymer matrices. The azo-polymer grafted cellulose nanocrystals in this study could be used for the uniform coating of various surfaces. Another study on biobased nanocellulose composites in this Special Issue is the work published by Dalle Vacche et al. [17] In this article, raw materials were derived from biomass waste. In particular, cellulose nanofibers were obtained from unbleached hemp fibers and used as a filler. The authors used UV light to cure the composites and were able to produce nanocomposite films that were transparent, hydrophobic, water-resistant, and a brownish color. Moreover, they showed a high flexibility and rubbery behavior at room temperature due to their low glass-transition temperature [17]. These studies demonstrate the new opportunities offered by biobased materials to be used as both structural and functional materials in the future.

When designing structural composites, certain consideration should be given to the z-direction reinforcement. Specifically, z-pin reinforced laminates were explored by Knopp and Scharr [18]. They experimentally investigated the effect that circumferentially notched z-pins with different notch designs had on the in-plane tensile properties of unidirectional fiber-reinforced composites. It was found that the notches at the z-pin surface had no significant effect on the mechanical in-plane properties of the pinned composite. In terms of tensile strength, all notch designs experienced the same reduction caused by the z-pins as compared to the unnotched pins. However, the notch distance at a constant notch depth and width slightly affects the resulting tensile strength with the long notch distances performing better than the short notch distances. In terms of Young's modulus, no effects were observed when comparing the z-pinned to the unnotched z-pinned specimens. While structural properties have been experimentally and theoretically determined in these papers, composite processing must also be studied to bring the designed composites to reality. Processing considerations change depending on the fiber and matrix materials. A specific system containing glass and carbon fibers, binder and a foam core material in anionic polyamide 6 was investigated by Herzog et al. [19] The problem with polyamide 6 is that it is very sensitive to moisture absorption, and so the water sorption behavior of the composite constituents were studied in order to determine its proper processing protocols. It was found that the moisture absorption was 1 mg/g for the fibers, 14–70 mg/g for the binder and foam, and 110–500 mg/g for the matrix. While the absorption seemed low for the fibers, they are typically 40–60% of the volume of the composites, so they should be dried prior to being embedded in the matrix. Herzog et at. also recommended drying the foam core prior to composite processing. Overall, they highlighted that material handling concerns exist when processing composites, especially moisture sorption in the case of polyamide 6, and proper protocols must be used in order to avoid the degradation of the matrix material.

Advanced modeling techniques are required to predict the behavior of FRP composites because they consist of multiple phases with different characteristics. Depending on the arrangement of the fillers, a proper modeling approach should be utilized or developed. A common approach for modeling composites is employing a proper homogenization technique [20]. Dhimole et al. used a two-step homogenization scheme to model aperiodic heterogenous 3D four-directional braided composites [21]. In the first step, the microscale effective mechanical properties were determined by considering fibers and the matrix, while in the second step, the final effective mechanical properties of the mesoscale model were obtained by considering yarns and the matrix. The results were comparable to finite element results performed by a commercial software. Although purely elastic models are simple and yet provide useful information about the composites, more advanced models should be developed for emerging composite materials. In an article by Lüders, [22] a nonlinear-elastic orthotropic material model of an epoxy-based polymer was proposed to capture the tension/compression asymmetry of the resin in FRP composites. Comparing the results with the literature and finite element analysis (FEA), they showed a high accuracy of the proposed model for matrix-dominated loading conditions. In addition to predicting the effective elastic properties, it is important to study the strength of the components made from FRP composites. Kanno et al. [23] investigated the through-thickness stresses of woven glass FRP composite laminates under a combined tensile and shear loading. They calculated the stress distribution through FEA simulations and examined the failure conditions of the specimen [23]. This study provided useful information regarding the relationship between interlaminar tensile and shear strengths of glass fiber composites under both tensile and shear loading.

Mechanics models can be also used to optimize the structure, when designing composites for structural applications. Mehl et al. [24] investigated these structural optimizations by improving topology optimization tools to account for material stiffness and property anisotropy in both the reinforcing fibers and matrix and in hybrid structures that utilize short fibers and locally continuous fibers. This effort resulted in the optimized beam structures with less struts, thus reducing the manufacturing complexity. Advanced modeling can also be implemented to generate virtual tests of composites. Giannopoulos et al. [25] developed two numerical strategies of differing levels of fidelity to predict damage during ballistic impact. They performed ballistic impact experiments to benchmark the two numerical models. It was found that the low- and high-fidelity models differed in their ability to capture inter- and intra-laminar damage and overall energy absorption. Overall, it was found that the low-fidelity tests provided a good prediction of the impact damage thus the 80% higher computational cost of high-fidelity models could be avoided by using the low-fidelity model to produce useful impact damage predictions from ballistic impact.

Lastly, two review articles are published here: one on the additive manufacturing of FRP composites and one on the multiscale experimental study of natural fiber composites. The article by Krajangsawasdi et al. [26] reviews the fused deposition modelling (FDM) of fiber-reinforced polymer composites and provides insights into how the mechanical and thermal properties of 3D-printed fiber-reinforced thermoplastic composite materials are affected by printing parameters and constitutive materials properties such as polymer matrices and the type of fillers [26]. The review article by Teramoto [27] discusses the role of compatibilizers in cellulosic FRP composites as one of the popular carbon-neutral fillers for reinforcing polymers. In particular, the author presents a progress report on recent multiscale experimental methods used for the detection of covalent bonds between the cellulosic filler and compatibilizer, estimation of nanoscale interphases, and the micron-scale dispersibility of the fillers [27]. These works highlight the importance, challenges, and opportunities in the additive manufacturing of FRP composites and biobased composites as new trends in this field. As we observe the increasing use of fiber-reinforced polymer composites in industry, we expect to see an increase in the research and development of advanced composite materials with enhanced structural performance and embedded functionalities.

Conflicts of Interest: The authors declare no conflict of interest.

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