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Intermingled and Commingled Yarn-Based Thermoplastic Composites: Fundamental Principles and Processing Routes

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Abstract
Thermoplastic textile composites produced from intermingled and commingled yarn systems have attracted increasing attention due to their improved impregnation efficiency, recyclability, and suitability for high-volume manufacturing. In these hybrid yarn structures, thermoplastic matrix filaments are intimately mixed with reinforcement fibres at the filament level, enabling rapid consolidation without the need for liquid resin impregnation. This first part of the review paper presents the fundamental principles governing intermingled and commingled yarn technologies, including yarn formation mechanisms, fabric architectures, and consolidation routes based on hot press moulding. The influence of filament distribution, weaving structure, and processing parameters on impregnation quality and structural integrity is critically discussed. Particular emphasis is placed on the role of textile preform design in controlling fibre volume fraction, porosity, and consolidation efficiency. The reviewed studies demonstrate that filament-level mixing significantly reduces impregnation distances and enhances process reliability compared to conventional thermoplastic composite manufacturing routes. This paper establishes the processing–structure framework required for understanding the mechanical and functional performance of such composites, which will be systematically compared in Part II of this review.

Keywords
intermingled yarns, commingled yarns, thermoplastic composites, textile preforms, hot press moulding, woven fabrics

1. Introduction

Thermoplastic composites have attracted increasing attention in recent decades due to their recyclability, high damage tolerance, short processing cycles, and suitability for automated manufacturing. Compared to conventional thermoset-based composites, thermoplastic systems offer significant advantages in terms of reprocessability, welding capability, and sustainability, making them particularly attractive for transportation, aerospace secondary structures, and industrial applications [1–4].

Despite these advantages, one of the main challenges in thermoplastic composites remains achieving effective impregnation of high-viscosity polymer melts into fibrous reinforcements. Traditional prepreg technologies, while well established for thermoset systems, often require complex and costly processing routes when applied to thermoplastics, including solvent-based impregnation or melt film stacking approaches [5–7]. These limitations have driven the development of alternative reinforcement architectures capable of enhancing impregnation efficiency while maintaining mechanical performance.

In this context, hybrid yarn technologies, particularly commingled and intermingled yarns, have emerged as promising solutions. In these systems, thermoplastic matrix filaments are intimately mixed with reinforcing filaments at the filament level prior to fabric formation. This configuration significantly reduces the impregnation distance during consolidation, enabling faster and more homogeneous matrix flow during hot press moulding or thermoforming processes [8–11].

Woven fabrics produced from commingled or intermingled yarns can be directly used as ready-to-mold preforms, eliminating several intermediate processing steps. As a result, these materials offer a combination of processing simplicity, mechanical robustness, and design flexibility. Previous studies have demonstrated that fabric architecture, hybridization strategy, and consolidation conditions play a crucial role in determining the final mechanical properties of such composites [12–15]. The influence of weaving structure and hybridization on tensile behaviour, for instance, has been clearly demonstrated in woven hybrid composite systems [16].

Furthermore, recent research has expanded the scope of commingled and intermingled systems to include recycled polymers, bio-based thermoplastics, and natural fibre reinforcements, highlighting their potential contribution to sustainable composite development [17–21]. Comparative investigations on thermoplastic and thermoset textile composites, as well as hybrid reinforcement systems, further emphasize the relevance of filament-level mixing concepts in improving interlaminar and impact performance [22–25].

The present review is structured in two complementary parts. Part I focuses on the fundamental principles of commingled and intermingled yarn-based thermoplastic composites, covering yarn manufacturing methods, fabric formation, and consolidation mechanisms via hot press moulding. Part II provides a comparative assessment of mechanical, thermo-mechanical, and damage-related properties of these composites, benchmarking them against conventional textile composite systems. By combining processing fundamentals with performance-oriented analysis, this two-part review aims to provide a comprehensive reference for researchers and engineers working in the field of thermoplastic textile composites.

2. Definitions and Yarn Architecture

Hybrid yarns used in thermoplastic composite manufacturing are generally classified as commingled or intermingled yarns, depending on the filament mixing strategy and manufacturing approach. Although these terms are sometimes used interchangeably, clear distinctions exist in terms of yarn architecture and filament distribution.

Commingled yarns consist of continuous reinforcing filaments and thermoplastic matrix filaments combined into a single yarn bundle with a relatively uniform spatial distribution. The primary objective of commingling is to minimize melt flow distance during consolidation, thereby facilitating rapid impregnation and improved consolidation quality [5, 6].

Intermingled yarns are typically produced using air-jet intermingling technology, in which separate reinforcing and matrix filaments are entangled by turbulent airflow inside a nozzle. This process creates intermittent entanglement points along the yarn length, providing yarn coherence without twist insertion [9–11]. Compared to fully commingled yarns, intermingled yarns may exhibit localized variations in filament distribution, depending on processing parameters.

Yarn architecture plays a critical role in determining fibre volume fraction, impregnation behaviour, and void formation in the final composite (Figure 1). Parameters such as filament diameter, linear density ratio between matrix and reinforcement, and yarn packing density directly affect melt flow and wetting during consolidation [6–8]. Enhanced interlaminar properties have been reported for filament-level hybrid yarn systems compared to non-hybrid counterparts [17, 19].

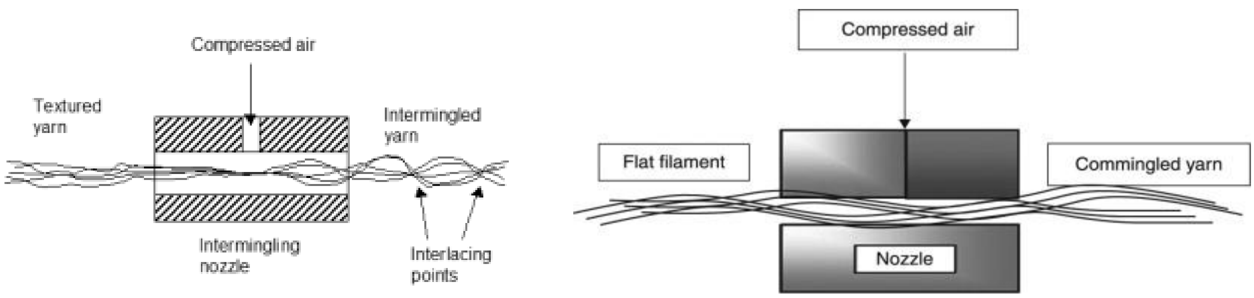

Fig. 1. Schematic representation of (a) intermingled and (b) commingled yarn structures used in thermoplastic textile composites, illustrating the degree of filament-level mixing between matrix and reinforcement fibres [1–4, 6, 14]

Recent studies have also extended commingled and intermingled concepts to natural fibre and recycled polymer systems. Comparative evaluations of natural fibre characteristics and their suitability as composite reinforcements demonstrate the adaptability of hybrid yarn architectures across a wide range of material systems [20–22].

3. Manufacturing Principles of Commingled and Intermingled Hybrid Yarns

The manufacturing route of hybrid yarns governs filament dispersion, impregnation efficiency, and ultimately composite performance. Commingled yarns are generally produced by mechanically or pneumatically combining reinforcing and thermoplastic filaments into a single bundle, ensuring controlled filament distribution along the yarn length [5,6].

Intermingled yarns are most commonly produced using air-jet intermingling. In this process, reinforcing and matrix filaments are fed into a high-velocity turbulent airflow, causing filament entanglement and formation of intermingling nodes [9–11]. Air pressure and overfeed ratio are the dominant parameters controlling entanglement intensity and yarn coherence.

The linear density ratio between matrix and reinforcement filaments determines the achievable fibre volume fraction and influences melt flow behaviour during hot press consolidation (Figure 2). Insufficient matrix content may lead to incomplete impregnation, whereas excessive matrix content reduces reinforcement efficiency [5,6].

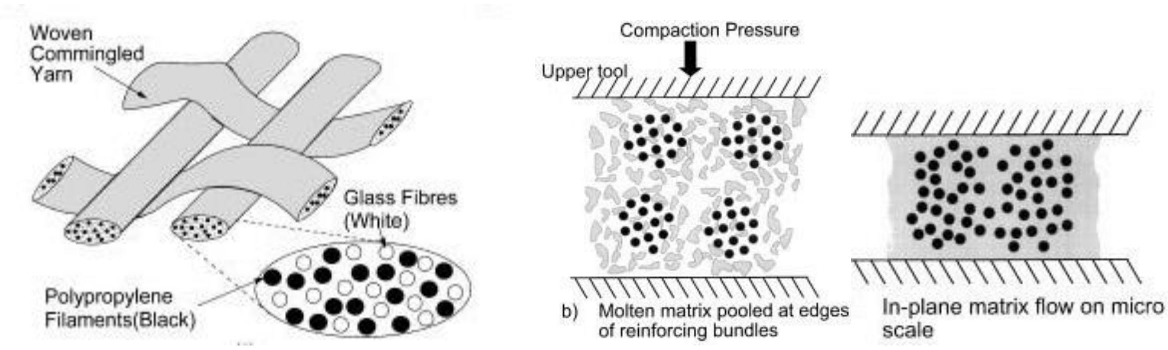

Fig. 2. Typical woven fabric architectures produced from intermingled/commingled yarns and their influence on fibre crimp, inter-yarn contact, and resin flow during consolidation [5, 7–10, 15]

Microstructural investigations using scanning electron microscopy have shown that commingled yarns provide shorter impregnation times and more uniform matrix distribution than film-stacked or powder-impregnated systems [6,8]. Intermingled yarns, while sometimes exhibiting localized filament clustering, still offer significantly reduced impregnation distances compared to non-hybrid yarn architectures [9–11].

Hybrid yarn manufacturing principles have been successfully applied to recycled thermoplastics and hybrid natural–synthetic fibre systems. Studies on recycled PET and polypropylene intermingled yarn composites demonstrated mechanical properties comparable to virgin polymer systems when processing parameters were optimized [23]. Similarly, commingled synthetic–natural fibre preforms have shown balanced mechanical performance and sustainability potential [25].

4. Fabric Formation and Preform Design

Fabric formation is a critical step linking hybrid yarn architecture to composite consolidation and performance. Woven fabrics produced from commingled or intermingled yarns serve as dimensionally stable, ready-to-mold preforms suitable for hot press consolidation.

Plain, twill, and satin weaves are the most commonly used textile architectures. Plain weaves provide high stability but increased yarn crimp, whereas twill and satin weaves offer reduced crimp and improved drapeability, which can enhance impregnation and mechanical efficiency [12–14]. The influence of weaving structure and hybridization on tensile properties has been clearly demonstrated in woven composite systems [12].

Fabric areal density and yarn packing density directly affect permeability and melt flow during consolidation. Excessively tight fabrics may hinder matrix flow and increase void content, while overly loose fabrics can lead to matrix-rich regions and reduced stiffness [5, 6].

Hybrid textile architectures, such as woven/knitted combinations, have been investigated to improve impact resistance and energy absorption. Experimental studies reported enhanced damage tolerance for woven/knitted hybrid composites, particularly in thermoplastic systems where matrix ductility plays a significant role [15,19].

Comparative studies on thermoplastic and thermoset woven fabric composites indicate that thermoplastic matrices generally provide superior toughness and resistance to delamination [17, 27]. Recent work has also shown that woven fabrics produced from recycled thermoplastic intermingled yarns can achieve competitive mechanical performance when fabric design and consolidation parameters are properly optimized [23].

Overall, fabric formation and preform design strongly influence permeability, impregnation efficiency, and mechanical response. Understanding the interaction between yarn architecture and textile structure is essential for optimizing woven thermoplastic composite preforms prior to consolidation.

5. Hot Press Consolidation of Woven Hybrid Yarn Preforms

Hot press consolidation is the most commonly employed method for converting woven preforms made from commingled or intermingled yarns into fully consolidated thermoplastic composites. The process involves simultaneous application of heat and pressure for a defined dwell time, enabling melting of the thermoplastic matrix, flow into the reinforcement architecture, and subsequent solidification upon cooling [1–3]. Compared to liquid resin infusion techniques, hot press moulding offers a solvent-free and relatively rapid processing route, which is particularly compatible with filament-level hybrid yarn systems.

The consolidation mechanism of hybrid yarn-based preforms can be divided into three main stages: matrix melting, impregnation and flow, and cooling under pressure. During the heating stage, thermoplastic matrix filaments soften and melt, reducing viscosity and enabling matrix mobility. Because the matrix filaments are already distributed within the yarn bundle, the characteristic impregnation distance is significantly reduced compared to film-stacked or powder-based systems [5, 6]. This fundamental advantage is the key reason for the effectiveness of commingled and intermingled yarn architectures in thermoplastic composite processing.

Pressure application during consolidation promotes intimate contact between yarns and drives the molten matrix into inter-yarn and intra-yarn voids. The magnitude of applied pressure must be sufficient to overcome capillary resistance and fabric compaction effects, while avoiding excessive fibre distortion or resin squeeze-out [2, 4]. Previous studies have shown that optimized pressure levels lead to improved fibre wetting and reduced void content, which directly correlate with enhanced mechanical performance [5, 6].

Dwell time at consolidation temperature is another critical parameter. Insufficient dwell time may result in incomplete impregnation and residual porosity, whereas excessively long dwell times can promote matrix degradation or unnecessary cycle time extension. For most semi-crystalline thermoplastics, consolidation temperatures are typically selected above the melting temperature of the matrix to ensure adequate flow, followed by controlled cooling to promote desirable crystalline morphology [6, 7].

The influence of fabric architecture on consolidation behaviour is particularly pronounced in woven hybrid yarn preforms. Yarn crimp, fabric permeability, and areal density all affect matrix flow pathways and compaction behaviour. Fabrics with lower crimp and higher permeability generally facilitate more uniform impregnation, whereas tightly packed fabrics may require higher pressures or longer dwell times to achieve comparable consolidation quality [12–14].

Void formation remains one of the primary quality concerns in hot press consolidated thermoplastic composites (Figure 3). Voids may originate from trapped air within the fabric, insufficient matrix flow, or inadequate pressure application. Studies on thermoplastic textile composites have consistently shown that commingled and intermingled yarn systems exhibit lower void contents than non-hybrid reinforcement architectures under comparable processing conditions [5, 6, 17]. Reduced void content has been directly linked to improvements in interlaminar shear strength and impact resistance.

Recent investigations have also demonstrated that hot press consolidation is well suited for advanced hybrid material systems, including recycled thermoplastics and bio-based matrices.

Intermingled yarn composites produced from virgin and recycled PET and polypropylene have shown comparable consolidation quality and mechanical performance when appropriate processing windows are employed [23]. These findings support the applicability of hot press moulding as a robust and scalable consolidation technique for sustainable thermoplastic composite systems.

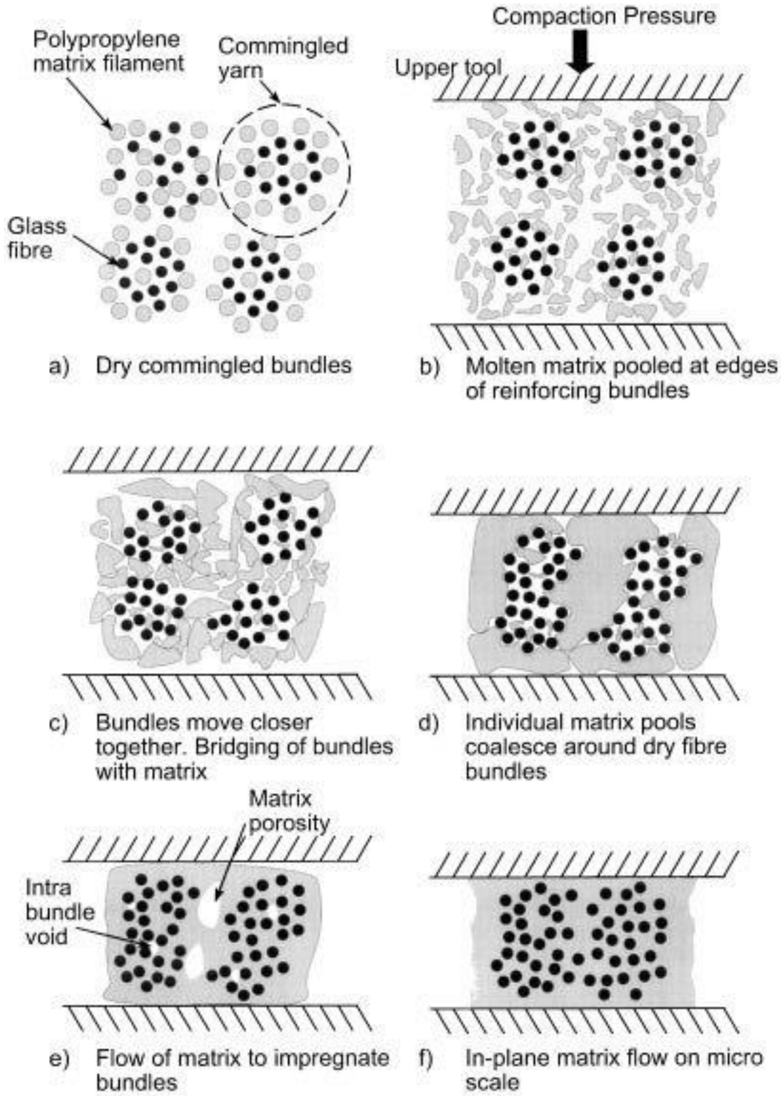

Fig 3. (a) Dry commingled bundles; (b) Molten matrix pooled at edges of reinforcing bundles; (c) Bundles move closer together. Bridgin of bundles with matrix; (d) Individual matrix pools coalesce around dry ®bre bundles; (e) Flow of matrix to impregnate bundles; (f) In-plane matrix ¯ow on micro scale

Overall, hot press consolidation provides an efficient and controllable route for manufacturing woven thermoplastic composites reinforced with commingled or intermingled yarns. The success of the process relies on careful optimization of temperature, pressure, and dwell time in conjunction with yarn architecture and fabric design (Figure 4). Understanding these interdependent factors is essential for achieving low void content, uniform microstructure, and reliable mechanical performance in hybrid yarn-based thermoplastic composites.

6. Advantages, Limitations and Processing Window

Commingled and intermingled yarn-based thermoplastic composites offer several advantages over conventional thermoplastic impregnation routes and thermoset-based textile composites. One of the most significant benefits is the inherently reduced impregnation distance resulting from filament-level mixing of matrix and reinforcement. This feature enables rapid and relatively uniform impregnation during hot press consolidation, even for thermoplastics with comparatively high melt viscosity [5, 6]. As a result, shorter cycle times and simplified processing routes can be achieved compared to film-stacking or powder-impregnation techniques [1, 2].

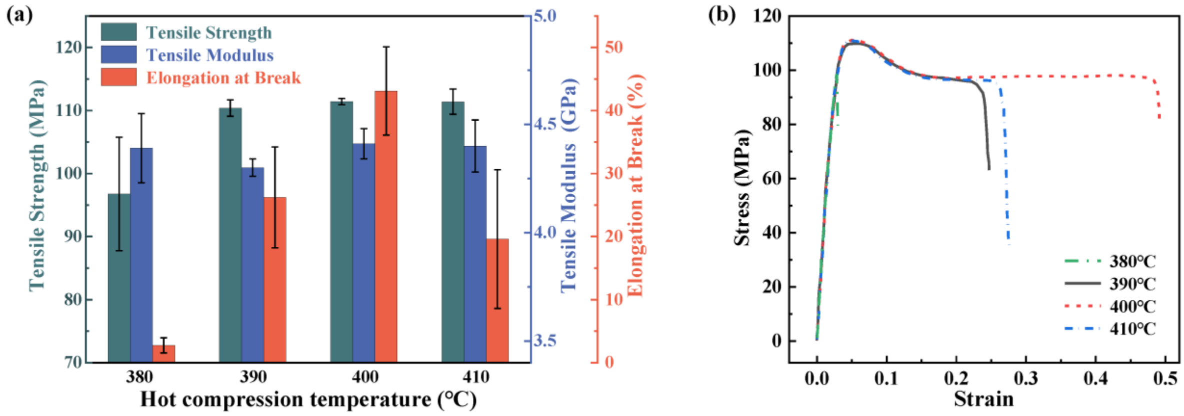

Fig. 4. Relationship between processing parameters (temperature, pressure, and holding time) and resulting structural quality and mechanical performance of thermoplastic textile composites reinforced with intermingled and commingled yarns [19–27]

Another important advantage lies in the elimination of solvents and intermediate prepreg production steps. Woven fabrics produced from hybrid yarns can be directly used as ready-to-mold preforms, improving process robustness and reducing manufacturing complexity [3,4]. In addition, thermoplastic matrices provide intrinsic toughness, reprocessability, and recyclability, which are increasingly important for sustainable composite manufacturing [21–24]. The compatibility of commingled and intermingled yarn architectures with recycled and bio-based thermoplastics further strengthens their potential for environmentally responsible applications [23, 24].

From a structural performance perspective, hybrid yarn-based thermoplastic composites have demonstrated competitive tensile, interlaminar, and impact properties when appropriate yarn architecture, fabric design, and consolidation parameters are employed [12, 15, 17, 19]. Reduced void content and improved fibre–matrix contact contribute to enhanced interlaminar shear strength and damage tolerance compared to non-hybrid reinforcement systems [5, 6, 17]. These characteristics make such composites particularly attractive for applications requiring high toughness and resistance to impact or delamination.

Despite these advantages, several limitations must be considered. The manufacturing of commingled and intermingled yarns requires specialized equipment and careful control of process parameters, which may increase material cost compared to conventional reinforcement yarns [9–11]. In intermingled systems, non-uniform filament distribution and localized clustering may occur if air pressure and overfeed ratios are not properly optimized, potentially affecting consolidation quality and mechanical consistency.

Processing sensitivity represents another challenge. The consolidation window for hybrid yarn-based thermoplastic composites is strongly influenced by matrix melting behaviour, fabric permeability, and applied pressure. Insufficient temperature or pressure may lead to incomplete impregnation and residual porosity, whereas excessive processing conditions can cause fibre distortion, resin squeeze-out, or thermal degradation of the matrix [2, 6]. Semi-crystalline thermoplastics additionally require controlled cooling rates to achieve desirable crystalline morphology and stable mechanical performance [6, 7].

The concept of a processing window is therefore central to the successful implementation of commingled and intermingled yarn systems. Optimal processing conditions must balance temperature, pressure, and dwell time in relation to yarn architecture and fabric design. Studies have shown that this window can be relatively narrow for high-performance thermoplastics but becomes more tolerant when filament-level hybridization is effectively implemented [5, 6]. The establishment of robust processing windows is particularly critical for industrial-scale production and quality assurance.

Overall, commingled and intermingled yarn-based thermoplastic composites provide a compelling combination of processing efficiency, mechanical performance, and sustainability potential. While challenges related to yarn manufacturing and processing sensitivity remain, these limitations can be effectively addressed through careful material selection, yarn architecture optimization, and consolidation parameter control. The fundamental principles discussed in this part of the review provide the necessary framework for the comparative performance analysis presented in Part II, where mechanical, thermo-mechanical, and damage-related properties of these systems are evaluated in detail.

7. Conclusions and Outlook

This review has presented the fundamental concepts and processing principles of thermoplastic textile composites reinforced with intermingled and commingled yarn systems. By integrating matrix and reinforcement filaments at the yarn level, these hybrid structures enable efficient impregnation during consolidation, eliminating the need for conventional melt infiltration or resin transfer processes. The reviewed literature clearly indicates that filament-level mixing is a key parameter governing impregnation quality, porosity reduction, and consolidation reliability [1–27].

The formation of woven fabric preforms from intermingled and commingled yarns provides additional control over fibre orientation, crimp, and inter-yarn contact, which directly influence consolidation behaviour during hot press moulding. Processing parameters such as temperature, pressure, and holding time were shown to strongly affect matrix flow, fibre wetting, and final composite quality. However, an optimal processing window must be carefully defined to balance sufficient impregnation with the risk of fibre distortion or thermal degradation, particularly for high-performance polymer matrices.

Despite the clear processing advantages, several challenges remain. The degree of filament dispersion in intermingled yarns can be less uniform compared to commingled systems, leading to local variations in matrix distribution. In addition, weaving-induced crimp and fabric compaction behaviour may limit achievable fibre volume fractions for certain applications. These aspects highlight the necessity of tailoring yarn architecture and fabric design in parallel with processing conditions.

Overall, Part I of this review establishes a comprehensive processing–structure framework for thermoplastic textile composites based on intermingled and commingled yarn technologies. Building on these fundamentals, Part II will focus on a systematic comparison of mechanical, impact, thermal, and durability-related properties, with particular emphasis on the influence of yarn type, fabric architecture, and matrix system. Such a comparative evaluation is essential for guiding material selection and design strategies for structural and semi-structural composite applications.

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