Woven Fabrics for Composite Reinforcement: A Review

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Abstract: Fibres in different textile forms (woven, knitted, stitched, and non-crimp) are used to reinforce composites for multifaceted applications, including automotive, aerospace, marine, rail, energy, construction, and defence sectors. Textile fabric-based fibre reinforcements for composites possess some outstanding features, such as good dimensional stability, subtle conformability, deep draw moldability/processability, lightweightness, high strength and stiffness, and low cost. The greatest advantage of textile fibre-reinforced composites is the freedom to tailor their strength and stiffness properties for specific applications. Therefore, the design of composites involves defining the fabric geometry, stacking sequence, and orientation of fibres to optimise the system. Compared to knitted, stitched, and non-crimp fabrics, woven fabric-based fibre-reinforced composites are widely used in the industry. The properties of woven fabric-reinforced composites depend on several factors, such as types of fibre, compositions, polymeric matrices, and fibre/matrix interfacial strength. Some of the advantages are reduced preforming process steps, good impact and delamination resistance, and thermo-mechanical properties. This review has been written to provide detailed information and discussions, including the fabrication processes, relationship between fabric structure and composite properties, and morphological characteristics encompassing the current state-of-the-art in woven fabrics for composite reinforcement.

Keywords: woven; textile; fabric; reinforcement; composites; material properties; mechanical properties

1. Introduction

Fibre-reinforced polymer (FRP) composites are widely used in many structural applications owing to their low densities, high specific strength and stiffness, ease of processibility, good corrosion and weather resistance, and low weight [1–6]. For any structural application, the mechanical properties of FRPs are tailored by using fibres in the form of fabric reinforcements with specific orientation, interlacing, and stacking sequences to mechanically supplement the elasticity and ductility of the matrix [7–11]. FRP laminates are manufactured using two or more laminae with similar or varied fibre orientations stacked together to ensure improved strength and stiffness [12–15]. Unlike unidirectional FRPs, textile fabric-based fibre reinforcements offer improved strength and stiffness in two perpendicular directions [16–19]. Through design optimisation at the fabrication stage, the mechanical properties of FRPs with textile fabric reinforcements can be enhanced in directions of primary importance, generally in areas of highest stress concentrations [20].

The foundation for the manufacture of textile fabric-reinforced composites is the fabrication of a laminate stack or preform corresponding to the fibre structure and geometry of the final composite part. Conventionally, numerous 2D plies are stacked together to build up the laminate. Ply stacking is labour-intensive; therefore, preforming accounts for nearly 50% of the overall composite component cost [21]. Two-dimensional weaving is an evolving technology widely used for the production of textile fabrics where two orthogonal sets of yarns/rovings are interlaced together [22]. The first use of this technique dates to the Neolithic/Endolithic period [23]. In the past, the primary motivation behind manufacturing woven fabrics was to provide safety to humankind through clothing and shelter. But
owing to modernisation of human civilisation, nowadays fabrics are used for fashion and technologies [24]. At the very beginning, weaving was performed by hanging the warp yarns from tree branches, and then weft yarns were inserted manually to give the first aspect of a ‘loom’. ‘Loom’ generally refers to a technique of balancing the warp threads parallelly and enabling the weft threads to be interlaced at approximately 90° angle, forming a web-like structure [25]. Following this technique, the ‘vertical loom’ was developed and was further followed-up by the ‘horizontal loom’. The horizontal loom is the direct precursor of the modern weaving loom. However, the development of modern looms from handlooms underwent many phases of change throughout history and was only dedicated to two-dimensional (2D) woven fabrics [25].

Presently, computer-aided designing techniques, in conjunction with finite element modelling principles, have developed novel directions for traditional weaving [26], which include smart integrations for electronics, reinforcements, medical applications, 3D contour weaving in 2D platforms, and multi-axial weaving. In woven composites, warp yarns are the lengthwise ones that are held in tension on a frame or loom, while the weft yarns are drawn through and inserted over and under the warp yarns [27], as illustrated for a plain weave fabric in Figure 1.

![Figure 1](image_url)

Figure 1. A typical woven composite with warp and weft yarns (redrawn from [26]).

The warp direction represents the lengthwise axis of the fabric roll, and the weft direction is the width of the roll. Four weave styles are commonly used as fabric reinforcements for reinforced plastics and composites: plain, twill, crowfoot, and satin. Different textile fabric structures are illustrated in Figure 2. The geometry of woven fabric reinforcement is important for the realisation of the optimum mechanical performance of the materials. The most classical paper on textile cloth geometry is by Peirce [28], which has provided the basis for many studies on woven-fabric geometry. The paper provides rigorous formulae in terms of the angles of bending, and lengths of intertwining threads are given to present the idealised geometry of plain weave fabric. Any plain weave fabric is fully defined by a pair of two related points, which can be located on the main graph to give numerical values for ten of the eleven variables that define a fabric structure. The eleven variables consist of five pairs, in which one value is assigned to the warp yarns and the other to the filling (weft) yarns, together with the eleventh variable, D, the sum of the diameters. The five variables are p, the thread spacing (mils), l, the thread length in the unit cell (mils), h, the thread amplitude (mils), C, the fractional crimps (100C = %C), and θ, the angle of inclination of the thread (radians) [28].
Womersley [29] used calculating machines and sound methods of interpolation to translate the work of Peirce into tables for the analysis of the fabric geometry. Peirce [30] recognised the difficulty of the considerable calculation and lengthy interpolations from tables required to make use of his work and suggested the use of graphs for particular relations. Painter [31] carried this idea further and presented one graph that depicts all the geometrical relations of the ideal plain weave geometry in the manner of a psychrometric chart or Mollier diagram. Painter’s main graph is used to determine the three major changes in the shape of the unit cell that cause concomitant changes in fabric dimensions: crimp interchange (from warp tensioning), yarn swelling, and yarn flattening. A tight weave fabric was chosen by Painter to demonstrate the use of the jam line in defining limiting values. For a fabric in which none of the yarns are jammed, it is necessary to fix four of the eleven variables. If one yarn is jammed, only three of the values are needed for the definition of the fabric structure. If both yarns are jammed, only two values need to be known. In the latter case, the geometry of the structure can be defined by the ratio $\lambda = l_1/l_2$, but the scale will not be fixed unless one of the lengths is known. The variable $D$ can be regarded as a scale factor that fixes linear fabric dimensions.

2. Fabrics

Warp (0°) and weft (90°) yarns are interlaced in a regular weaving pattern to manufacture textile woven fabrics. Coherence inside the fabric is maintained by the mechanical interlocking of the fibres in the yarns. Certain features of the fabrics, such as drapability, overall stability, and smoothness, are ensured by adopting different weaving techniques.
(plain, twill, satin, etc.) [32]. The weaving style also influences the areal weight of fabrics, which is an important parameter to decide if a fabric would be most suitable for its end use. The areal weight of fabric, \( A_f \), is defined using Equation (1) as follows:

\[
A_f = 2N_fN_Tr_f^2\rho_f
\]

where, for a balanced fabric, the parameters are as follows: number of filaments per tow \((N_f)\), number of tows in unit length per width of fabric \((N_T)\), radius of fabric cross-section \((r_f)\), and density of fibre \((\rho_f)\).

For unbalanced weaves, for correct prediction of composite properties, it would be appropriate to report data for both tows per metre in the warp and weft directions. Crimp will generally increase the fabric areal weight by approximately 1% at 10°, 3% at 20°, or 6.5% at 30° maximum crimp angle, assuming that the yarn follows a sinusoidal path [33]. Crimp is generally referred to as the waviness of a fibre and is normally expressed numerically as either ‘the number of waves of crimps per unit length’ or ‘the difference in distance between points on the fibre as it lies in a crimped condition and the same two points when the fibre is straightened under suitable tension’. The mechanical properties of composites gradually increase as the crimp decreases, but drape and in-plane permeability normally decrease as the crimp decreases [33].

Two-dimensional woven fabrics are made by the conventional weaving process. The well-developed weaving loom technology provides high productivity and reduces manufacturing costs for composites. The interlacing of yarns gives the lamina stability during handling and permits conformability to form complex shapes with no gaps. The yarn/tow is normally considered to have a circular cross-section before textile processing. However, bending and sliding against looming machinery may cause abrasion and fibre breakage, and the interlaced yarns can induce crimping in the fabric structure. The schematic of the conventional 2D and 3D weaving loom is illustrated in Figure 3, which follows a sequence of different weaving techniques in the following order [34].

**Warp left-off**: Warp yarns are wound parallelly under even tension on the warp beam. The beam turns specific steps for each weaving cycle, corresponding to the required filler weft yarn count per unit length, feeding the warp yarns into the weaving zone under controlled tension with the aid of tensioning devices.

**Shedding**: Every warp yarn passes through a heddle eye, which is attached to the lift shafts. Warp yarns having the same state in weave pattern have their heddles attached to the same shafts. For each weaving cycle, parts of the lift shaft move up and down to separate the warp yarns into two layers, creating appropriate space between them across the loom, called the shed, which allows the insertion of filler yarn across the loom width. The distribution of warp yarns as well as the sequence of lifting the shafts across the weaving produce the desired weave pattern for the fabrics.

**Weft insertion**: Weft yarns are inserted in every weaving cycle through the sheds, and they pass across the loom width. Different apparatus, for example, a shuttle, rapier, projectile, and air jet, are utilised to carry the filler yarn.

**Beating**: During the beat-up process, the weft yarns are tightly packed close to the fabric using a reed, which is generally closed through the gaps between the blades. The warp yarns are passed over the weft. The number of warp yarns passed in each space with respect to the count of blades per unit length determines the number of warp yarns per unit length of the fabric loom. The reed maintains a sequential order, moving back and forth from the fabric formation line to account for the shedding and insertion of weft yarns as well as to pack the inserted yarn.

**Fabric take-up**: The packed yarns are removed from the weaving zone and rolled up on the fabric beam. The fabric roller and the beam then turn one step, corresponding to the filler yarns per one-unit length of the fabric.
Figure 3. Schematics of conventional weaving processes: (a) 2D technique, (b) 3D weaving loom (redrawn from [34,35]).

However, a key issue for all these weaving formats is the mechanical properties of the fabric, particularly the ‘drape’ and ‘conformability’ of the fabric textile [35,36]. The terms ‘drape’ and ‘conformability’ are currently used interchangeably in the composites industry. Drape refers to the natural ability of a fabric to hang in sinusoidal types of folds without assistance. The conformability of fabrics is referred to as the ability of a fabric to conform to a double-curvature surface without any assistance. Different standards exist for a variety of ways to test drape/conformability, for example, ASTM D1388-08, ASTM D5732-01, BS3356:1990, ASTM D4032-08, and BS5058:2007 [37].

2.1. Plain Woven Fabrics

Plain woven fabrics depict the simplest woven fabric architecture. In a plain woven fabric, corresponding warp and weft yarns are consecutively placed over one another (Figure 1). Plain woven fabrics are generally symmetrical, demonstrate good stability, and have porosity. However, plain woven fabrics generate higher crimp levels due to the high interlace density in the structure, which has a negative effect on the mechanical properties of these fabric-based composites [34]. Plain woven fabrics can be further classified as (a) warp rib weave and (b) weft rib weave [34]. Warp rib weaves are also termed warp-faced structure fabric as they consist of two or more picks in the same shed. Crimps and cover factors are relatively higher in warps than they are in the weft. In weft rib fabrics, the fabric ends (two or more) are tightly woven into one structure. Weft rib fabrics are generally more expensive than their warp counterparts [34].
2.2. Twill Woven Fabrics

In twill woven fabrics, one or more warp yarns are woven above and under corresponding weft yarns in a regular pattern. Please refer to Figure 2, which provides further insight regarding the fabric structure. A straight/broken diagonal appearance of the rib structure is depicted in the fabric architecture. Additionally, good drapeability and wet out properties are also observed in twill woven fabrics. However, if twill woven fabrics are mechanised and manufactured to reduce crimps in the fabric structure, then it is possible to obtain higher mechanical performances from the composites manufactured using twill woven fabric reinforcements [32].

2.3. Satin Woven Fabrics

In the satin weaving process, low-twisted warp yarns are passed over four or more filling yarns (Figure 2). These warp yarns produce high lustre effects on one side of the fabric. Satin weaves are generally flat, with higher drapeability and wettability. Additionally, it is possible to enhance the mechanical properties of satin weaves through design optimisation by lowering crimps. The weaving pattern in satin weaves is produced in close proximity, resulting in tightly woven fabrics. Care should be taken when using satin fabrics as reinforcements, as the two faces have the majority of fibres remaining in mutually perpendicular directions.

2.4. Leno Woven Fabrics

Two or more leno weaves are not normally used for composite parts due to their openness, which leads to a low fibre volume fraction. However, the stability of leno weave fabrics can be improved if fewer fabric yarns are used.

2.5. Two- and Three-Dimensional Woven Fabrics

Textile fabrics with relatively lower thickness as compared to the length and width of the fabric are loosely defined as 2D woven fabrics [34]. Three-dimensional woven fabrics are substantially thicker relative to their length and width. In 3D woven fabrics, separate yarn components are aligned in three orthogonal directions—x, y, and z. The z-yarn reinforcement refers to the through-thickness direction [38]. Major distinctions between 2D, 2.5D, and 3D woven fabrics are illustrated in [39]. In 2D woven fabrics, fabric yarns are generally interleaved in a single plane; for 2.5D woven fabrics, constituent yarns are disposed in two mutually perpendicular planes, whereas for 3D woven fabrics, the constituent yarns are disposed in three mutually perpendicular planes. Three-dimensional woven fabrics are not limited to three sets of yarns but include two or more than three sets of yarns [40,41].

Three-dimensional fabrics are preferred over 2D woven fabrics in ballistic applications. Plain and twill woven fabrics with high in-plane properties are more suitable for soft petroleum vest applications. Satin woven fabrics are often used in armour applications [42]. However, low through-thickness mechanical properties and poor delamination resistance under impact loading restrict the application of 2D woven fabrics in some aerospace and automobile applications [43,44]. Fibrous yarns, rods, or pins aligned with carbon nanotube forests are often used as through-thickness reinforcement for composites manufactured using woven fabrics [45], collectively known as z-reinforcement, to improve their delamination resistance and impact tolerance [46]. Three-dimensional weaving, stitching, and z-pinning are some of the most commonly used techniques for z-reinforcement [46]. Schematic representations of typical 3D woven, 3D stitched, and 3D woven z-pinned fabrics are illustrated in Figure 4. Stitching and z-pinning can enhance the impact damage tolerance of the composite; however, this might affect the in-plane properties of the composite [47].
weaving and tube-carrier weaving. The results demonstrated a significant improvement were used in the study, i.e., warp, weft, and bi-directional. The authors observed that bi-
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et al. [54] developed 3D woven T-shaped fabrics by utilising a narrow multilayer weaving
in the transverse direction as compared to warp and weft interlock reinforcements. Ali
directional interlock woven fabric composites demonstrate better mechanical performance
further classified into four categories: 3D solid, 3D hollow, 3D shell, and 3D nodal.

Forming Methods for 3D Woven Fabrics

Bilisik [49] classified 3D woven fabrics depending on the orientation of fabric yarns
and types of interlacements. In another study [50], 3D woven fabrics were classified
depending on the weaving type and structure of the fabric. Three categories were signified
to classify 3D woven fabrics based on the weaving process: 2D weaving—3D fabrics, 3D
weaving—3D fabrics, and noobing. ‘Noobing’ is a nonwoven 3D forming technique that
is developed to bid linear yarns arranged in either uniaxial or multiaxial orientation to a
layerless and crimpless pattern [51]. Based on the fabric structure, 3D woven fabrics are
further classified into four categories: 3D solid, 3D hollow, 3D shell, and 3D nodal.

Following a conventional 2D weaving process, three types of fabrics are generally
manufactured: 2D, 2.5D, and 3D fabrics [51]. ‘Multi-layer weaving’ and ‘noobing’ are the
two conventional 2D weaving processes that are used for manufacturing 3D woven fabrics. Although both ‘noobing’ and ‘multi-layer weaving’ are 2D weaving techniques, there is
a clear distinction between them, as illustrated in [51,52]. However, in [51], it was also
claimed that the ‘noobing’ process does not fully comply with the 2D weaving principles
owing to the lack of a shedding mechanism.

Three-dimensional angel interlock woven fabrics manufactured using the multi-layer
2D weaving technique can be classified as orthogonal interlock and angle interlock
structures [53]. These fabrics based on the crossing pattern of the yarns can be further subdivided
into layer-to-layer interlock and through-thickness interlock fabrics.

Umair et al. [53] investigated the mechanical properties of 3D orthogonal layer-to-
layer interlock woven composites. Three different types of 3D woven fabric reinforcements
were used in the study, i.e., warp, weft, and bi-directional. The authors observed that bi-
directional interlock woven fabric composites demonstrate better mechanical performance
in the transverse direction as compared to warp and weft interlock reinforcements. Ali
et al. [54] developed 3D woven T-shaped fabrics by utilising a narrow multilayer weaving
machine. The results demonstrated significant improvements in the flange-web peel-off
strength and impact strength of the composites.

Multi-axis 3D woven fabrics are also manufactured using bias yarns in the fabric struc-
ture [55,56]. Bilisik [56] developed two 3D multi-axis weaving methods called tube-rapier
weaving and tube-carrier weaving. The results demonstrated a significant improvement
in delamination resistance and in-plane properties of 3D woven fabrics following the incorporation of bias yarns [56,57]. However, following the incorporation of the bias yarns, the 3D orthogonal woven fabrics demonstrated a reduction in bending properties under comparison [58].

3. Woven Fabric-Reinforced Composites

Woven fabric composites (WFC) or woven textile fabrics (WTF) are manufactured using stacked woven fabrics embedded in a polymeric resin component. WFCs are widely used in transport, defence, and construction industries for their good mechanical properties, good energy absorption characteristics, and fatigue behaviour. The relatively high fibre volume fraction of woven fabric yarns imparts a significant advantage for woven fabrics compared to braided and knitted fabrics. However, woven fabric yarns demonstrate crimp along the lengthwise direction, which has a detrimental effect on the stiffness and tensile strength of composites [59]. Laminated composites manufactured using two or more layers of stacked woven fabrics are susceptible to debonding at the fibre/matrix interface and delamination between layers. Summerscales [60] has reported that fibres in a woven fabric are not uniformly distributed, with denser fibres at the interface point and sparser fibres on the outer edge of the curve. This produces relatively resin-rich volumes on the outer edge and may initiate early failure [61]. Further, the earlier study [60] suggested that fibre strain varied with position along the fibre in a periodic manner, with wavelength corresponding to the repeat distance in the curve. Delamination is also a major issue in WFCs, which significantly affects the strength and stiffness of the composites. Delamination in WFCs can occur at the time of load application under compression, especially as a crimp in the form of buckling, tension, bending, pressure, and at different energy levels [62]. Many studies [63–65] in the literature have investigated the potential cause of delamination in WFCs, which will be further discussed in the following sections.

Fibre crimp is another major challenge in WFCs, which strongly impacts their efficiency. Fibre crimping in WFCs is responsible for localised stress concentrations in the laminated composite, which can lead to matrix cracking because of fibre/matrix debonding. Progressive damage modelling techniques are useful to analyse the stress distribution in the matrix and corresponding damage mechanisms both in 2D and 3D WFCs [66,67]. One of the studies [67] concluded that damage in WFCs occurs due to the dissipation of fracture energy at the time of failure, with the extent based on the displacement relative to each failure mode.

Liquid composite moulding (LCM) is a generic term for a variety of closely related manufacturing processes where a liquid reactant is caused to flow into woven fabric reinforcement contained either in a mould or a vacuum bag. However, the use of LCM as an economic and efficient means to manufacture high-performance fibre-reinforced composites is critically limited by the permeability of reinforced fabrics. Permeability of a resin relates the fluid flow rate to the pressure gradient, viscosity of the fluid, and the dimensions of the bed of the porous medium [68–71]. Darcy’s law describes the saturated (wetted) flow of a fluid through a porous medium but is often used to model LCM processes, notably resin transfer moulding (RTM) and resin infusion under flexible tooling (RIFT) techniques. Summerscales [72] reported that the measured permeability in the unsaturated (wetting) flow may vary with the permeating fluid. Therefore, the use of saturated flow techniques or of a model fluid (which is often a non-curing resin) to measure the permeability may generate incorrect fill times for LCM flow models. However, in LCM processes, especially in open-sided moulding techniques such as RIFT, an increase in pressure transverse to the fluid flow can reduce porosity and hence permeability but will generally increase the fabric fibre volume fraction. The compressibility of preforms in LCM processes is crucial to attaining the desired fibre volume fraction, \( V_f \) [73]. According
to Quinn and Randall [73], $V_f$ (%) is a function of the square root of pressure, $P$ (N/m$^2$), which can be modelled using Equation (2) as follows:

$$V_f = K_1 + K_2 \sqrt{P}$$  \hspace{1cm} (2)

where $K_1$ and $K_2$ are the constants and $P$ is the applied pressure (N/m$^2$).

Toll and Manson [74] proposed the following generic Equation (3):

$$P = kE \left( V_f^n - V_{f0}^n \right)$$  \hspace{1cm} (3)

where $k$ is the power-law coefficient, $E$ is the through-thickness elastic modulus of the fibre pack (GPa), $V_f$ is the fibre volume fraction (%), $V_{f0}$ is the limiting fibre volume fraction (%) below which $P = 0$, and $n$ is a power-law exponent.

Tables 1 and 2 present fabric compressibility based on Quinn and Randall and the Toll and Manson models, respectively.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Fabric</th>
<th>Equation</th>
<th>%$V_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>Continuous strand mat</td>
<td>$V_f = 9.7 + 0.37 \sqrt{P}$</td>
<td>24</td>
</tr>
<tr>
<td>E-glass</td>
<td>Chopped strand mat</td>
<td>$V_f = 20 + 0.46 \sqrt{P}$</td>
<td>38</td>
</tr>
<tr>
<td>E-glass</td>
<td>Roving</td>
<td>$V_f = 32 + 0.75 \sqrt{P}$</td>
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</tr>
<tr>
<td>E-glass</td>
<td>Woven fabric</td>
<td>$V_f = 40 + 0.45 \sqrt{P}$</td>
<td>58</td>
</tr>
<tr>
<td>E-glass</td>
<td>Woven fabric</td>
<td>$V_f = 21 + 0.60 \sqrt{P}$</td>
<td>45</td>
</tr>
<tr>
<td>Kevlar</td>
<td>Fabric</td>
<td>$V_f = 47 + 0.51 \sqrt{P}$</td>
<td>67</td>
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<tr>
<td>Carbon</td>
<td>Unidirectional cloth</td>
<td>$V_f = 34 + 0.80 \sqrt{P}$</td>
<td>66</td>
</tr>
<tr>
<td>Carbon</td>
<td>±45° fabric</td>
<td>$V_f = 35 + 0.51 \sqrt{P}$</td>
<td>55</td>
</tr>
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</table>

<table>
<thead>
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<th>$V_{f0} %$</th>
<th>$n$</th>
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</tr>
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<td>Wool</td>
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<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Planar</td>
<td>4500</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Spun glass roving</td>
<td>820</td>
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<td>8.5</td>
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<tr>
<td>Fluffy glass roving</td>
<td>260</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Straight glass roving</td>
<td>700</td>
<td>-</td>
<td>15.5</td>
</tr>
<tr>
<td>Graphite roving</td>
<td>500</td>
<td>-</td>
<td>14.5</td>
</tr>
<tr>
<td>Mat</td>
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<td>Mat</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Weave</td>
<td>15</td>
<td></td>
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**Mechanical Performance**

The mechanical properties of woven fabric-reinforced composites depend on a number of factors, such as yarn geometry, types of fibre, orientation, stacking sequence, matrix, fabrication technique, fibre/matrix interfacial characteristics, curing of the resin matrix used, chemical cross-linkage, molecular weight, number of plies, and fabric properties.

Several studies in the literature have focused on the mechanical behaviour of woven fabric-reinforced composites under in-plane tension, where weave pattern and geometry were found to play a critical role in determining the mechanical behaviour of woven fabric composites [75]. Quasi-linear [76,77] and non-linear stress/strain relationships with clear stiffness degradation demonstrating knee behaviour [78–81] were reported under on-axis tension. The effects of pattern and geometry on elastic modulus and Poisson's ratio have
also been reported in the literature [82–85]. The fabric architecture is also considered to have a significant effect on the tensile strength of woven fabric composites. Osada et al. [78] investigated the knee behaviour and fracture in plain woven and satin woven fabric composites manufactured using a single ply under tensile loading conditions. The results indicated a strong influence of fabric geometry on stress conditions. The knee behaviour corresponded to debonding of the transverse fabrics, typically at 0.2–0.25% strain. Kim et al. [79] compared the in-plane strength of woven fabric composites with different weave patterns and reported that the strength increased with the increasing radius of the yarn’s curvature. Abot et al. [80] proposed that the mechanical response of laminated composites under interlaminar shear loading conditions was a function of woven fabric architecture. They concluded that the interlaminar shear modulus was not significantly affected by the fabric architecture, but interlaminar shear strength showed dependence on the amount of crimp in woven fabric. Zhou et al. [75] investigated the evolution of properties in woven fabric composites of various architectures under a multiaxial stress state. The strength and modulus of the composites were not significantly affected; however, different failure behaviours were observed. Kiasat et al. [82] reported differences in tensile deformation of woven composites because of the effects of fibre bundle size and consequent resin-rich volume on mechanical properties.

Damage in textile fabric-based composites generally initiates at a lower strain rate; however, crack initiation does not immediately result in catastrophic failure, unlike uni-directional composites [75]. Various damage detection methods, for example, optical microscopy [83–85], acoustic emission [86–90], X-ray [91–94], and digital image correlation (DIC) [82,89,90,95–97], have been applied to analyse damage in woven fabric-reinforced composites. In-situ observation using micro-CT [98,99] has also been proven to be a powerful technique to investigate damage in woven fabric composites. Many studies focused on interpreting the damage mechanisms in woven fabric composites. A few studies in the literature have also focused on analysing the evolution of damage in woven fabric composites and how it is affected by the structural geometry and local stress state. In [77], damage in a 5-harness satin weave was analysed, and it was reported that the linear stress/strain curve was little affected by initial crack development at a lower strain rate. Nicoletto et al. [79] investigated failure mechanisms in twill woven composites under tensile loading by finite element analysis. The results indicated that a high fibre crimp ratio and a high maximum crimp angle significantly reduce the mechanical strength of the composites and generate a non-linear response due to early damage initiation. In another study, Tang et al. [100] computationally investigated damage behaviour in woven fabric composites with five different weaves. With similar fibre volume fractions, tow waviness, and tow cross-sections, weave architecture had a significant influence on the failure behaviour of the composites. Woven fabric composites with different weave architectures were reported to demonstrate different mechanical properties with diverse damage evolutions [87,101].

The simplest weave is a plain weave, which represents a square weave unit of 2 × 2. The derivatives of plain weave are rib and matt weaves [102]. The objectives behind developing derivatives of plain weave are to obtain physical and morphological characteristics in composites somewhat different from plain weave fabric composites due to their longer float [103]. Many studies in the literature have focused on analysing the tensile and impact properties of woven fabric-reinforced composites. In [104], a numerical model was developed to predict the mechanical hygro-thermoelastic properties and strength of woven fabric composites. The chain-of-bundles model and a MonteCarlo method were proposed in [105] to simulate the failure progress of plain woven fabric composites under uniaxial tension and to predict the tensile strength of composites. They concluded that under uniaxial tensile loading, the critical length of plain woven fabrics changes due to the change in cross-over point frictional forces resulting from crimp interchange. The energy method and Castigliano’s theorem were used in [106] to investigate the load extension behaviour of plain woven fabric composites with respect to friction. They observed that the effect of friction between the components of fabric, yarns, and fibres had a more significant impact on
the load-extension behaviour than the reciprocal effects of the yarns. Another study [107] evaluated the mechanical properties of plain woven fabric-reinforced glass/graphite-epoxy hybrid composites and reported that the thickness of the composite and hybrid combination affected the stress-strain behaviour and impact properties of the composite.

The effect of weave architecture on the ultimate mechanical properties of plain, twill, and matt woven sisal fibre-reinforced polyester composites was investigated by Li et al. [108]. Composites with matt-weave architecture demonstrated a 52% and 100% improvement in tensile strength and modulus as compared to composites manufactured using other weave architectures. The tensile properties of glass matt or plain woven fabric santoprene composites were studied in [109]. Their study reported that the tensile properties of the composites were reduced by a higher void content. This contains the findings of Judd and Wright [110] and Ghiorse [111].

In [112], the physical and mechanical properties of copper core yarn, stainless core yarn, glass core yarn, and copper ply yarn of plain, twill, and sateen (sateen weaving technique involves floating the weft yarns over multiple warp-yearns, resulting in a smooth and shiny surface) woven fabric composites were investigated. They observed that there was a significant difference in the tensile strength of the composites along the warp and weft directions of the core yarn. The tensile strengths of cellular and diced woven fabric composites were investigated and compared with those of plain woven fabric composites in [113]. Cellular and diced woven fabrics are further illustrated in the schematics in Figure 5.

![Figure 5. Schematics of (a,b) different cellular weave patterns and (c) dice weave patterns (redrawn from [113]).](image)

Plain woven composites demonstrated better static modulus strength during tensile tests, whereas cellular and diced woven composites performed better during bursting and impact tests. The influence of interlacements on the impact properties of multilayer woven interlocked 3D composites was studied in [114]. They observed improvements in the impact properties of the composites with an increase in interlacements. Hosur et al. [115] investigated the impact response of seven-layer plain and satin weave carbon fibre-reinforced composites under low-velocity impact. Satin weave composites demonstrated better impact properties than plain weave composites. Atas and Sayman (2008) [116] presented an overview of the impact response of woven fabric composites manufactured using glass fibre as the reinforcement embedded in an epoxy resin matrix. A number of impact tests under different incident energies ranging from 4–45 J were performed. The results demonstrated that the damage process in individual specimens could be reconstructed by comparing the corresponding load/displacement curves, energy profile diagrams, and images of damaged specimens. Padhye et al. [117] reported that the high velocity impact of multi-layered plain woven fabric composites can be improved by incorporating wool into the weave structure. Thomas et al. [118] determined the static and dynamic mechanical properties of plain woven banana stem fibre and glass fibre-reinforced polyester composites. The results demonstrated that the impact strength of composites increased disproportionately with an increase in the number of layers and fibre volume fraction of composites.
For 3D woven fabric composites, various complex structures are prepared through changing yarn interlace patterns, which significantly complicate the analytical or numerical analysis of their mechanical behaviour as compared to 2D woven laminates [119–121]. The properties of 3D woven fabrics can be tailored by the type and arrangement of their z-yarns. High stiffness/high strength fibres in the z-reinforcement can be modulated by mixing with thermoplastic fibres or by weave pattern selection. Various structural components, especially in the aerospace industry, are manufactured using 3D woven fabric-reinforced composites, for example, fan blades of aeroplane engines and landing gear [122–124]. Layer-to-layer type and through-the-thickness type are two types of interlock weaves. In angle interlock weaves, there is no separate binder yarn system. However, single warp yarns change the layers at specific weave points towards the top or bottom and consequently ensure the connection of the weave layers [125–127]. In 3D woven fabrics, the warp yarns can be oriented in the direction of interlaminar shear stress to contribute to the impact resistance of the composite. Orthogonal 3D woven fabrics are manufactured as non-crimp weaves where the in-plane fibres are straight. In orthogonal yarns, layers of warp and weft yarns are linked across the through-thickness direction [125,128,129]. The non-crimp in-plane fibres result in an increase in in-plane stiffness when compared to interlock reinforcement [125,130].

A major challenge in designing and developing 3D woven composites is the balance of in-plane and out-of-plane mechanical properties [131,132]. Fibre crimp plays a key role in determining the in-plane stiffness and tensile strength of 3D woven fabric-based composites, where an increase in fibre crimp gradually decreases the tensile strength and in-plane stiffness of the composites. The high out-of-plane tensile properties and fracture toughness of 3D woven fabric composites were found to be beneficial for their increasing demand in ballistic applications as structural reinforcements. However, in these types of applications, the effect of fibre crimp was considered insignificant due to the relatively lower requirement of high in-plane stiffness or strength of the composites [132]. Stig and Hallstrom [133] experimentally investigated the in-plane and out-of-plane mechanical properties of 3D woven carbon fibre-reinforced composites. The three-dimensional woven fabrics used in their study were manufactured using a fully interlaced preform weaving process. The results were compared against 2 × 2 twill woven fabric 4-ply composite and 4 ply non-crimp single layer fabric composites. The test results demonstrated that the out-of-plane tensile strength and shear strength of 3D woven fabric composites were relatively higher than those of twill woven and non-crimp fabric composites. It was also concluded that the inclusion of additional stuffer warp yarns improved the fibre volume fraction and in-plane mechanical properties [133]. The effects of weave pattern and number of layers on the mechanical behaviour of 3D woven fabric composites were investigated by Bilisik et al. [57]. Three-dimensional woven fabric composites with plain, twill, and satin weaves were manufactured. The authors reported that the yarn-to-yarn spaces of the 3D woven fabric composites were higher than the traditional 3D woven structure (orthogonal, through-thickness, and angle interlock) in the fabric width. The weave pattern also demonstrated a marginal influence on the angles and crimps of the yarn in the 3D woven fabric composites. Additionally, the number of layers also slightly affected the yarn crimps but significantly affected the arc length as well as the length of z-yarn in the fabric thickness direction. The results further demonstrated that the 3D woven 3D fabric preforms could improve the energy absorption properties in soft ballistic applications and damping properties in structural applications.

In [134], it was reported that crimp in textile fabrics significantly influences the stiffness of composites manufactured using textile fabric reinforcements. The stiffness of 3D woven fabric composites is highly anisotropic in nature and is also influenced by the fibre type, yarn density [135]. Stig and Hallstrom (2013) [135] developed three non-linear analytical models that were used to predict the effect of fibre crimp on the longitudinal Young’s modulus of carbon fibre 3D woven fabric composites. The three models developed in this study were based on three different yarn paths—zigzag, trapezoid, and helix. In all
three models, a similar observation was made: the longitudinal stiffness of the composites gradually decreased non-linearly with an increase in fibre crimp. The results from the trapezoidal model and the experimental analysis were in good agreement. In addition, it was also reported that the variations in cross-sectional shapes of the fibre strands significantly influenced the stiffness values reported from the zigzag and trapezoidal models [135].

Composite beams with different cross-sections, such as T or I beams, are used in the construction industry. These beams are manufactured from fabric sheets subjected to bending or folding to create webs or flange-like features. These webs, or flanges, are then joined together as required [131]. A T’ beam is manufactured by joining a ‘web’ section perpendicularly to a composite laminate called ‘skin’. This is performed by splitting the ‘web’ into two equally thick flanges, resulting in a double-sided L’ shape, and finally attaching these two flanges to the skin [136]. However, this process leads to the development of a cavity at the root of the web, between the flanges and skin. As a result, this junction remains susceptible to delamination due to the absence of through-thickness reinforcement at the section. Therefore, a ‘fillet’ material is used to fill this cavity.

In the aerospace industry, unidirectional prepregs are used as the fillet material [131]. In [136], Ekermann and Hallstrom (2019) investigated the application of 3D woven fabrics as the fillet material by analysing their mechanical properties through pull-off tests and comparing the results to conventional unidirectional fillets. The results reported relatively higher failure loads for T-joints with unidirectional fillets than 3D fillets. The 3D fillets also demonstrated less variability in strength data as compared to the unidirectional ones, which recommended that a relatively lower factor of safety margins can be used for T-joints with 3D fillets than presently in practice [136].

Resin permeability significantly influences the impregnation time for textile fabric-reinforced composites, such as 2D or 3D woven composites [137]. Many studies in the literature [138–140] have investigated the resin permeability of different 2D and 3D woven fabric composites. Stig et al. (2015) [137] first reported the permeability of woven fabric composites manufactured using fully interlaced 3D woven reinforcements. The study also investigated the effect of other textile parameters on the in-plane permeability of the matrix during impregnation using the unsaturated parallel flow technique. The results indicated that the permeability of the composites was not significantly influenced by the fraction of surface layers or fibre crimp. However, in-plane permeability was significantly influenced by the fibre volume fraction of composites. With a higher fibre volume fraction, the in-plane permeability gradually decreased due to reduced inter-yarn porosity [137].

Tahir et al. (2015) [141] performed computational fluid dynamics (CFD) modelling to investigate the effect of fibrous architecture on resin permeability and to predict the effect of inter-yarn porosity on the permeability of 3D woven composites. The results indicated a significant influence of inter-yarn porosity on permeability, while the effect of intra-yarn porosity was insignificant, attributing to the necessity of accurate representation of geometrical features in the space between yarns. Additionally, the study also predicted that the overall permeability is anisotropic; however, with an increase in inter-yarn porosity, the permeability became increasingly isotropic [141].

Stig and Hallstrom (2012b) [142] reported that the existing models used for 2D fabrics are not useful to predict the permeability and mechanical properties of 3D woven fabric composites. A mesoscale finite element model was developed to analyse the internal strand geometry of 3D woven fabrics. The fabric yarns were represented as tubes, and the tube properties were mimicked for the dry yarn properties. The model did not require any geometric measurements as input and only required a few input parameters, such as the weave pattern, warp and weft counts, yarn crimp, fibre diameter, average fibre volume fraction, and the dimensions of the representative volume elements (RVE). The authors claimed that the modelled geometry could be used for mechanical or permeability analysis of 3D woven fabric composites, and the model was insensitive to the variation of the tube properties, which was attributed to the challenges in measuring the yarn crimp and other imperfections in the real structure rather than flaws in the model [142].
In another study [143], Stig and Hallstrom (2012a) developed a finite element model to predict the elastic properties of 3D woven fabric-reinforced composites. Four models with four different weaves were developed, and the results were compared with the experimental data. The authors demonstrated that warp crimp had a significant effect on the longitudinal Young’s modulus, while the effect on the transverse modulus, shear moduli, and Poisson’s ratio was comparatively low. It was also observed that with the inclusion of stuffer warp yarns, the longitudinal stiffness, transverse stiffness, and shear moduli of the composites increased [143]. A progressive damage model was developed in [144] to simulate the mechanical behaviour and failure mechanisms in 3D woven fabric composites. The progressive damage model is comprised of three modules: stress analysis, failure analysis, and material property degradation. The Hashin failure criterion was considered in the model, and the results were validated through comparison with the experimental observations in [133]. The modelling results were in good agreement with the experimental findings. The predicted mechanical properties indicated good out-of-plane characteristics, which were attributed to the reinforcement in the normal direction. The initiation and progression of different damage mechanisms were predicted using the progressive damage modelling technique [144]. For 3D woven fabric composites, it was observed that meso-scale modelling approaches have the best potential to describe the sub-yarn behaviour, which can be further investigated to account for the optimisation of fibre structure and forming processes [145,146].

4. Conclusions

Textile fabric-based fibre-reinforced composites are increasingly becoming popular for industrial applications. Advanced manufacturing technologies and high-performance fabric yarns have facilitated the development of textile fabric-based reinforcements for industrial applications that can demonstrate a high modulus-to-weight and strength-to-weight ratio as compared to traditional materials such as steel. The development of multifunctional composites using textile fabric-based reinforcements has aided different engineering solutions, such as reductions in processing steps, time, complexity, material wastage, and combining multiple products into a single one. Textile fabric-based composites have found new production routes demonstrating superior performance characteristics and the potential to replace traditional manufacturing methods. The use of 3D woven fabrics in composite preforms significantly reduces the processing steps required when using 2D woven fabrics. However, modelling 3D woven fabrics with complex inner microstructures poses significant design challenges. Presently, 3D woven fabric-based reinforcements are not widely used in the composites industry, apart from some individual and high-specific solutions. Advantages of 3D woven fabric reinforcements include superior impact and delamination resistance and a reduction in preforming steps; however, some of the disadvantages are poor in-plane properties of the composites. This is further accompanied by less-known knowledge regarding 3D woven fabric structure and composite properties. Therefore, although some basic knowledge regarding a relationship between fabric structure, production parameters, and structural-mechanical properties of fabrics and composites is available for 3D woven fabric reinforcements, further research is required for their development to meet the increasing demand in terms of technical, economic, and environmental performance. In general, high production of textile fabric-based composites for industrial applications has the potential to reduce costs and energy consumption, which would further abate the pressure on the environment. Furthermore, utilising state-of-the-art technologies, such as numerical modelling tools, advanced polymeric materials, processing routes, fabric treatments, nanomaterial loading, and naturally originated fabric reinforcements, can ensure sustainability and bring revolutionary changes.

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