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Sustainable Hybrid Composites for Formula Crash-box Design: Experimental and Numerical Analysis

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Passive safety components in racing automotive vehicles operate at the intersection of lightweight, structural efficiency, and energy absorption. Although in motorsport applications, carbon fibers remain the standard composite reinforcements with demonstrated mechanical performance and guaranteed structural integrity, growing sustainability requirements have spurred interest in alternative green materials. In this context, natural fibers have been a prominent focus of recent research and industry studies. Their renewability, wide availability, low environmental impact, and good energy-absorption capability make them a promising sustainable alternative to synthetic reinforcements such as carbon fibers. Nonetheless, their mechanical properties are inferior, making the application of natural fibers to structural components still challenging. These structures, indeed, operate under extreme performance conditions whilst simultaneously meeting stringent lightweighting requirements. A possible solution to balance sustainability benefits and performance reduction is hybridization, which integrates conventional and bio-based materials. The ultimate goal of this study is to incorporate flax fibers into a Formula crash-box, aiming to meet certification requirements while reducing the carbon footprint. A design methodology is developed that integrates experimental procedures and finite element analyses to reduce the time and cost of the prototyping phase and optimize the overall design process. The crushing efficiency of the carbon/ and flax/epoxy materials is evaluated by conducting impact tests under varying loading conditions and geometric configurations, with a focus on the effect of curvature on energy absorption. Flat and corrugated coupons, circular and square tubes are tested using pure carbon and flax reinforcements, as well as interply hybrids. Optimized material cards derived from the mechanical characterization of the composites of interest are applied to the properly designed numerical models, which accurately predict the experimental responses. A macro-scale model is then developed to reproduce the structural-level performance observed in standard homologation tests for a carbon crash-box. Finally, flax fibers are successfully incorporated into a hybrid carbon-flax configuration. In particular, a genetic optimization is implemented to determine the optimal stacking sequence that maximizes crashworthiness performance and sustainability of the crash-box. The optimal carbon-flax solution is then tested under the homologation conditions and shows good agreement with the numerical simulation prediction, achieving energy absorption comparable to that of the pure carbon fiber alternative while remaining within the imposed weight limit.

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