Abstract

The evolution of textiles has significantly influenced human civilization from its earliest days. Initially used for protection against environmental elements, textiles have progressively branched out into myriad applications including adornment and, more notably, into a spectrum of industrial and technical domains over the past five decades. Textiles, whether natural like silk, wool, and cotton, or synthetic like nylon, polyester and high-performance fibers, are fundamentally classified by their fiber composition and structural characteristics, which dictate their suitability for specific applications. This classification spans simple two-dimensional structures to complex three-dimensional and hybrid constructs, each engineered to meet the precise demands of diverse applications ranging from medical textiles to aerospace and defense. The advent of technical textiles has marked a dynamic shift in the textile industry, promoting intensive research and skill development well beyond traditional textile manufacturing. The drive for innovation in this sector has fostered the development of advanced materials, notably three-dimensional (3D) textile structures, designed to overcome the limitations of conventional 2D laminates such as poor delamination resistance and inadequate out-of-plane impact properties. These 3D structures are crafted through sophisticated weaving techniques that integrate high-performance fibers like Kevlar, Zylon, and carbon, offering enhanced mechanical properties and reduced weight, making them ideal for high-stakes applications in ballistic protection, automotive, and structural reinforcements. 3D woven structural composites are materials reinforced with textile preforms, which can range from two-dimensional weaves to intricate three-dimensional frameworks, and bonded with a resin matrix. These composites offer a remarkable array of benefits over traditional materials such as steel or wood, including superior specific strength and stiffness, lightness, robust fatigue resistance, pronounced

directional properties, and enhanced design flexibility. 3D woven fabric-reinforced composites (3DWFRCs) excel in their interlayer bonding and shear strength, showcasing remarkable tolerance to damage and proficiency in energy absorption when subjected to impact forces. These attributes streamline the processing and reduce the production time compared to more traditional composite materials. Owing to their lightweight yet robust nature, these composites are increasingly being adopted in sectors demanding high-performance materials, such as the aerospace industry, high-speed transport, and personal and vehicle armor. The integral structure of three-dimensional textile composites, with fiber bundles permeating the material's thickness, imparts exceptional resistance to cracks and fatal fractures, making these materials particularly adept at withstanding wear and tear. The ability to net-shape manufacture the reinforcement means that uniquely contoured components can be created using one-step molding processes, circumventing the potential weaknesses introduced by conventional joining techniques. The versatility of textile structures, coupled with their amenability to form complex configurations, affords textile structural composites significant advantages in crafting intricately shaped parts that other composites may struggle to achieve. Consequently, the microstructure of these composites can be tailored to maximize impact resistance, providing a strategic advantage in designing materials for a variety of cutting-edge applications.

The primary goal of this study is to provide a comprehensive framework for the development and mechanical assessment of a wide variety of 3D woven solid structures with applications in cutting-edge engineering. The aim is to comprehensively investigate the dynamic impact resistance and damage tolerance of 3D woven fabric-reinforced composites (3DWFRCs) under controlled low-velocity impact (LVI) settings. This study investigates the resilience of 3DWFRCs to LVI events that simulate the real-world conditions these materials would face when integrated as structural components within complex engineering systems, with a primary focus on enhancing their effectiveness and reliability for high-performance applications. To achieve this, a diverse set of systematic methodologies were developed to explore the influence of various weaving aspects on the mechanical properties of 3D woven structures and their composites. In the first phase, the investigation specifically focused on three distinct categories of 3D woven dry solid structures to determine their impact response to low-velocity impact events. Manufacturing these 3D woven preforms, primarily using E-glass roving and varying weave architectures, presented challenges that necessitated numerous precautions to ensure high-quality outputs with consistent areal density. Results reveal that various factors, including different binder yarn pathways, stuffer binder ratios, inter-yarn crossover points, and the preform's fiber volume fraction (FVF%) in the stuffer, warp, weft, and binder directions, significantly influence how dry woven preforms respond to low-velocity impacts. It was observed that structures with high inter-yarn crossover points exhibited enhanced impact resistance in out-of-plane impacts across both single and multiple impact scenarios. The inter-yarn crossover points are crucial in determining the formability of the structures, influencing their compactness and how the primary reinforcements react during the low-velocity impact (LVI) events. It has been determined that a higher number of inter-yarn crossover points positively affects the structure during transverse impact events, as the longitudinal, transverse, and through-thickness reinforcements synergistically act as primary responders, effectively managing the impact with minimal back-face deformation. The study also explored the effects of hybridization in the through-thickness direction, the impact of 3D woven hybrid solid structures on out-of-plane impact responses under multiple impact scenarios, and the influence of weave architectures—whether through-thickness or binder yarn pathways—on the LVI response of various 3D woven solid structures. Significantly, the results exhibited that hybridization in the through-thickness direction markedly affects the dynamic response of these structures to loading. Moreover, binder yarns in the through-thickness direction proved crucial in preventing projectile penetration during LVI events. These investigations were critical in assessing the performance of 3D woven dry preforms under both single and multiple LVI events. This meticulous approach allowed for detailed measurements of how these preforms responded to projectile impacts before their transformation into composites, and how hybridization could enhance their transverse impact properties through the strategic use of through-thickness reinforcement.

In a subsequent phase, these dry woven preforms were converted into composites using the vacuum-assisted resin transfer method (VARTM), one of the most reliable techniques to ensure consistent fiber-volume fractions when the matrix is infused. This method facilitated the creation of 3D woven fabric-reinforced composites (3DWFRCs), effectively carrying forward the preliminary objectives of the initial woven preforms into the final composite materials. Findings indicate that while certain weave patterns enhance formability and moldability, crucial for effective resin infusion, they also affect the composites' ability to absorb and dissipate energy during impact. Notably, configurations with higher inter-yarn crossover points, while contributing to stiffness and rigidity, can lead to uneven stress distribution and resin-rich zones, adversely affecting the impact performance. The investigation revealed that the manipulation of weave patterns, particularly the orientation and maneuverability of binder yarns within the weave architecture, significantly affects the composites' ability to absorb and dissipate energy upon impact. The study discovered that 3D woven structures with greater densities of inter-yarn crossover points enhance stiffness but may compromise the capacity to absorb energy, a critical factor for impact resistance. In addition, these structures are prone to producing resin-rich areas, resulting in early Hertzian failure via matrix cracking and uneven stress distributions under the impact, where reinforcement had been under a lot of stress prior to responding to impact load. Conversely, woven constructions with fewer crossover points and optimized binder yarn float lengths demonstrated improved energy absorption and reduced risk of structural compromise.

This research elucidates the influence of various weave architectures on the structural integrity and impact response of these composites through methodical experimentation. In this point-of-view, the study examines how different stuffer layers and the maneuverability of binder yarns affect the composites' structural integrity and low-velocity impact (LVI) response. Optimizing the weave designs, stuffer layers number, and binder yarn orientation is crucial for improving the impact resistance of the composites. The research also emphasizes the necessity for continuous exploration of 3D woven structures to fully harness their potential in engineering applications that demand materials capable of withstanding dynamic impact forces. This study also investigated the impact of binder (Z) yarn maneuverability on the low-velocity impact responses of various 3D woven hybrid fabric-reinforced composites. Two specific weave architectures were examined: the orthogonal plain 1X1, characterized by mutually perpendicular reinforcements and common in 3D weaving, and the angle-interlock twill 3X3, which features non-perpendicular binder reinforcements and longer under yarn float lengths. The research demonstrated how the interplay between weave architecture, fiber characteristics, and composite thickness influences a material's response to low-velocity impacts. High-performance reinforcements such as Kevlar and Zylon, used as binder yarns, were found to significantly enhance the composites' energy absorption capabilities and stiffness. Data from force-displacement and energy-time curves indicated that hybrid composites, incorporating both Kevlar and Zylon, exhibit superior impact toughness and energy dissipation compared to composites made solely with E-glass. These hybrid structures enhance resistance to peak forces and distribute this force over a prolonged period, crucial for applications subject to dynamic loads. The observed flatter slopes in velocity-time and force-time curves for these composites suggest a greater capacity for sustained energy absorption, underscoring the benefits of hybridization in improving dynamic impact performance.

The study evaluated the out-of-plane low-velocity impact (LVI) response of 3D woven fabric-reinforced composites (3DWFRCs) using co-wrapped hybrid yarns made from E-glass and polypropylene. The study focused on matrix properties. To match thermosets' fiber-volume fraction (FVF%), these yarns were integrated into 3D woven preforms with consistent areal density and compressed into thermoplastic composites. Due to the resilience of thermoplastic resin, thermoplastic 3DWFRCs outperform thermoset composites in impact resistance and energy absorption. Despite slight thickness increases, these composites absorbed over 50% of impact energy and had higher SEA values. Orthogonal matt 3X3 weave outperformed orthogonal plain 1X1 weave across both composite types in impact resistance. While bending stiffness varied little, thermoplastic composites had higher peak forces, indicating a better dynamic response to loads. Thermoset composites showed exceptional stiffness and dimensional stability during quasi-static mechanical testing, but dynamic impact tests showed thermoplastic composites' ductility and toughness. The findings emphasize the importance of material selection tailored to specific engineering applications, the benefits of thermoplastic composites in dynamic environments, and the potential to improve composite structure performance and durability across industries. Out-of-plane impacted 3D composite structures were evaluated for impact toughness, transverse and longitudinal crack damage, energy absorption, and composite thickness by NDT. This analysis also assessed low-velocity impact (LVI) damage and examined the relationship between energy absorption and projectile-reinforcement internal friction. Variable weave factors affect 3D woven fabric-reinforced composites (3DWFRCs) dynamic impact response. Lower inter-yarn crossover points, higher binder yarn float lengths, and lower stuffer binder ratios can improve out-of-plane impact energy absorption. Energy absorption does not linearly affect ductility. Impact resistance can be improved by hybridization and stuffer layers, but fiber-volume fraction must be balanced. This research focuses on the significant effects of weave architecture, hybridization, impact energy thresholds, and matrix influences on 3DWFRC impact resistance and damage tolerance under LVI conditions to help design lightweight 3D woven composites for advanced engineering applications.

To summarize, this thorough examination of 3DWFRCs not only enhances our comprehension of their performance during dynamic impact events but also emphasizes the complex interaction between weave architectures, reinforcement selection, binder yarn maneuverability, and overall composite structures in attaining exceptional impact resistance. This knowledge is crucial for the future advancement of specialized composite materials designed for specific applications in industries where durability and impact resistance are of utmost importance.