J Mater Sci

Review

Potential fabric-reinforced composites: a comprehensive review

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Received: 9 March 2021
Accepted: 12 May 2021

ABSTRACT

Fabric-based laminated composites are used considerably for multifaceted applications in the automotive, transportation, defense, and structural construction sectors. The fabrics used for composite materials production possess some outstanding features including being lighter weight, higher strength, and lower cost, which helps explain the rising interest in these fabrics among researchers. However, the fabrics used for laminations are of different types such as knit, woven, and nonwoven. Compared to knitted and nonwoven fabrics, woven fabrics are widely used reinforcement materials. Composites made from fabric depend on different properties such as fiber types, origin, compositions, and polymeric matrixes. Finite element analysis is also further facilitating the efficient prediction of final composite properties. As the fabric materials are widely available throughout the world, the production of laminated composites from different fabric is also feasible and cost-effective. This review discusses the fabrication, thermo-mechanical, and morphological performances of different woven, knit, and nonwoven fabric-based composites.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
UV	Ultraviolet
GSM	G/m^2
FEA	Finite element analysis
CDM	Continuum damage mechanics
WFC	Woven fabric-reinforced composites
AgNP	Silver nanoparticle
MDI	Methylene diphenyl diisocyanate
MUF	Melamine–urea–formaldehyde
PP	Polypropylene
NRC	Nonwoven reinforced composite
KFRC	Knitted fabric-reinforced composites
PLA	Polylactic acid
PHBV	Poly(3-hudroxybutyrateco-3-hydroxyvalerate)
PE	Polyethylene
PVC	Poly(vinyl chloride)
PS	Polystyrene

Handling Editor: Stephen Eichhorn.

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https://doi.org/10.1007/s10853-021-06177-6

Springer

Published online: 26 May 2021

MOR	Modulus of rupture
MOE	Modulus of elasticity
TGA	Thermogravimetric analysis
DTG	Derivative thermogravimetric
DSC	Differential scanning calorimetry
R&D	Research and development
PBS	Poly(butylene) succinate
SWOT	Strengths, weaknesses, opportunities, and threats

Introduction

Composite materials acquire increased mechanical strength in the reinforcing phase. The ultimate composite products are stronger, stiffer, and harder than the matrix. Recently, fabrics have received increasing attention when compared to other reinforcement materials like particles, fibers, and so on. Although the fibers are applied for three-dimensional (3D) or two-dimensional (2D) structures [1, 2], the architectures are also used through textile fabric (such as woven, nonwoven, knitted, and braided) [3–9]. In 3D fabrics, the fibers are intermeshed lengthwise, thickness-wise, and crosswise, while 2D woven fabrics are made of two sets of yarn (one is lengthwise 0° and the other is crosswise in a 90° direction) through conventional weaving technology. Nevertheless, the low fatigue and stiffness resistance characteristics of 2D fabric when applied to shear stress make them a challenge to use. In addition, composites made of 2D structures are weaker and tensed to delaminations. However, 3D fabrics enhance the thermal stability and mechanical performances in the composites as well as reduce the delamination for the fibers present in perpendicular directions. The design of the fabrics could be tuned during the manufacturing stages to increase the ultimate performances from the final composite products according to the requirements.

Textile fabrics possess notable potentiality for composites used in automobiles, construction, furniture, and buildings. Both natural and synthetic fiber-based fabrics are used in composite production. Natural fibers include hemp, ramie, flax, jute, sisal, cotton, agave, and so on [10–13], whereas synthetic fibers are carbon, glass, nylon, polyester, ultra-high molecular weight polyethylene, and so on [14–20]. However, composites made from natural fiber-based fabrics are becoming increasing popular due to their environmental sustainability. Conversely, synthetic fabric-based composites are also used extensively for their low cost and ease of production. Most aerospace, marine, and automotive companies currently use synthetic fiber-based composites [21, 22]. Fiber properties, fabric structure, the number of fabric layers, and areal density all play significant roles in composite performance. Furthermore, together with enhanced mechanical properties, different polymeric material/nanoparticle loading also plays a notable role in providing composite materials with different functionalities like antibacterial properties and UV-resistance. Generally, different thermoplastic, thermosetting, and cementitious materials are used for developing laminated fabric-based composite panels [23–27]. The use of polymeric matrix in laminated composite depends on the necessities as some polymers are suitable for better mechanical properties generation, while others are better for water absorbency and thermal conductivity. The classifications of different fabrics and the associated structures used as the reinforcement of composite materials are shown in Figs. 1 and 2, respectively.

Fabrics possess excellent drapability around any device or tool; this can be further facilitated with a suitable tool shape and fabric surface [30]. Various processing methods, such as compression forming, roll forming, diaphragm forming, molding, and machining, are applied for the formation of fabric-reinforced composites. Previously, researchers were involved with unidirectional fabric composites developments [31–33]. However, following this, researchers began to investigate discontinuous unidirectional fabric composites [34, 35]. Woven fabrics were considered as potential composite material, but the usage of knitted fabrics also became popular in later periods. However, polymeric material used with the fabric reinforcement indicates numerous potentialities for high-performance composite materials. Researchers are currently examining numerical simulation software to predict material properties, which could facilitate the adequate corrective actions prior to production. This review provides an overview of various woven, nonwoven, and knitted fabric-based composites, polymeric matrices, reinforcement methods, numerical modeling, application areas, and marketing aspects. This work can help facilitate future researchers and industrialists with broad information

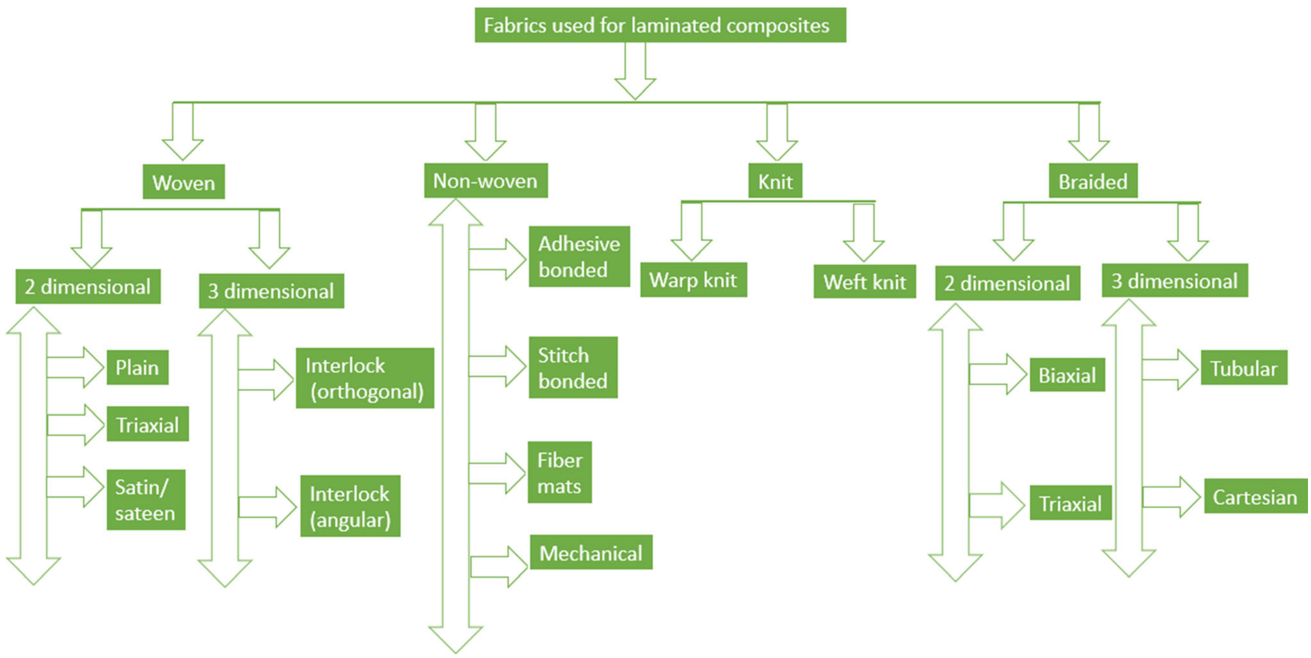
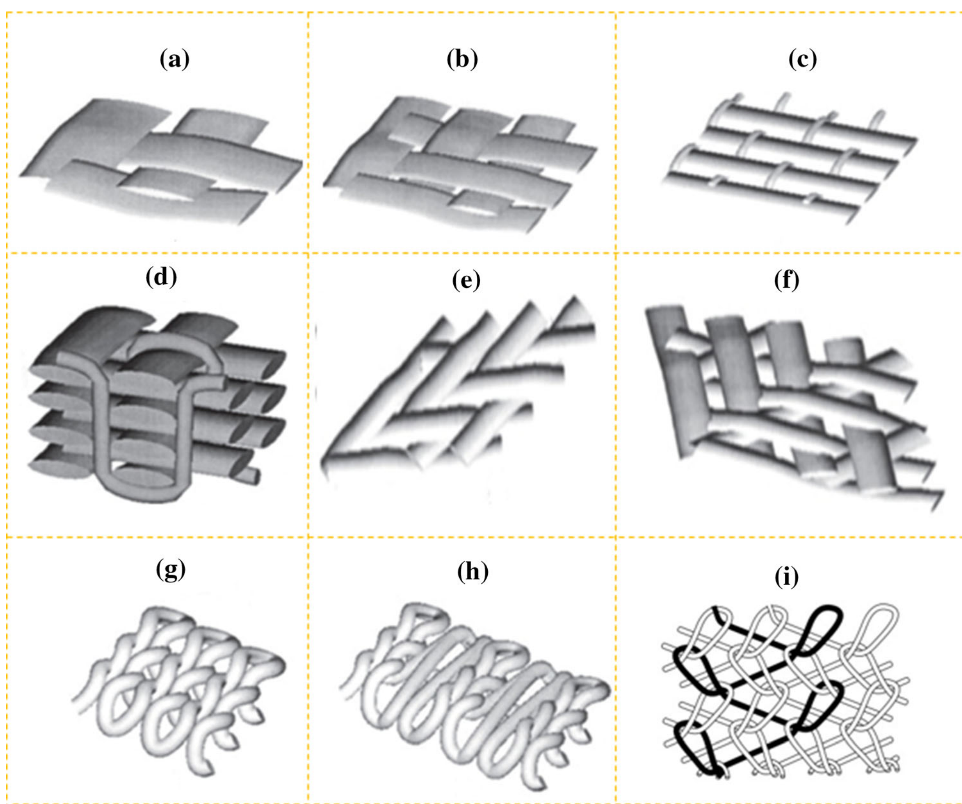


Figure 1 Structural classification of fabrics used for laminated composites production.

Figure 2 Textile fabrics structure: 2D woven fabric (**a**–**c**), 3D woven fabric (**d**), braided woven structured fabric (**e** and **f**), knitted fabric (**g** and **h**), and warp knitted fabric. Adapted with permission from Elsevier [28, 29]. Copyright Elsevier, 2005 and 2016.



regarding new and potential routes for laminated composite production.

Fabrics used for composites

Textile-reinforced composite materials are not only cheaper and more widely available, they are also increasingly being produced via automated rather than manual methods. In this regard, textile fabrics (Fig. 3), which is pre-formed in terms of weaving, knitting, braiding, stitching, nonwoven, and so on, are being increasingly considered. However, the structure of selected fabrics for reinforcement plays a significant role for achieving the expected performance characteristics from composites. Fabrics with higher twist provide higher strengths than those with lower twists due to efficient distributions of stress [36]. Zhou et al. [20] have conducted an experiment where they studied different structures of carbon-based woven fabrics in terms of plain and twill structure and found that differences in fabric structure at uniaxial directions exert limited influences on the strength and modulus of the composites. The same study further claimed that particular fabric structure also exerts influences on the stress concentrations and crack propagations [20]. In another study, Aghaei et al. [37] mentioned that fabric geometry (woven) plays a vital role in influencing the mechanical performances of the composites. Researchers are also becoming increasingly interested in knitted fabric as another prominent potential reinforcement material for composite development. Chen et al. developed sandwich composite panels with higher tensile strengths (124.28 ± 18.64 MPa for carbon fabric/epoxy/glass knit fabric and 332.36 ± 53.18 MPa for carbon fabric/epoxy/carbon knit fabric) and compressive performances by using weft knitted structured fabrics [38]. Ramakrishna conducted research on wale (lengthwise yarn) and course (crosswise yarns) directions of knitted fabric reinforced with epoxy composites tested in terms of tensile strengths and elastic modulus where the elastic modulus was predicted as per laminated plate theory and cross-over modeling [39]. The same study reported that tensile property is strongly dependent on the fiber content in composite systems whereas the strengths grew by the increased fiber contents [39]. Furthermore, knitted fabric-reinforced composites exhibit higher tensile strengths in wale directions compared to the course direction of fabric [39]. Fiber content could be increased via the following parameters:

(a) through increasing the linear density of the yarns,
(b) through increasing the stitch density or loop of the fabrics, and
(c) through increasing the number of plies in the yarns.

Furthermore, preforms (Fig. 4) of fabric-based composites are also important in the design and fabrication. In this regard, Quan et al. [40] modeled multi-directional preforms according to fused filament fabrication methods [41]. Tejyan et al. conducted research on nonwoven fabric of 400 and 600 GSM (g/m^2) with resin through implementing a hand-layup technique. The researchers found significant flexural strengths, impact energy, and thermal conductivity [42]. They summarized that composites thermal conductivity decreases as mechanical strengths and associated fabric density increases [42]. Polyethylene terephthalate (80%) and Kevlar (20%) were blended together to form nonwoven fabric and later, as-produced fabrics (two pieces) were inter-layered with the needle-punching method by

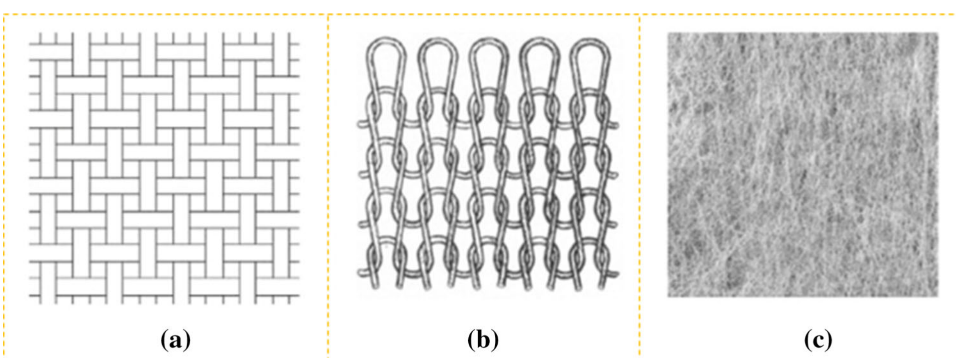


Figure 3 Typical fabric structures used for composites: **a** woven, **b** knitted, and **c** nonwoven. Adapted with permission from Elsevier [44]. Copyright Elsevier, 2016.

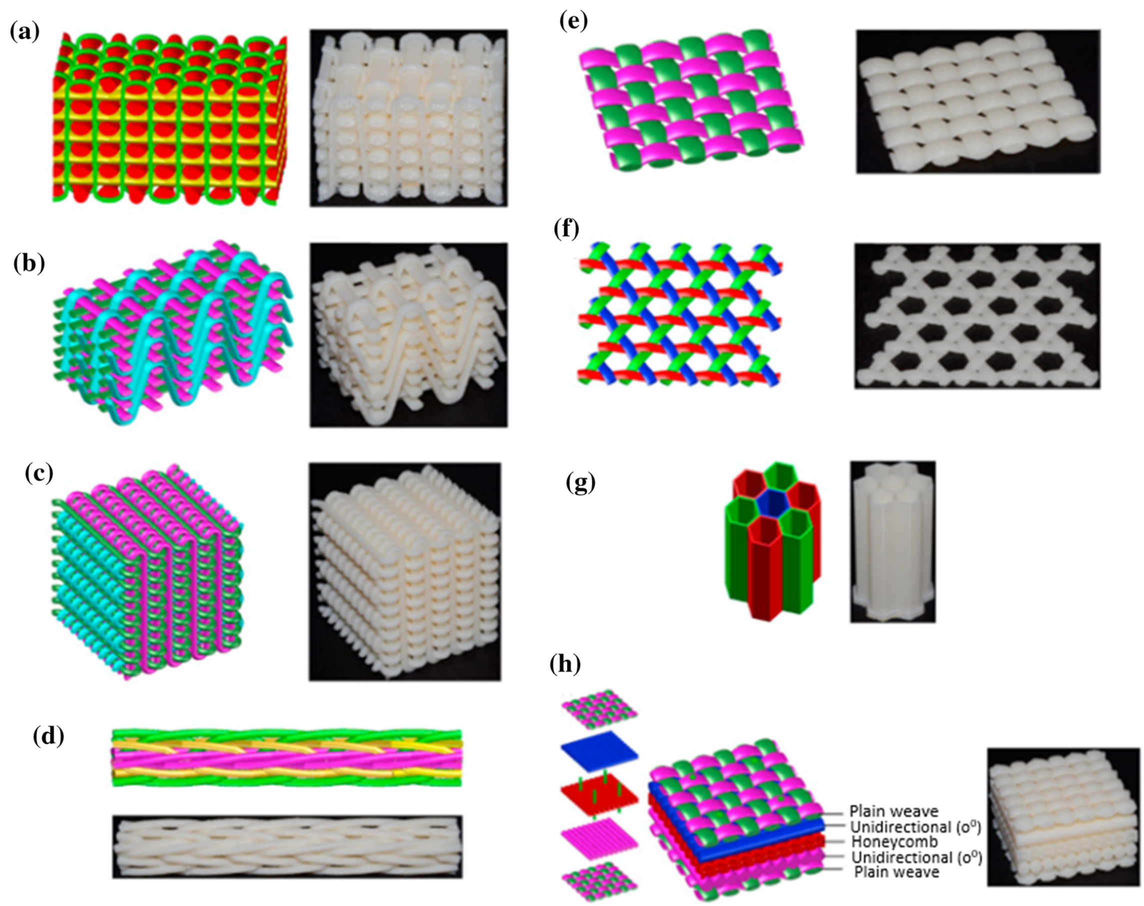


Figure 4 Some multi-directional fabric-reinforced composite preforms demonstrating the model design on the left side and fabricated object on the right side: **a** interlock woven (3-D across the thickness), **b** interlock woven (3-D layer-by-layer), **c** Orthogonal woven (3-D), **d** 4-step braided (3-D rectangular), **e** plain woven (2-D), **f** woven (2-D triaxial), **g** honeycomb (hexagonal cells), **h** multilayered sandwich (Z-pinned). Adapted with permission from Elsevier [40]. Copyright Elsevier, 2015.

enclosing a carbon fiber [43]. Later, a sandwich composite was produced by using the produced fabrics as bottom and upper layers by interlaying polyurethane foam and spacer fabrics [43]. The produced composites provided 1099.61 N residual stress and 7608.92 N bursting stress [43].

Woven fabrics

Woven fabrics are manufactured by interlacing warp (0°) and weft (90°) yarns in a regular weaving pattern. Fabric integrity is maintained through the mechanical interlocking of fibers in the yarn from which the fabrics were made. However, the required characteristics of fabrics, such as drapability, stability, and surface smoothness are controlled with specific styles (plain, twill, satin, etc.) and parameters during the weaving operations.

Plain woven fabrics

The simplest woven fabric structure is where the weft/filling yarns are alternately passed through over and under a warp yarn (Fig. 5). Similarly, every warp yarn is also passed through over and under the filling yarns. Plain weave fabrics are considered structurally symmetrical, having good porosity and stability. On the other hand, despite advantageous features of plain weave structured fabrics, some disadvantages like higher creep level are generated due to the excessive drapability of this structure, which negatively influences the mechanical properties of the composites [45]. Taffeta, crepe, muslin, and organdy are some of the commonly used examples of plain weave structured fabrics. Furthermore, plain weave fabrics are also classified into a further two categories: (a) warp rib weave and (b) weft rib weave.

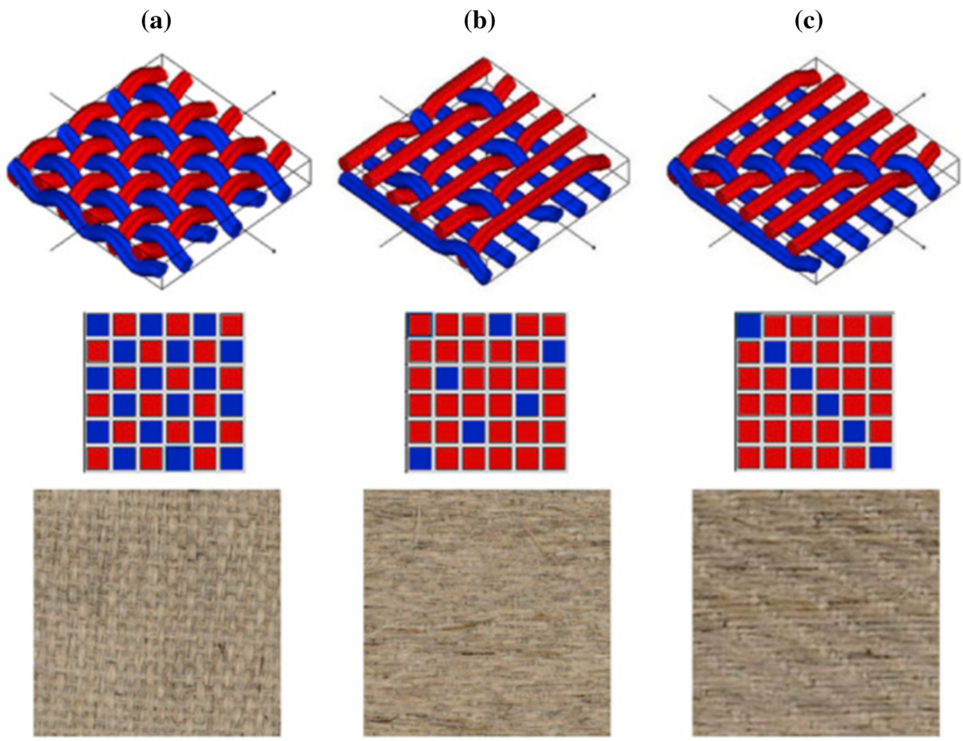


Figure 5 Different derivatives of woven fabrics: **a** plain weave, **b** six weft satin effects, and **c** six weft twill effects. Adapted with permission from Elsevier [46]. Copyright Elsevier, 2020.

The warp rib weaves are performed through the insertion of picks (two or more) in the same shed, which is why it is also termed a warp-faced structured fabric. Furthermore, the cover factor and crimps are higher for warp than they are for weft. Conversely, with weft rib fabrics, the ends (two or more) are woven together as one structure. In this case, however, the cover factor could have an increased possibility of having a higher cover factor as two ends are woven into one. Nevertheless, weft rib woven structured fabrics are more expensive than warp rib woven structured fabrics, which explains why they are not commonly used.

Twill woven fabrics

Warp yarns (one or more) are woven under and over weft yarns (two or more) in a regular pattern to form twill woven fabrics (Fig. 5). However, a straight/broken diagonal appearance of rib structure is found for this type of fabric. Compared to rib fabrics, a superior drapability and wet out property is observed in twill fabrics; however, a slight decline in stability is observed. Nonetheless, if the fabric is mechanized and produced to ensure minimized creeps, it is possible to obtain a positive attribution toward higher mechanical performances. Figure 6(a) contains physical photographs of twill flax woven fabric.

Zigzag weave

A zigzag effect on woven fabric is created if the diagonal directions in a twill fabric are reversed across the width periodically. With this special weave, two different S and Z twill effects are used with equal repeats.

Diamond twill

Two zigzag weaves having equal repeats (symmetrical) are combined to produce diamond effects on woven fabrics. The fabrics are symmetrical across vertical and horizontal directions in diamond twill.

Herringbone weave

The line of twill is commenced in a usual pattern in the case of herringbone twill; however, the direction of twill is also reversed periodically as it is in zigzag patterns of weave, but the interlacement order is also reversed at the reversal points.

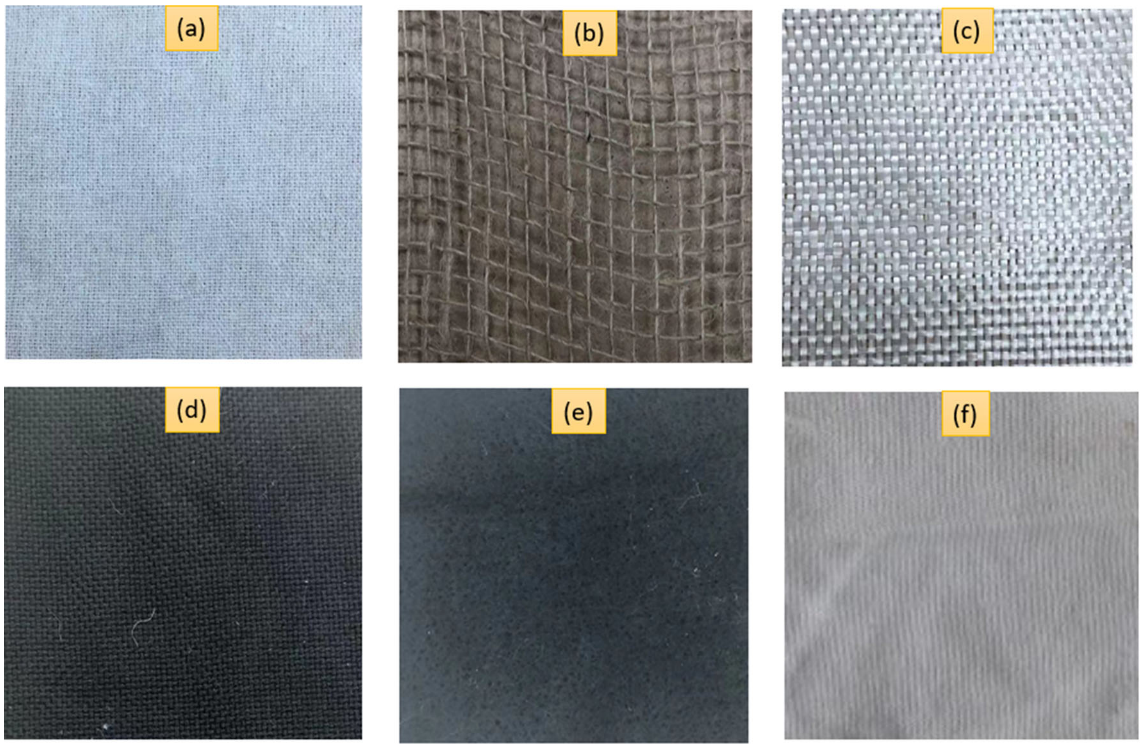


Figure 6 Different fabrics (physical photograph) used for composites production: **a** flax woven fabric, **b** jute woven fabric, **c** glass woven fabric, **d** carbon woven fabric, **e** carbon nonwoven fabric, and **f** cotton knit fabric.

Diaper weave

Two herringbone designs are combined together to produce diaper woven fabrics. However, this design is symmetrical to the diagonal lines.

Sateen/Satin weave

The high luster effects on the one side of the fabric are produced through the use of the floating yarns via weaving operations. With the satin/sateen weaving processing, low twisted warp yarns float through filling yarns (four or more) (Fig. 5). These kinds of fabric are flat and have higher drapability and wet capability. Furthermore, it is possible to achieve improved mechanical performances to generate lower crimps. Moreover, the typical weaving pattern for satin/sateen weaves the yarn in the closest proximity, which results in tightly woven fabrics.

Leno weave

The stability of open fabrics could be enhanced by using a lower yarn count for this style. Leno weave fabrics are used in conjunction (generally) with different weave design styles. Otherwise, leno weave fabrics could not be efficiently used as a composite material due to their openness.

Knitted fabrics

Knitted fabrics are also termed as porous and elastic fabric materials, which are produced in terms of yarns interlocking through the use of needles. Knitted fabrics are cheaper and are employed in a higher volume of production than woven fabrics. Knitted fabrics (Fig. 6f) are made of loops (Fig. 7); the vertical loops are called wales and horizontal loops are called course. However, knitted fabrics are more elastic and lighter. Generally, knitted fabrics are of two types: (a) weft knitted fabrics and (b) warp knitted fabrics. However, weft knitted fabrics exist in many derivatives including single knit, double knit, and specialized knit. Single knit fabrics are classified as single jersey and lacoste, which are widely manufactured by the production houses. Conversely, double knit derivatives are entailing rib, purl, interlock, cardigan, bird's eye, Pointelle, and Milano ribs. Terry, fleece, French terry, velour, silver knit, and jacquard jerseys are some examples of specialized knitted fabrics. On

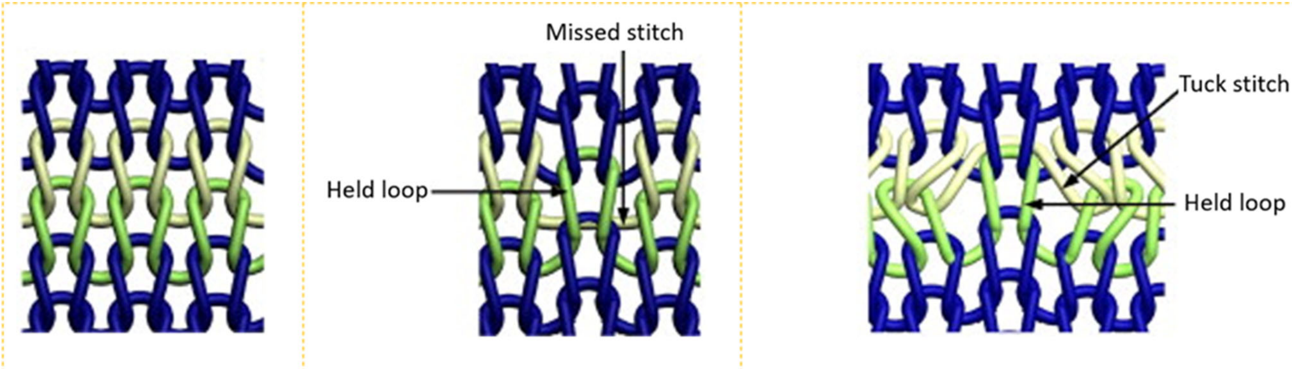


Figure 7 Different types of loops used for knit fabrics production: **a** knit, **b** tuck, and **c** miss stitches. Adapted with the permissions from Elsevier [50]. Copyright, Elsevier 2009.

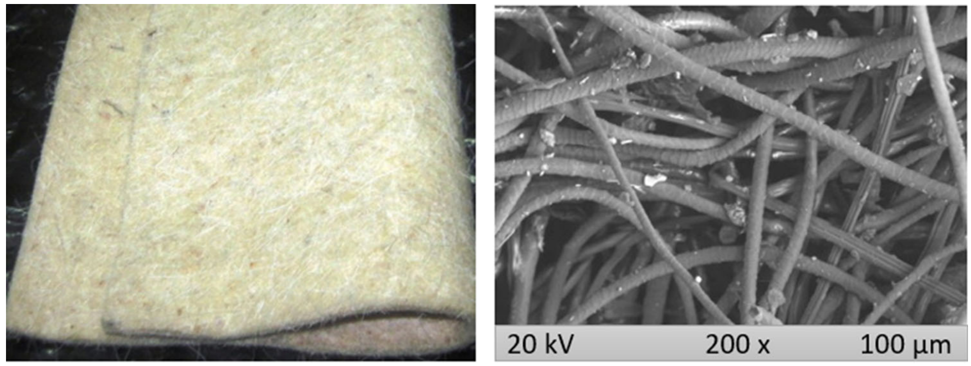
the other hand, tricot and Rachel are two other well-known warp knitted fabrics. The above discussions are collected according to "Textile School" [47]. Cuong et al. conducted a research on aramid and glass fiber-reinforced composites to investigate the cooling effects on PP-reinforced composite and found that flexural properties are influenced by cold conditioning [48]. Furthermore, the gradual cooling of samples also displays higher crystallinity. The same study also reported interesting findings such as higher flexural strength in the wale directions compared to course directions of the fabrics [48]. Qi et al. conducted another research study on weft knitted fabric composites in biaxial directions and found superior tensile performances [49].

Nonwoven fabrics

Generally, nonwoven fabrics are considered advanced materials produced from short and long fibers (chopped/irregular fibers) that are bonded through mechanical and chemical processes or through the application of different solvents [51]. The bonding reagents used are spraying, coating, printing, or saturation techniques for chemical bonding to produce nonwoven fabrics to keep the fibers together. Stiffness and water repellency properties are also executed for this kind of chemical agents in terms of functional finishing. Furthermore, bonding reagents could also be facilitated further to improve enhanced flammability, surface roughness, and visual appearance [51]. However, according to manufacturing techniques, nonwoven fabrics are divided into several classifications like spun-bonded, heat sealing, spunlace, needle punched, hydrophilic, melt-blown, stitch-bonded, airlaid pulp, and wet nonwoven fabrics [52]. The recycled fibers could be utilized for nonwoven fabric preparations. However, nonwoven fabrics are water permeable and are weaker when wet. Moreover, nonwoven fabrics are comparatively cheaper. Nevertheless, it is interesting that nonwoven fabrics could be used for multifaceted applications and in application areas ranging from civil and mechanical engineering [51] to clothing. Comparatively, nonwoven fabrics are much cheaper than other types of fabrics. Shi et al. developed composites from nonwoven cotton fabric reinforced with polydimethylsiloxane through microwave absorption for fabrications and found high-performance electromagnetic wave absorbance characteristics [53]. Wang et al. developed a laminated composite from carbon black incorporated with nonwoven fabric reinforcements with polypropylene and found a significant toughening property [54]. A report by Kakati et al. mentioned that the developed composites from a blend of unsaturated polyester matrix reinforced with nonwoven jute was found to have improved thermo-mechanical and water resistance performance. A physical and morphological representation of needle punched nonwoven fabric is shown in Fig. 8.

Factors affecting the fibers, yarns, and fabric structure in composites

The straight geometry of yarns in the fabric structure is extremely significant in order to achieve the efficient reinforcement effects in polymeric composites. The factors are discussed below:



(a) (b)

Figure 8 Nonwoven fabrics (need-punched): **a** physical picture and **b** morphological photograph. Republished with permission from Elsevier [55]. Copyright Elsevier, 2020.

Influence of fracture

Impact property is extremely important as the structural laminated composites are not always flat, but occasionally curve in one, two, or even more directions. However, studies on impact properties are still limited. If this property is not considered thoroughly during the composite development, it could, consequently, cause destruction and could lead to accidents when applied to marine-based applications or other relevant cases [56]. It is challenging to design and develop models to understand the factors and phenomena associated with impact damage and related resistance characteristics. Johnson et al. [57] discussed FEA (finite element analysis) and composite modeling that could demonstrate the frameworks within in-ply as well as delamination failure against impact load. They [57] proposed a CDM (continuum damage mechanics) model for laminated composites from fabric. However, several parameters influence impact damage on laminated composites [58]; these are listed below:

- Laminate stacking sequence
- Laminate geometry
- Properties and nature of associated matrix and reinforcements
- Composite mass and velocity

Influences of stitching and layout

Fabric reinforcement, different stacking sequences, composite dimensions (2D/3D), and other factors significantly influence the mechanical properties of composites. The delamination shape of interface in the composite system could be determined through the geometry of fractured areas and the sequence of stackings near the interface. However, the mechanism of intraply cracking is triggered by shear stress (transverse). Moreover, major energy is dissipated by the dominant fracture processes of crack propagations in the laminates. However, the properties of associated fiber are responsible for the anticipated damage in the composite matrix systems. Ahmad et al. [55] conducted research on fabricating hemp/polyethylene terephthalate interwoven laminated composites by using vacuum infusion methods reinforced with epoxy resin and found satisfactory thermo-mechanical performances.

Influence of material characteristics

The characteristics of laminated fabric and associated fibers along with their interface and matrix play a significant role in determining the ultimate performance of the laminated composites. Costa et al. reported that void content and associated size are dependent on the resin applied to the laminated composites [59]. The same study also found that epoxy/carbon-laminated composites produce more void than bismaleimide/carbon [59]. The reason for this difference in characteristics may be the use of bio-based bismaleimide, which influenced the creation of fewer voids. In another study, Corbin et al. [60] noted that even the structure (like weaving pattern) of reinforced fabrics could influence the mechanical performances of the composites. Furthermore, the incorporation of different natural and synthetic fiber-based fabrics together with polymeric resin could also influence the improved mechanical properties more than the individual reinforcements [61].

Influence of preload

Research to understand the preload of composites in terms of tensile stresses against crack resistance has also been conducted. Schoeppner et al. [62] reported that the time required for stiffening effects started to decline on pre-tension for reaching the maximum load with the increased indentation depth. The effects of tensile preload were studied by Langella et al. [58] for thinner woven fabric laminated composites for helicopter blades. The researchers monitored the final fractured shape and load versus the associated displacement curve for tensile loads. They noticed that the size of impact fracture/damage grows with the increase of tensile loads, perpendicularly to the tractions [58].

Influence of environmental condition

Generally, structural composites are subjected to various environmental conditions; hence, they can absorb moisture/solvent/oil from the surrounding atmosphere, which influences the thermal, electrical, mechanical, and physical properties significantly [62]. The strength and stiffness of composite materials are influenced by moisture absorption with temperature changes. However, very few studies have been conducted to investigate this phenomenon. Sateesh et al. [63] performed another investigation to identify the impacts of moisture on the mechanical properties of E-glass/polyester polymeric resin composite by exposing it to water for 6-month durations. The results indicated a significant decline in flexural modulus. The reason for that is the loss in bonding strengths between the fiber and polyester resin in the environmental conditions. However, hydrophobic film could be used to create a thinner film barrier of polyvinyl fluoride, polytetrafluoroethylene, polyimide, polyether ether ketone on the composite surfaces [62]. However, the following factors could influence the effects of moisture:

- Matrix characteristics
- Properties of reinforcement fabrics in laminates
- Degree of curing the polymers in composite systems
- Polarity, porosity, and homogeneity of constituent fiber materials in the laminates
- Exposed environmental conditions (relative humidity, temperature, and pressures) of laminates
- Surface hydrophobicity
- Dimensional characteristics of composites (like thickness, density, etc.) and the architectural design of final products.

Influence of crack propagations

The degree of delamination during the application of tensile and bending force to estimate the residual characteristics of laminated composites also needs to be understood. However, a detailed prediction regarding fracture could not be precisely defined as delamination is mainly responsible for decreased mechanical performances; displacement sizes could be predicted. Hirshikesh et al. [64] conducted a study to uncover the routes for crack propagations and the influence of fiber to matrix interactions on these cracked routes. This study summarized that fiber orientations and composite load-bearing capacity influence fracture patterns. Nonetheless, this phenomenon is not workable in similar patterns when fiber interspacing is higher [64]. Researchers and manufacturers frequently choose woven fabrics for their higher fracture toughness and better transverse properties [65]. This study further claimed that the damage of fiber/matrix delaminations in glass/carbon woven fabric occurs due to the adhesive layer at interface [65]. Consequently, higher energy is required to pull out fibers.

Influence of residual properties

Damage tolerance and associated corrective actions to prevent it requires the determination of developed fractures phenomenon/state on the laminate. This term demonstrates the behavior of composite structures against applied force and associated damage to predict residual properties. Zhang et al. [66] conducted a study on fiber-reinforced laminated composites and polymeric composites and investigated micromechanical characteristics via higher temperature curing methods. The study further reported that the residual stresses start to decline with time. After a duration of 34 h, stresses showed a smaller asymptotic value [66]. Furthermore, remaining residual strains could still influence the damage evolution in cross-ply laminates against subsequent tensile loads [66]. Different techniques to determine residual stresses like destructive, non-destructive, and slitting methods are available [67]. Nonetheless, with destructive and non-destructive methods, the strains are assessed from the attribute residual stresses. Tabatabaeian et al. conducted an experiment on polymeric composites from multiple glass-reinforced composites [68]. Their responses were investigated in terms of mechanical performance and residual stresses [68]. However, they [68] determined residual stresses through the application of slitting methods [69]. The results revealed that variation of fiber directions in the laminates significantly changes stress response [68]. Furthermore, residual stresses of the composites also showed a decreasing trend with the exposure of thermal fatigue [68].

Composites from fabrics

Woven, nonwoven, and knitted fabrics are widely used to produce composite materials. The composites from different fabrics are discussed below:

Composites from woven fabric

Woven fabric-reinforced composites (WFCs) are made of stacked fabric and polymers in the composite system. WFCs are advantageous for their higher strength, stiffness, satisfying energy absorption, and superior fatigue behavior. Woven fabrics are constructed with two sets of yarns or tows through interlacing (warp-lengthwise directions and weft-crosswise directions) by weaving operations in loom. Woven fabrics are classified as plain, herringbone, satin/sateen, twill, diamond, and zigzag-based on the different yarn patterns. The higher packing density of yarn in terms of fabric thickness is a competitive advantage of using woven fabrics compared to the braided and knitted structures. However, the yarns are crimped across the lengthwise directions in woven fabric, which results in composites with reduced stiffness and tensile strengths in the case of unidirectional laminates [70]. However, with the advancement of textile technologies, WFCs are gaining popularity. The usage of thermoplastic resins with the fabric reinforcements induces fast and automated production by ensuring higher mechanical performances. Nevertheless, laminated composites formed from a different number of layers of woven fabrics are susceptible to cracking problems with various failure modes in composite surface interface. Delamination is another major challenge that significantly affects the stiffness and strength of the woven fabric-reinforced composites structure. Delamination may occur when applying the load by means of compression, tension, bending, pressure, and different levels of energy during composite formation, which may affect the polymeric structure. Consequently, researchers are focused on resolving this challenge [71]. The samples of different fiber-based WFCs developed in our laboratory are shown in Fig. 9.

Fiber crimp is another critical challenge for laminated composites efficiency. Fiber crimp causes local stress on composites—hence, the matrix may crack due to the debonding in the fiber interface. Consequently, numerous studies were conducted to discover the causes of delamination in woven fabric-reinforced composites [72–74]. The mechanical properties of WFCs are influenced by the surface treatments of the biofibers. The unidirectional tapes of woven fabrics have facilitated WFCs by increased fracture toughness. The main challenges and benefits of WFCs manufacturing could be divided into two broad categories: (a) improving the material properties of composites, (b) modifying the fiber structure/architecture [71, 75]. There are also tools such as PDM (progressive damage modeling) for predicting the stress distribution in the matrix along with the possible damage/failure mechanism both for 2D and 3D WFCs [76, 77]. According to the model, damage occurs due to the dissipation of fracture energy at the time of failure; the amount is determined by the displacement in each failure mode. Different studies also tried to investigate the fatigue damage of plain WFCs by using the PDM model [78].

Some studies have reported on fabrics from similar fibers, but with variable matrices (thermoset/thermoplastics) or different fabrics with same matrices to manufacture laminated composites. Impact strength is associated with a tough matrix, as reported for carbon-based WFCs with thermoplastic and thermoset polymers [79].

Composites from nonwoven fabric

The fibers or filaments are entangled together by thermal, chemical, or mechanical bonding through

Figure 9 Composite samples from different woven fabrics developed in our laboratory: **a** flax woven fabric-reinforced PP composites, **b** jute woven fabric-reinforced MDI composites, **c** flax woven fabric-reinforced MDI nanocomposites (AgNP loaded), **d** flax woven fabric-reinforced PLA composites, **e** hemp/glass woven fabric-reinforced epoxy composites, (**a**) glass/flax woven fabric-reinforced MUF composites.

sheet, yarn, fabric, or web structure in nonwoven fabrics to provide structural stability. Fibers of different origin and properties or a combination of both are brought together by employing nonwoven technology to produce composites from nonwoven fabric. Recently, some recycled materials (such as waste fabrics) are also used to form nonwoven fabrics by using the needle punch method through compression molding. In addition to the application of nonwoven fabric-based composites, nonwovens are also used for geotextiles, filtration, medicine, and acoustic purposes. Researchers also report some efforts for preparing nonwoven composites from kenaf, polypropylene, and fruit bunch [80]. With nonwoven fabrics, the conversion of fibers into yarns is not required to make the fabric like woven/knit. Nonwoven reinforced composites are widely used for non-structural parts of automobiles. The selection of composite type is highly significant especially for the high-velocity and low-velocity impacts of crash performance. Sometimes, the damage may not be seen at the composite surface, but the delamination and cracking could be imparted inside. The collision of tools due to lack of maintenance and exploitation conditions may create low-velocity impacts during the manufacturing of composites [81]. Fibrous composites are applied significantly in products such as vehicles, pipelines, aircrafts, sporting items, protective devices (personal), and in lightweight constructions.

Nonwovens are made with an assembly of soft, voluminous, and porous materials, but provide a support for mechanical damage. Previously, nonwovens were considered as low-cost replacements for conventional textiles; however, they are now used in technical, medical, and consumer products with diversified potential applications in terms of economic perspectives. The tensile elongation and strength of the composites from nonwoven fabrics are strongly influenced by fiber content and fabric direction [80]. The composites made from nonwoven fabrics can supply efficient engineering solutions through the manufacturing of multifunctional products by replacing several products with a single one, thereby providing an economically feasible aspect as well.

Classifications of composite nonwovens

Composites from nonwoven fabric can be broadly classified in following categories:

Complex nonwoven reinforced composites (NRC) The composites are formed by needle-punching, thermo-bonding/stitching, hydroentangling, and latex-bonding through bonding with nonwoven fabric or two and more webs.

Laminated NRC Nonwoven fabrics are combined with two or additional layers to form a stable single layered laminated composite by using adhesive or thermal treatment. The laminated NRCs are stronger than complex NRCs in terms of internal bonding. However, if the bonding is not adequate for technical reasons, separation of the sheets could be challenging.

Blended NRC The fibers are of different origins but have similar characteristics or dissimilar characteristics but different origins or with a combination of both are mixed together to produce technology-blended NRCs.

Technology combined NRC Different technologies of web-bonding or web forming or a combination of both are used to manufacture technology combined NRCs.

Coated NRC Coating materials (biocides, abrasive particles, antimicrobials, metal ions, activated carbon, preservative agent, super absorbent, and so on) are applied on both or single surface of composites either permanently or temporarily to provide various functionalities.

Hybrid NRCs Knitted, braided, and woven fabrics, foams (with tissue), and films are combined with the nonwovens to develop a tri-layer composite by hydroentangling one woven fabric sheet between two nonwoven sheets.

Composites from knitted fabric

Knitted fabrics have opened a new branch of fabric-reinforced composites comprising the yarns laid into a 3D stitching system and held tightly between the looped yarns in the fabric in assembly. Knitted fabric-reinforced composites (KFRCs) have some special benefits when compared to the conventional designs. These benefits include lower thermal expansion, lower production costs, simple recycling, and high resistance against corrosion. KFRCs have potential applications for helmets (bulletproof), rescue tents, air ships, inflatable boats, and roofing membranes. KFRCs are soft composites, so they could be easily utilized for applications where the tearing and tensile characteristics are of prime concern [82]. Knitted fabrics are composed of course and wales yarns made through knitting process. However, when the fabrics are transformed into composite materials, both the course and wales directions of fabrics showed an improvement in strength with the increased loop density, which showed an agreement with the finite element model analysis [83].

Polymers used for laminated composites preparations

The polymeric matrixes are the base chemical reagents for binding laminated fabric materials together. As with other composite materials, fabric-reinforced composites could also be prepared with thermoplastic, thermosetting, and cementitious materials. Recently, bio-based polymers like thermoplastic styrene elastomers, PLA, poly(hydroxy urethane), polyhydroxyalkanoates, and PHBV (poly(3-hudroxybutyrateco-3-hydroxyvalerate)) have drawn attention due to their enhanced sustainability [84–88]. However, some synthetic polymers like PP (polypropylene), PE (polyethylene), and PVC (poly (vinyl chloride)) are frequently used by manufacturers [86, 89]. Furthermore, thermoset polymers are unsaturated polyester, polyurethane, epoxy, phenolics, MUF (melamine–urea–formaldehyde), and silicone [18, 90–95]. On the other hand, PP, PE, PVC, PS (polystyrene), and polyamide are some of the examples of thermoplastic polymers [86, 89, 96]. All of these chemicals possess distinct structures and groups, which enable them to function as strong binding agents in composite systems. Furthermore, both thermoset and thermoplastic polymers contain some advantages and disadvantages. Together with lower viscosity, thermoset polymers are suitable to facilitate the composites with better wetting of constituent fibers. Conversely, thermoplastic polymers are easy to post-form and recycle. However, thermoset polymers are brittle in nature. Unlike thermoset polymers, they are not recyclable and post-formable. Furthermore, thermoplastic polymers require a higher temperature than the melting temperature as the melt flow is low. However, thermoset polymeric laminated composites could be processed even at room temperature.

Finite element analysis on fabric-based composites

Mechanical and thermal properties of the composites have received special attention in the composite materials sector. However, the prediction of the properties is drawing great interest through the use of various analytical and numerical modeling techniques [97–108]. A schematic model of laminated composite where Green et al. [109] described different processing steps of woven fabric laminated composites is shown in Fig. 10. The same study [109] also considered textile geometry before predicting the fabric-reinforced composite mechanical properties. However, it is difficult to predict the mechanical performances of fabric-reinforced composite for the complex mechanisms of fibers in the yarn and yarn in the fabrics [110]. Wang et al. conducted a study on braided composite where they also showed the yarn-level delamination in composite systems for sports protection applications [111]. Crack propagation between the matrix and yarn in laminated composite system is shown in Fig. 11. Wang et al. also stated that shear stresses caused crack propagation and associated delaminations [111]. Furthermore, the out-plane and in-plane deformations also exert significant influence on the mechanical deformations of laminated composites [110]. Moreover, the deformation mode is also responsible for determining the ultimate composite performances. FEA has become a prominent software-based technology for predicting the performance of the materials. The software also allows for the implementation of necessary corrective initiatives to achieve expected performances. A failure mechanism against applied loads/stresses as per FEA analysis is illustrated in Fig. 12. The mechanism saves a great deal of time, effort, and workload by providing the prediction of possible performances before the start of production.

De Carvalho et al. [112] demonstrated different failure locations upon maximum stress criteria (Fig. 12) whereas physical-based criteria displayed different failure locations. Chen at el. [113] developed laminated hybrid composite from unidirectional woven fabrics for ballistic performances and simulated the fabrics in yarn level as having a density of 6.73 threads/cm both in lengthwise and crosswise directions and fabric density 240 GSM. The fabric was modeled 10 × 10 cm^2 symmetrically in X and Z axis. The projectile velocity toward laminated composite was 500 m/s and the coefficient between the yarns was 0.14 [113]. The ballistic performance was measured as per Eq. 1.

$$\Delta E = \frac{1}{2} m \left(v_1^2 - v_2^2 \right) \quad (1)$$

where ΔE is loss of kinetic energy by projectile, m is projectile mass, v_1 is impact velocity, and v_2 is residual velocity of the projectiles. Finally, the FEA model was validated against the experimental data. The experimental results revealed that 0.053 J/g m^{-2} energy was absorbed by one layer woven fabrics, whereas unidirectional woven fabrics (single layer) showed 0.047 J/g m^{-2} [113].

In order to understand the impact effect on composite structure, a mathematical model could be developed for the prediction of contact force history and structural performance of the composites. The modeling of structural composite projectile dynamics and the indention of respective structures in terms of projectiles were determined. In this regard, inelastic

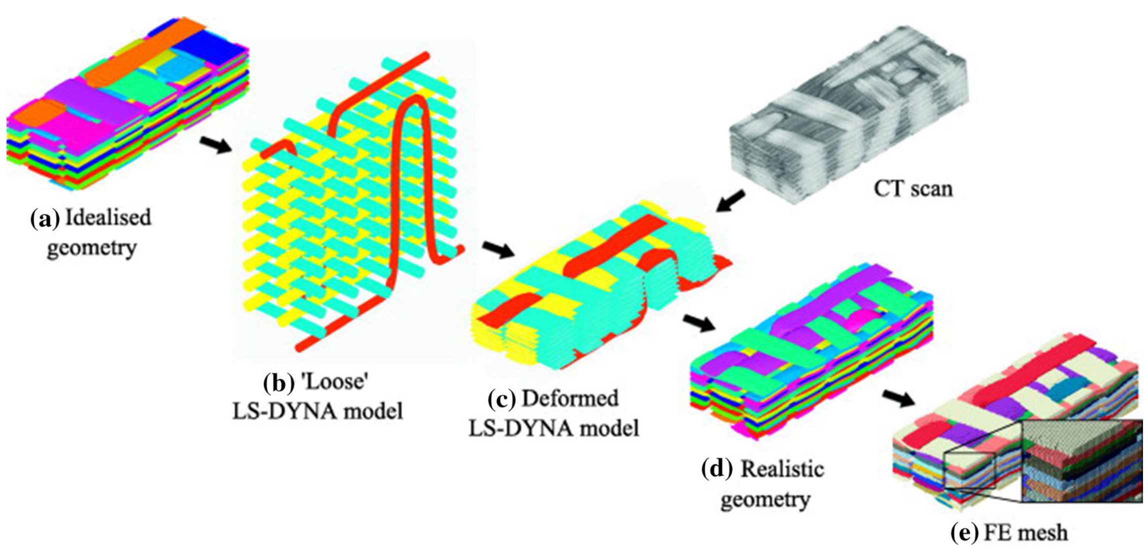


Figure 10 Workflow modeling process overview in terms of CT scan photographs. Republished with permission from Elsevier [109]. Copyright Elsevier, 2014.

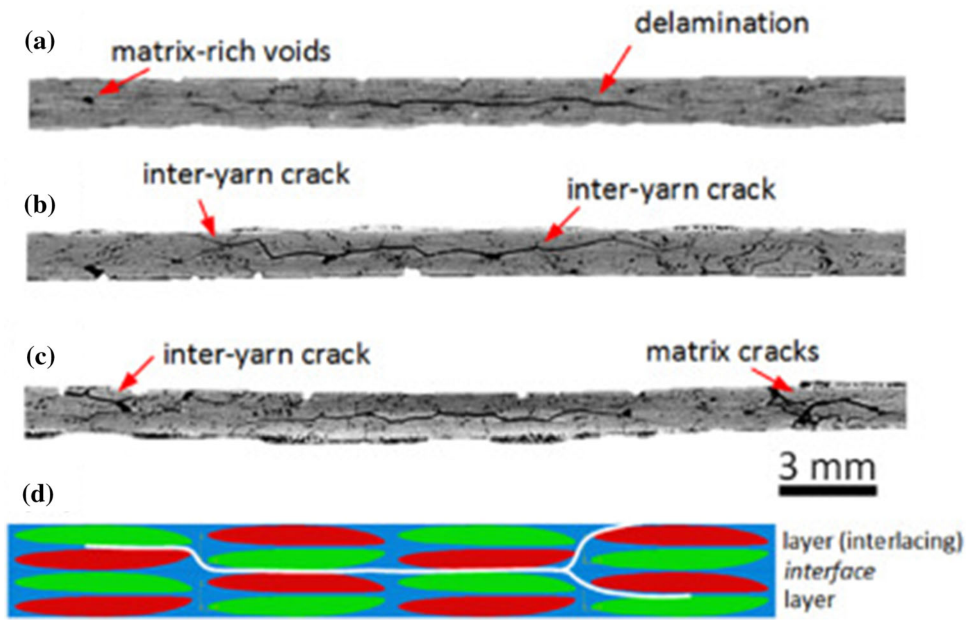


Figure 11 Delamination and crack propagations CT scan photographs of braided composite plates at diverse impact energies: **a** 3 J, **b** 6 J, **c** 9 J, and **d** crack propagation illustrations. Republished with permission from Elsevier [111]. Copyright Elsevier, 2017.

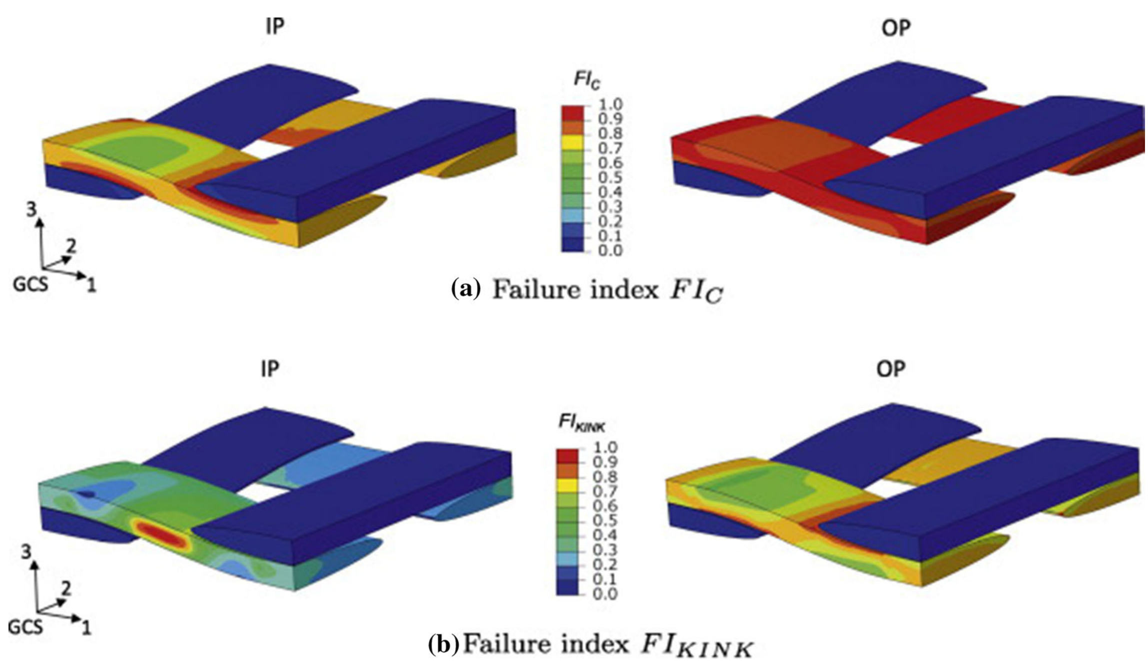


Figure 12 Failure indexes at compression failure under two criteria: **a** maximum stress (FI_C) and **b** physical-based (FI_{KINK}). Republished with permission from Elsevier [112]. Copyright Elsevier, 2017.

impact was studied by Lin et al. [56] as demonstrated by Eq. 2:

$$m_p V_p = (m_p + m_n) V_0 \tag{2}$$

where m_p indicate projectile mass, V_p initial velocity, $+m_n$ stands for mass of the n node, and V_0 is the initial velocity of node (impacted). Later, the projectile is considered as mass added to n node and dynamics of structures could be determined in terms of structural value problems.

Furthermore, micromechanical FEA is also getting attentions for characterizing composite materials through introducing adequate unit cells [114–119]. The unit cells could be formulated depending on the periodic conditions of respective problems. The boundary conditions are extremely important which needed careful considerations before going to FEA of the problems. However, the boundary conditions also sometimes based on as per the intuition of respective persons or sometimes subjected to the uniaxial tensions [118]. Nonetheless, shear loading also needed to consider which is not performed in so many cases generally as this is relatively difficult scenario. Moreover, the validation of unit cell is also very important. 'Sanity check' is also necessary for the formulated unit cell to compare with the experimental data although precise correctness is difficult to achieve. The thermal performances of the 3D braided fabric-reinforced composites could also be calculated effectively through employing FEA [120–122].

Fabrication of laminated composites from different fabrics

The production of fabrics for lamination is comparatively easier than other types of composites like fiber or particles. The hand-lay-up method is one of the most common and widely used fabrication methods for fabric lamination to produce composites due to the lost-cost manufacturing features. Recently, there were two types of laminated composites developed from our groups where flax and glass woven fabrics were the reinforcements and PLA, PP, and MDI were used as polymeric resin [123, 124]. In the case of flax/glass woven fabric/MDI composites, the MDI thermoset resin was sprayed over the stacked fabrics with a spatula and the lamination was created for six layers of fabrics. Later, the laminated fabrics were pressed by a pressing machine applying 3.50 MPa load at room temperatures for 5 min. The pressure was then released, and the laminated composites were cured at room temperature for 24 h. In the case of flax woven reinforced thermoplastic polymeric composites, initially the PLA and PP sheets were prepared by applying high temperatures (170 °C for PLA and 180 °C for PP). Later, the flax woven fabric, PLA and PP sheets with specific dimensions were laminated and hot-pressed again to produce the flax/PLA and flax/PP laminated composite panels. Monteiro et al. [125] developed fique (a special type of fabric) woven fabric-reinforced composites for armored vest applications. In this regard, they [125] dried the fabrics first and then poured the thermoset resin in the differently layered fabric stackings and pressed them (3 MPa) at room temperature (25 °C) for 24 h. Rouf et al. [126] developed laminated composites from eight plies of woven fabrics through implementing VARTM (vacuum-assisted resin transfer molding) methods. During this processing, all the plies were placed in zero degree directions. However, the asymmetric design was dominated by warp yarns in one face, whereas weft yarns were kept in another face. Moreover, the curing was conducted for 24 h at room temperature as well [126]. A schematic design of laminated composites is shown in Fig. 13.

Mechanical performances

The mechanical properties of composite are significant performance characteristics that require testing to examine the performance suitability of the products. Generally, the mechanical properties are investigated in terms of tensile, flexural, impact, and compressive properties. The mechanical properties depend on many factors like yarn geometry in fabrics, fiber types (natural or synthetic), matrix used for reinforcements, fabrication methods, heating/cooling rate for thermoplastic polymeric materials, and so on. Moreover, the chemical cross-linking, morphology, molecular weight, number of plies, fabric properties (like density, thickness, yarn count, etc.) also greatly influence developed laminated composite panels. The mechanical properties of different fabric-reinforced laminated composites are tabulated in Table 1.

Tensile properties

Tensile test measures the force required to break the test specimen (Figs. 14, 15) of composites and associated elongations at breaking point. Tensile properties in terms of tensile strength, modulus, breaking strength, elongation at break, load versus displacement curves are considered as the most important characteristics to discuss laminated composite performance behavior [86, 140]. Furthermore, Poisson ratio, ductility, and yield strengths could also be determined through tensile strength characterizations. The tensile tests are conducted as per different standards like ASTM D 638, EN 310, ISO 527-4, ISO 527-5, ASTM C 297, ASTM D 3039, and ASTM D 638 as per the requirements [141–144]. Tensile strengths of the laminated composites provide higher strengths

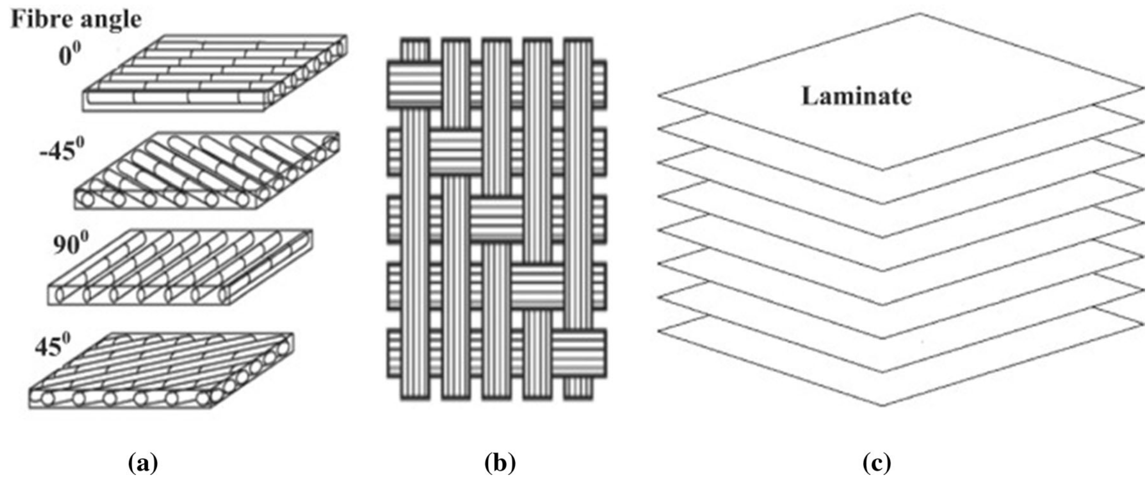


Figure 13 Fabric laminated composites: **a** orientation of ply, **b** satin weave, and **c** laminated ply (8-layer). Reprinted with permission from Elsevier [127]. Copyright Elsevier, 2016.

Table 1 Mechanical properties of fabric-reinforced laminated composites

Laminated composites	TS (MPa)	E (GPa)	MOR (MPa)	MOE (MPa)	IS (J/m)	Ref.
Glass woven fabric/epoxy	346.6	1.28	318.75	20.83	1470.5	[128]
Sisal woven fabric/epoxy	33.2	0.20	124.64	7.70	147.1	[128]
Sisal/glass woven fabric/epoxy	108.22	0.53	205.64	12.72	635.5	[128]
Cotton/cotton woven fabric/epoxy	72.92	–	82.08	–	–	[129]
Cotton/bamboo woven fabric/epoxy	85.37	–	107.02	–	–	[129]
Flax woven fabric/epoxy	91.07	1.96	109.5	6.39	295.65	[130]
carbon woven fabric/epoxy	406.6	15.2	–	–	–	[131]
Carbon/Jute woven fabric/epoxy	257.6	9.8	–	–	–	[131]
Hemp woven fabric/vinyl ester	46.61–56.3	5.81–6.19	77.13–90.54	4.28–5.07[132]	–	84]
Kenaf/carbon woven fabric	117	7.21	224	7.68	–	[133]
Ramie woven fabric	67.86 ± 1.71	–	104.93 ± 3.2	–	–	[134]
Knit fabric						
Co-woven knit fabric	606.72 ± 55.4	24.17 ± 2.01	–	–	–	[135]
Bamboo/cotton knit fabric/epoxy	–	–	140.44 ± 6.02	6.89 ± 0.523	–	[136]
Modal/cotton knit fabric/epoxy	–	–	192.83 ± 12.90	10.69 ± 0.95	–	[136]
Viscose/cotton knit fabric/epoxy	–	–	173.25 ± 13.13	9.14 ± 0.43	–	[136]
Nonwoven fabric						
Jute woven/nonwoven/polyester	25.09	–	2.83	–	–	[137]
Nonwoven kenaf/polyester	251.43 ± 49.29	17.39 ± 5.36	–	–	–	[138]
Nonwoven flax/PLA	90.4 ± 7.8	13.2 ± 1.3	–	–	–	[139]
Nonwoven flax/PHA	82.4 ± 4.1	10.3 ± 1.5	–	–	–	[139]
Nonwoven flax/PP	59.4 ± 2.1	8.2 ± 0.7	–	–	–	[139]

TS Tensile strength, *E* Elastic modulus, *MOR* Modulus of rupture, *MOE* Modulus of elasticity, *IS* Impact strength

especially in parallel directions compared to other types of directions. In one of our recent studies, we also found similar effects for flax or PLA and PP composites where strengths in warp direction were higher than weft directions for both types of matrices [145]. The failure of composites against applied load is depicted in Fig. 15.

Flexural properties

Flexural properties (strength and modulus) are another important parameter for demonstrating the mechanical characteristics of laminated composites. The test is performed against a three point bending load on the composite specimens (Fig. 16). The flexural modulus indicates the stiffness of composite specimens. The flexural properties of the materials could vary according to temperature; hence, the maintenance of ambient temperatures is needed to obtain optimum results. There are different testing methods like ASTM D790 and ISO 178 that are followed for flexural properties analysis [147]. The chemical structures of fibers in constituent laminates also greatly influence the flexural properties. In the case of natural fibers, if the cellulosic content and degree of polymerization is higher, then the flexural properties would also be higher [148]. Ries et al. [149]conducted an experimental analysis on flexural characteristics of laminated hybrid composites as per Fig. 16 setup.

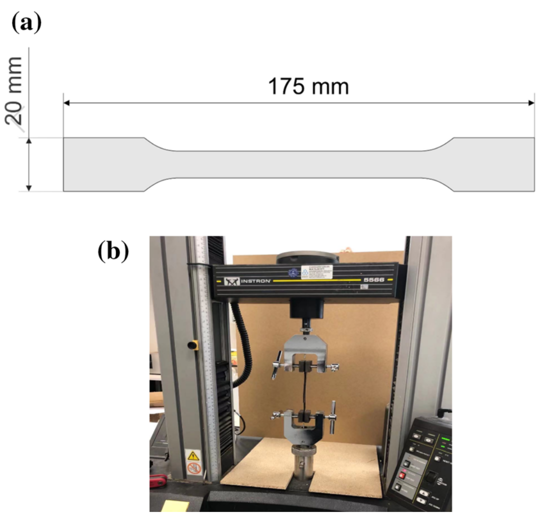


Figure 14 A schematic representation of tensile test: **a** samples for tensile test and **b** sample placed in Instron testing equipment. Drawn by Péter György Horváth.

The modulus of rupture (MOR) is calculated as per Eq. 3, where F indicates maximum load/force, l is span length (mm), b is specimen width, t is thickness, and a is deflection.

$$\mathrm{MOR} = \frac{3Fl}{bt^2} \tag{3}$$

$$\mathrm{MOE}, E_\mathrm{m} = \frac{l_1^3 \times (F_2 - F_1)}{4bt^3 \times (a_2 - a_1)} \tag{4}$$

MOE (Eq. 4) demonstrates modulus of elasticity, l_1 is span support, increased load (N) on the straight direction of the curve ($F_2 - F_1$). F_1 stands for 10% of F_{max}, F_2 stands for 40% of F_{max}. $a_2 - a_1$ is the increased deflections measured from sample center related with the increased load$F_2 - F_1$. This explanation was also reported in our previous research on flax woven fabric reinforced with PLA/PP thermoplastic polymers and cement-bonded fiber composite panel [140, 150]. Furthermore, a failed propagation

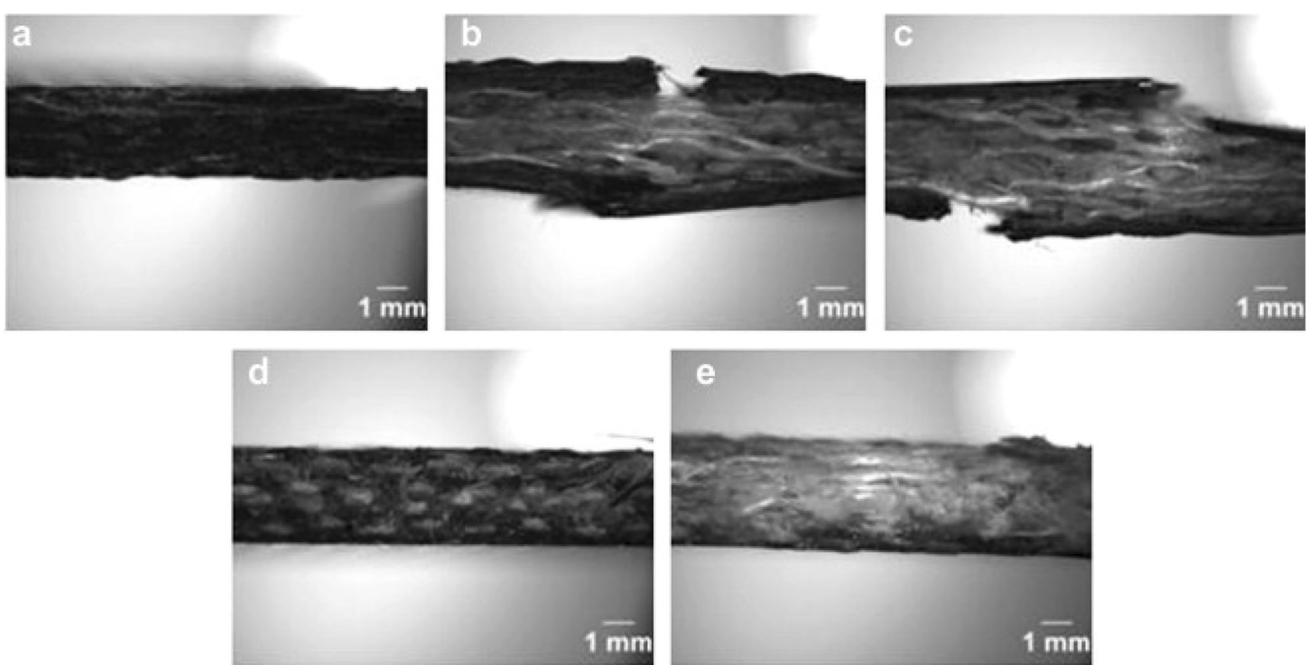


Figure 15 Microscopic photographs of failed laminated composites against tensile loading (**a**–**d**). Reprinted with the permission from Elsevier [146]. Copyright Elsevier, 2012.

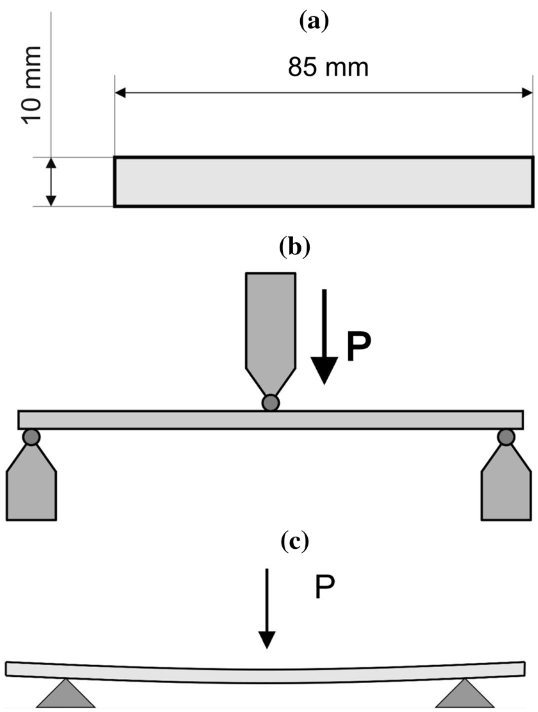


Figure 16 Flexural test: **a** samples geometry, **b** schematic diagram of three point flexural test design and place samples in the system, and **c** schematic diagram of bent samples during the test. Drawn by Péter György Horváth.

against flexural loading on laminated composite is shown further in Fig. 17.

Impact strength

Typically, an impact test demonstrates the response of a material upon sudden load applied to the specimen (Fig. 18). An impact test could also be utilized to discover the energy absorbed by the samples during the fracture of composites. Furthermore, an impact test is also popularly used for evaluating the brittleness, toughness, and notch-sensitivity in addition to the impact strengths [142]. The impact properties of the composites also depend on the fiber types and interlaminar shear strengths. The laminated composites exposed more vulnerability against impact damage compared to other structural materials. Likewise, smaller debris and stones could be propelled from the highway during aircraft departures and landings at higher tire velocity. It may happen with larger projectile velocity, although the velocity becomes lower. Furthermore, breakage/delaminations of fiber and cracking of matrix could also occur for structural laminates due to the lower velocity of the impact loading during the use/functioning of the materials. Moreover, catastrophic damage may also happen through the internal damage/failure of the composites. In this regard, it is essential to investigate the capabilities of energy absorption and impact resistance properties of the laminates before using them for particular applications. However, through preventing the ultimate failure of composites from structural laminates, such problems could be solved/improved [151]. Furthermore, stress distribution could be tuned by controlling the stiffness of fibers during the impact loading in composite systems. Impact strengths could be measured with the Charpy and Izod tests. However, there is a slight difference between these tests as the Izod test requires placing the notch facing striker [142]. Overall, impact tests ensure the safety and liability of the composite materials and are, therefore, a highly significant characterization.

Compression test

The buckling of composite materials is tested in terms of compression characterizations. Laminated panels are tested for compression where the samples are comparatively thinner, flat, and rectangular. The behavior of composite materials is characterized against crushing load, and the associated deformations and compressions are noted to calculate the stress and strain (compressive) upon different loads. Generally, there are three methods of introducing the compressive load on test specimen: (a) end load, (b) shear load, and (c) combined load [142]. The end load is applied into the flat end, shear load into wide faces, and combined load at the combination of end and shear load on a composite specimen [142]. Some of the commonly used compression methods are ASTM D 3410, ASTM D 695, ISO 14,126 [152–154]. The failure pattern of impacted and non-impacted buckling composite samples is illustrated in Fig. 19 where the buckling lines could be easily observed in both cases.

Thermal property

Thermal stability of the laminated composites is a highly crucial parameter that could be investigated in terms of TGA (thermogravimetric analysis), DTG

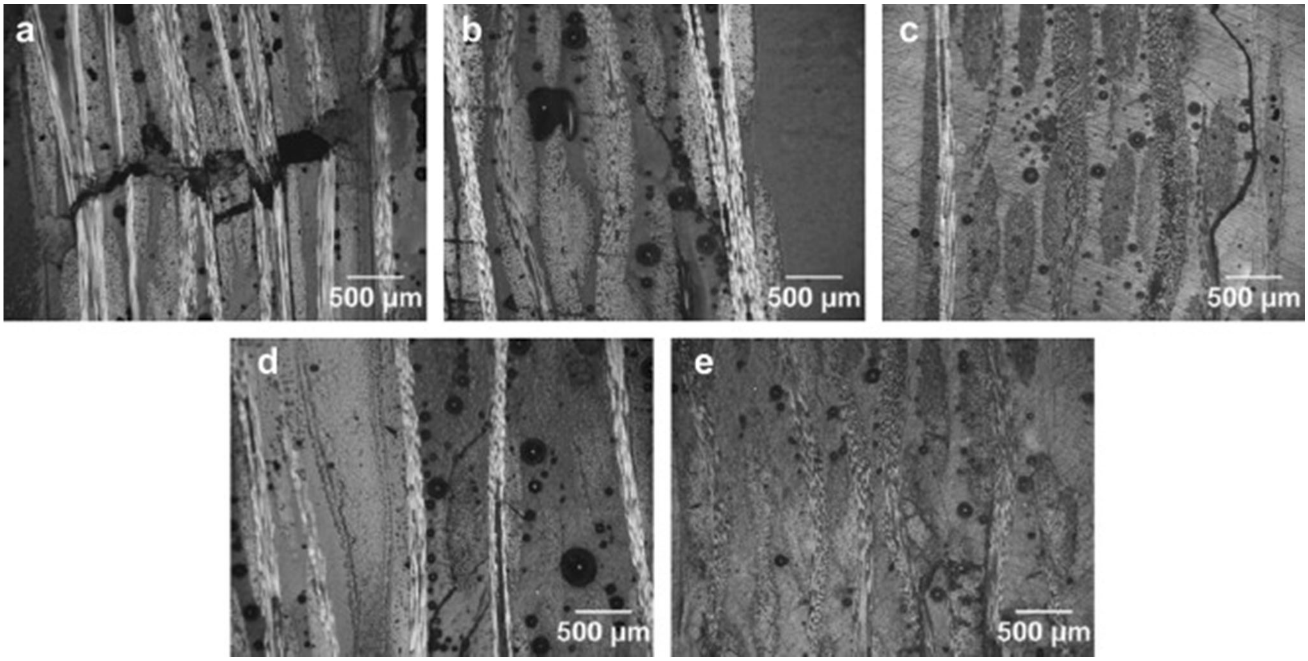


Figure 17 Microscopic photographs of failed laminated composites against flexural loading (a–d). Reprinted with permission from Elsevier [146]. Copyright Elsevier, 2012.

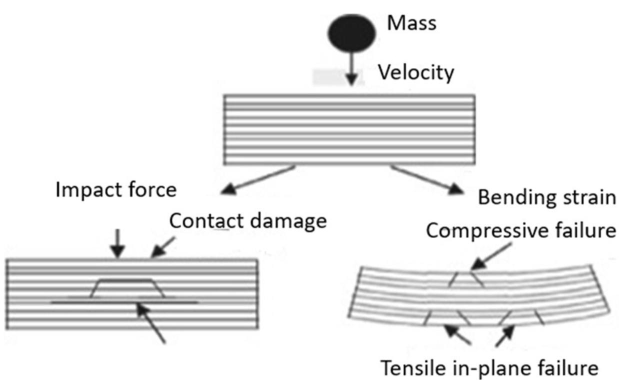
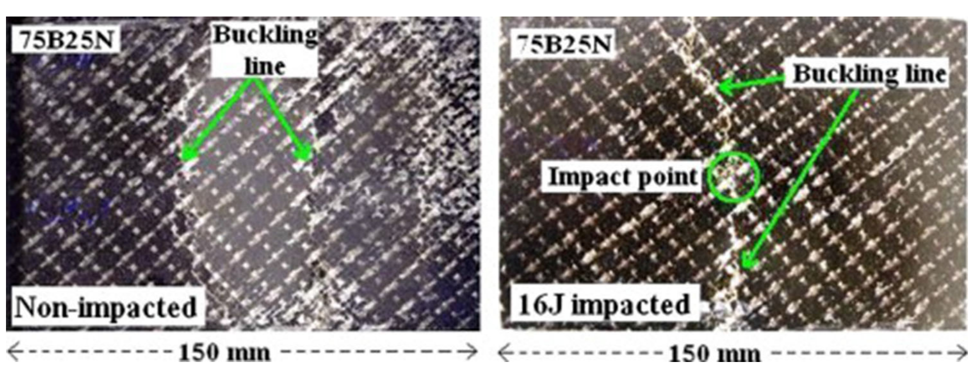


Figure 18 A drop-weight schematic diagram of impact damage. Reprinted with the permission from Elsevier [127]. Copyright Elsevier, 2016.

(derivative thermogravimetric, and DSC (differential scanning calorimetry) analysis. Kannan et al. [156] performed a study on flax interwoven fabric reinforced with PP composites. In the same study, they [156] found that control flax fabrics provided a three-step degradation (initially within 120–220 °C for moisture evaporations, a second step within 345–380 °C for hemicellulose and lignin decompositions, and a final step after 578 °C displayed the complete weight loss). However, PP shows the decompositions at high temperatures (initial and final) at 372 and 431 °C, respectively [156]. However, the loading of flax with PP improved the thermal stability of flax fabrics where the initial degradations

Figure 19 Failure pattern of impacted and non-impacted buckling composite samples. Reprinted with permission from Elsevier [155]. Copyright Elsevier, 2013.



starts from 200 °C, second step degradations at 333 to 375 °C, and final steps at 587 °C [156]. On the other hand, woven fabrics from synthetic fibers like glass display more thermal stability compared to natural fiber like flax woven fabric-reinforced polymeric (like MDI polymeric) composites [145].

Morphological properties

Surface morphology investigation is extremely important to understand the fiber to matrix compatibility as it determines the thermo-mechanical performances of laminated composites. However, interfacial bonding or fiber to matrix adhesion in the case of fabrics made of natural fibers could be improved by using pretreatment (like mercerization/alkaline treatment) of the fabrics. Furthermore, if the fibers are incompatible with the polymers, there could also be a decline in mechanical properties with associated cracking, which becomes noticeable during the tensile stresses. The fracture could happen for a variety of reasons including irregular fiber distributions during the yarn and fabric formations, mixing of matured and immature fibers, arbitrary fiber lengths and nodes, and so on [140]. Moreover, the failure of composite system likely occurs because of fiber breakage in the laminate systems, too. The debonding of fibers from matrix system against tensile load is another major reason for composites failure [157]. To overcome the embrittlement in composite system, it is necessary to select the suitable polymers for the respective reinforcement materials. A failed section of composite is shown in Fig. 20 where the pulling out of fibers could easily be observed in the matrix systems.

Physical properties

Studying physical properties of laminated composite is important to investigate the dimensional stability of the developed materials. Water absorption, thickness swelling, and moisture content of laminated composites are considered as the principal physical properties. The water absorption of laminated composites entails the effect of moisture content characteristics of composites, debonding between the fiber and matrix, and associated strength loss [158]. Furthermore, higher water absorption and poor thickness swelling results in decreased mechanical properties [159]. The natural fiber-oriented fabric-reinforced polymeric composites provide higher moisture contents than artificial fiber-oriented fabric-reinforced laminated composites because the natural fibers contain cellulosic polymers in their chemical structure [145, 160, 161]. The reason for the higher moisture contents of natural fiber-based [162] fabric composite is the presence of hydrophilic compounds like –OH, $–NH_2$, –COOH, and –CO groups in their polymeric structures. Furthermore, the pretreatment of fabrics before composite formation could also lead to improved moisture content, water absorbency, and thickness swelling properties [163]. Water absorbency of the composite samples is measured as per Eq. 5, thickness swelling by Eq. 6 and moisture contents by Eq. 7.

$$W_a = \frac{W_w - W_d}{W_d} \tag{5}$$

where W_a indicates water absorbency, W_d initial weight of specimens before submerging in water, W_w is the weight of specimens after being submerged in water.

$$T_s = \frac{T_w - T_d}{T_d} \tag{6}$$

where T_s indicates thickness swelling, T_d initial thickness swelling of specimens before being submerged in water, T_w is the thickness swelling of specimens after being submerged in water.

$$M_c = \frac{M_b - M_d}{M_d} \tag{7}$$

where M_c indicates moisture content, M_b initial weight of specimens before drying, M_d is the weight of specimens after drying. A schematic representation of samples submerging under the water is displayed in Fig. 21.

Hybridization of laminated composites

Hybrid laminated composites are formed by reinforcing two or three fabric types (such as fabric from different natural/synthetic fibers like glass/flax, different natural fibers like flax/hemp, and different synthetic materials like glass/carbon) with the polymeric matrix. The hybridization of laminated composites could provide superior thermo-mechanical

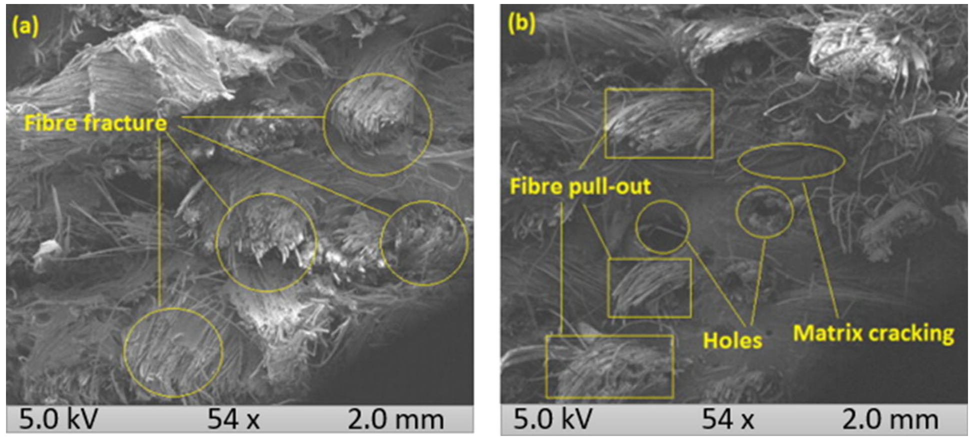


Figure 20 SEM photographs of fractured flax/epoxy composites: **a** control composite and **b** after exposure the composite to weather for 1500 h. Adapted with the permission from Elsevier [157]. Copyright Elsevier, 2015.

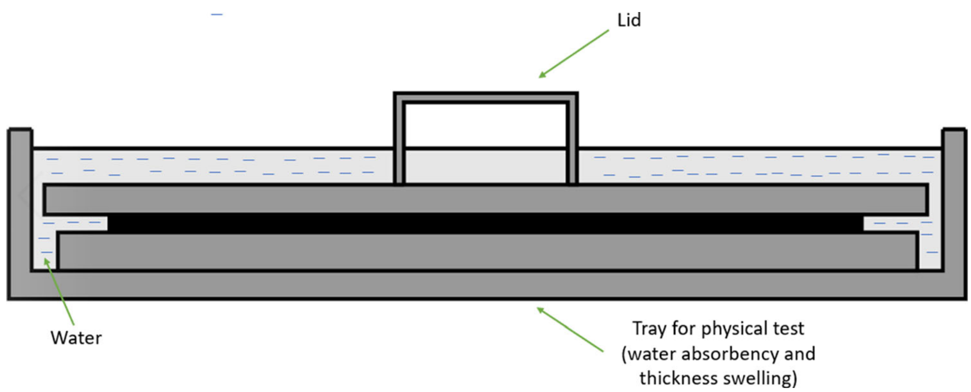


Figure 21 Schematic representation of water absorbency and thickness swelling test. Drawn by Péter György Horváth.

properties [145, 164, 165]. Sometimes, fabrics with lower cost and modulus are hybridized with fabrics possessing higher modulus and cost to minimize the product cost with enhanced performances. The world is becoming more sustainable and greener; hence, reinforcement of strong synthetic base material like glass/carbon fabrics with comparatively less strong naturally derived flax/hemp woven fabrics could provide a greener product with the presence of polymers. Generally, the hybrid composites could provide even higher thermo-mechanical properties compared to individual fabric-based composites [140, 145]. Sometimes the natural and synthetic fibers can also be interwoven together (Fig. 22) to get the hybridized performances from ultimate composite products. Kumar et al. [166] conducted research on flax/glass woven fabric-reinforced vinyl ester composites with a different stacking sequence. In their study, they found that pure flax stacking (4 layers) provided 73.94 MPa tensile strength and pure glass stacking (similarly 4 layers) provided 85.16 MPa tensile strengths whereas their hybridized stacking (4 layers flax and 3 layers glass, in total 7 layers)

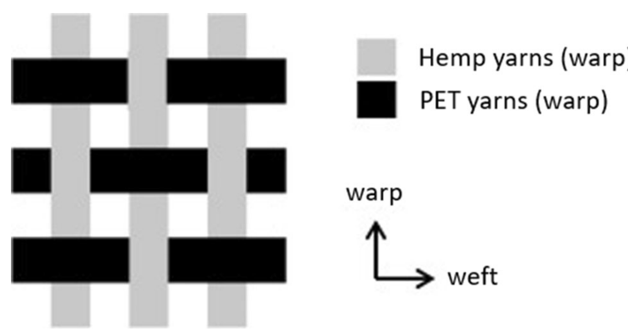


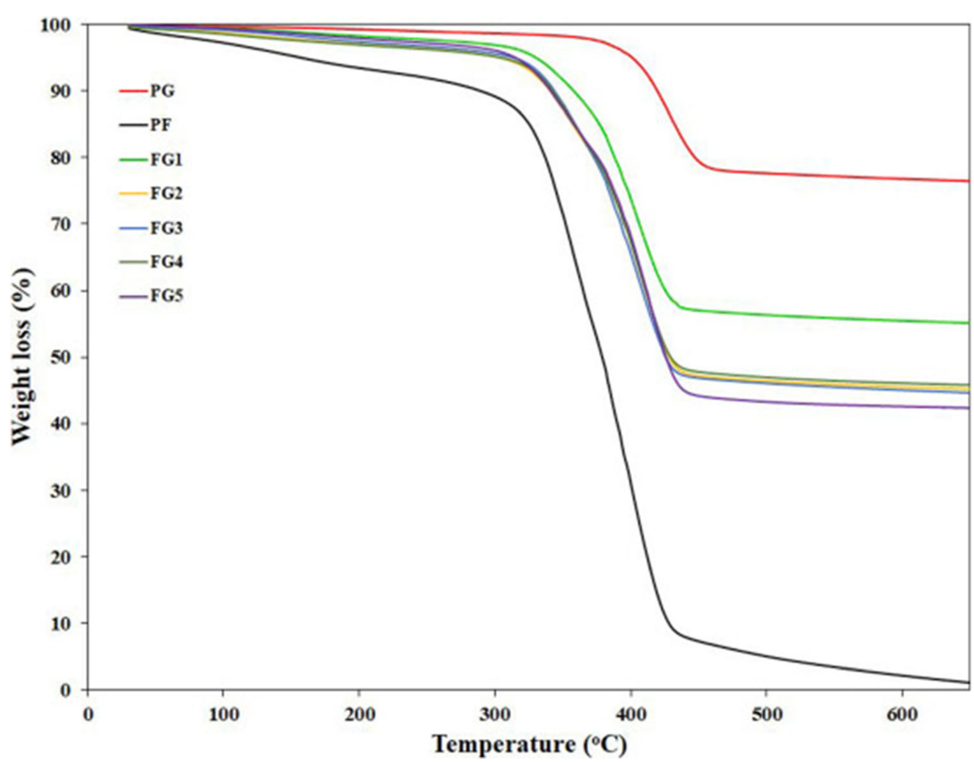
Figure 22 Direction of warp and weft for interwoven hybrid composite. Republished with permission from Elsevier [55]. Copyright Elsevier, 2018.

provided the highest tensile strengths (143.21 MPa) [166]. The results clearly demonstrated that glass woven fabrics have higher strengths compared to natural flax; however, their hybridization could generate even higher tensile strengths than their individual contributions. The same study by Kumar et al. also found improved thermal behavior from their hybridized composites whereas pure glass contains highest thermal stability. Pure flax lowers stability, but all the hybrid composites were found to have stability between the glass and flax (Fig. 23). Overall, it could be summarized that the hybridization of laminated composite displays new potentiality with improved mechanical performances.

Recent developments in fabric-based products

The composites sector is drawing increased attention for implementing state of the art technologies to improve performance and minimize processing costs by maintaining environmental sustainability. The implementation of FEA is also one of the prominent technologies for predicting performance, which could efficiently facilitate the minimizing of raw material usage and design from the operation protocols. The pretreatment of reinforcement [86] fabrics could also play a considerable role in developing thermo-mechanical performance by increasing fiber to matrix interactions. However, feasible pretreatment methods are limited; hence, more research to explore suitable routes of treating the fabrics in advance before laminations are needed. Laminated composites are becoming increasingly appealing for their superior application potentiality with multifaceted diversifications. However, the huge variation in knitting, weaving, and bonding could be tuned to bring a positive reinforcement attribution in the laminated composites through applying FEA. Furthermore, as laminated composites are gaining popularity for sensitive application areas like aerospace, researchers and manufacturers are also focusing on investigating and understanding the fracture behavior/failure mode of the laminations in composite systems. However, cracking could be identified by applying different methods such as finite element analysis, shear log model, and so on [167]. Typically, stiffness of the reinforced fabric materials is much higher compared to the polymeric matrix. Nevertheless, a considerable strain magnification occurs on the matrix system when the load is applied in transverse directions. Generally, the cracks are developed in off-axis directions [167]. Furthermore, due to the mismatching in-plane of composites transverse and longitudinal Poison ratio, the fracture could appear in longitudinal directions. Moreover, overall behavior and performances of the laminates are dependent on the cracking of matrix and internal damage against the applied load. In addition, modulus of laminates also declines significantly. Conversely, the residual thermal stress could be significantly developed at the curing stage, especially for synthetic/natural fiber-reinforced hybrid

Figure 23 Thermal characteristics (thermogravimetric analysis) of hybridized laminated composites: PG- 100% glass, PF- 100% flax, FG1 to FG5- different volume fractions of flax and glass. Reprinted with permission from Elsevier [166]. Copyright Elsevier, 2019.



composites like carbon/epoxy laminates. The utilization of waste materials from textile and clothing industries is also gaining potentiality from the perspective of creating environmentally sustainable products [168–170].

Zhang et al. [171] reviewed the FEA of composite plates after the 1990s and explored different models for designing the composites. Chen et al. [113] developed hybrid fabric panels with ballistic performance where they implemented FEA to predict the different fabric layer responses against impact load. Through FEA study, they summarized that the use of shear resistant material at front layer and tensile load resistant materials as rear layer could provide improved anti-ballistic performance for laminated composites [113].

Prospective research possibility and gap

The nonlinear behavior of structural composite is still a big challenge that needs to be explored to open more diverse routes of application. The failure and crack propagations while applying the cyclic load also requires further research. In addition, the damage related to micromechanical aspect is another needed research area. Moreover, multiscale modeling of crack propagations, crack initiations, and structure failure require more work to facilitate further improvements. The state-of-the-art design of laminated composite could also bring some significant revolutions in this sector, which could facilitate more advanced usage in multifaceted applications. Currently, the development of hybrid composites from natural and synthetic fiber originated fabrics are limited and not extensively used by manufacturers. This implies that more research and innovation could also facilitate the discovery of additional routes of potential laminated composites. Manufacturing industries also need to invest more into the latest machinery and software to ensure the feasible and convenient production of advanced, high-quality laminated composites. Efficiency demonstrates a higher production rate by maintaining qualitative products with minimized unit costs [172]. Generally, every manufacturing plant contains a research and development (R&D) unit, which could also efficiently facilitate the development of competitive and innovative products to meet market demands. Moreover, new methods of fabric-based reinforcement for high-performance cementitious materials are evolving [173]. However, the geometry of fabrics and associated yarns also plays a critical role in bonding between the reinforcements and matrix polymers like cements [174, 175]; more research to explore the most feasible routes is also required here. Moreover, fabric-reinforced laminated composites could be widely used for different parts of airplanes as shown in Fig. 24.

Environmental influence of fabrics-based composites

In the field of structural applications, reinforcement of fabric-based laminates in combination with natural and synthetic fabrics has garnered considerable interest due to environmental sustainability features. Numerous natural fibers (like flax, ramie, cotton, silk, wool, hemp, sisal, and so on) are used in fabric production and are becoming potential candidates for laminated composites manufacturing. The as-produced composites could replace traditional metallic composites. Furthermore, the increased utilization of natural sources, even in hybridization with synthetic materials, also minimizes consumption pressures in glass/carbon-based materials. These phenomena are creating positive environmental contributions by minimizing carbon footprints through environmentally-friendly sustainability. Furthermore, natural fiber-based fabric production consumes less energy and utilities than synthetic material production. On the other hand, waste (like woven/nonwoven/knitted fabrics) from textile manufacturing plants could also be utilized for composites production, which would minimize the extra-pressures on the environment via a reduction in solid waste disposal. Moreover, used fabrics could be utilized again through polymeric matrix reinforcement, which may impart significant mechanical properties by having extensive potentiality in terms of sustainable products through minimizing carbon footprints. Umar et al. [177] conducted a study on waste materials from a textile industry having both types of knit and woven wastes fabricated into laminated composites. The developed composites provided significant mechanical features that are compatible with glass fiber-reinforced composites [177]. Chen et al. conducted a study on recycled silk fabrics produced from silk waste and reinforced with epoxy poly(butylene) succinate (PBS)

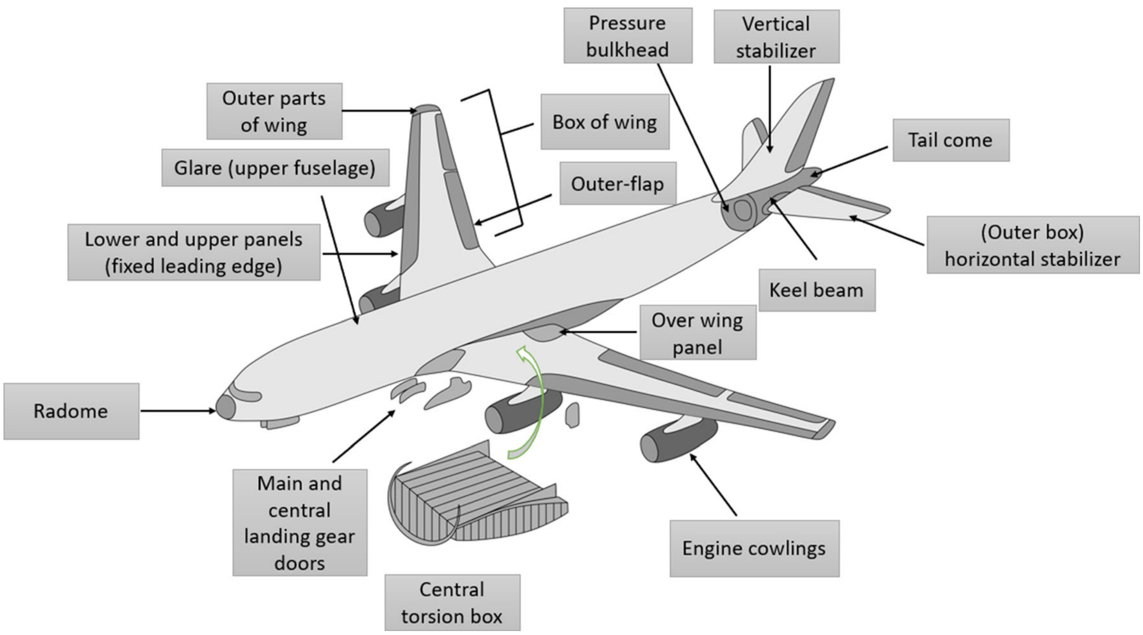


Figure 24 A schematic representation of where laminated composites could be used prominently on airplanes (A380 model of Airbus). Drawn by Péter György Horváth. Adapted with permission from Elsevier [176]. Copyright Elsevier 2011.

and found superior performance characteristics [178]. Sadrolodabaee et al. [179] conducted another study where they utilized nonwoven wastes collected from textile and garment industry residues reinforced with cement-based matrix. They revealed that all the composites provided satisfactory stress-bearing capabilities against applied load with remarkably improved and fortified properties.

Potential application and marketing aspects of laminated composites

The current global demand for composite products motivates manufacturers toward more decorative, advantageous, and diversified composite materials. Due to workforce availability and low material costs, China, Malaysia, Vietnam, Thailand, and Indonesia are currently the largest producers of laminated composites [172]. Manufactures use laminated composites extensively, although they have some limitations regarding fracture/damage of composite systems, which reduces the structural mechanical performances of the composites [180]. Due to their outstanding properties such as being light weight, anti-corrosion, superior thermo-mechanical characteristics, and overall large volume of production capabilities composites are extensively used in aircraft structural applications such as light weight aircraft, helicopters, sailplanes, light machinery parts, bridges, construction, buildings, and commuter planes [57]. Moreover, the shipbuilding sector also uses glass-reinforced laminated composites for smaller vessels like yachts and fishing boats [56]. Naval applications are also expanding from sustainable laminated composite panels [181]. Carbon-based laminations used in prominent vehicle parts are becoming more popular in automotive sector [182]. Laminated composites from glass are also being implemented in areas where safety and security issues, such as in aerospace, defense, automotive windshields, and solar cell module materials, all of which are designed from structural and architectural points of view [183–186]. Laminated composites could provide higher mechanical performances, security, and environmental sustainability as structural materials [187]. In a most recent study, Chillara et al. [188] discussed morphing technology for laminated composites. This technology could be used by soft robotics, aerospace, and automotive manufacturers as it could be shaped and tuned as per the desired performances over various ranges of operations. Defense industries are also using laminated composites [189, 190]. Furthermore, a business-friendly environment could nourish this sector significantly throughout the world. The increasing demand for sustainable and cost-effective products and technology is increasing worldwide as scientific knowledge expands. Different applications of fabric-reinforced composites are shown in Fig. 25. Laminated composites are becoming more appealing in the development of composites for aerospace and transportation applications.

SWOT analysis of laminated composites

SWOT analysis provides strategic planning for an organization/person to investigate strengths, weaknesses, opportunities, and threats and to obtain certain competitive benefits and ideas for businesses/operations. With this in mind, a SWOT analysis has been conducted to assess the potentiality of laminated composites (Table 2). Furthermore, through analyzing SWOT, corrective initiatives could be taken according to the necessity depending on the status of the operations/study.

Conclusion

Manufacturers produce fabric-reinforced laminated composites by combining various innovative, feasible technologies, and materials, which are recognized as advanced materials used for versatile applications. Researchers are continuously developing various fabric-based composites by combining different fibers and filaments with variable layers. Multifunctional composites with economic aspects from different fabrics also provide potential engineering solutions by reducing various processing steps and combining multiple products into a single one. High-performance fabrics are frequently reinforced with low-performance fabrics along with suitable polymeric materials to achieve the combined positive attributions from the final laminates through minimized costs. Fabric-based composites have found new production routes and potentialities with superior performance characteristics by replacing traditional composite manufacturing methods. However, ongoing research is required to develop novel fabric-based composites to meet the increased demand of consumers in terms of cost consciousness, environment friendliness, and durability with high performances. In addition, the high production rate of fabric-based

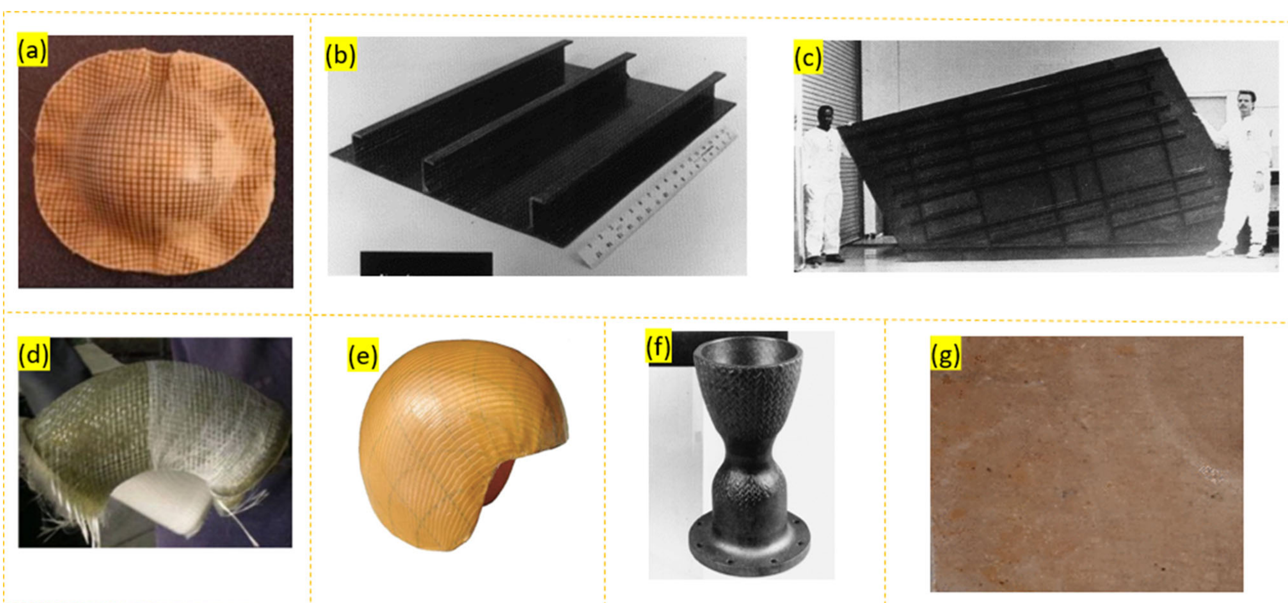


Figure 25 Various fabric-reinforced composite materials: **a** Bamboo woven fabric/PLA double curvature materials, **b** stiff-panel from rib structure, **c** nozzle of rocket made of braided fabric, Wing panel composite (stitched), **d** Elbow-fitted product, **e** woven-fabric molded helmet shell. Reprinted with the permission from MDPI (under CC-BY license) (**a**) [191] Elsevier (**b**, **c**, **d**, **e**, and **f**) [192–194] and ACS (under CC-BY license) [124]. Copyright, MDPI 2016, Elsevier (**b**, **c**, **d**, **e**, and **f**) 2013, 2016, and1999 and ACS (**g**) 2021.

Table 2 SWOT analysis of fabric-based laminated composites

Strength	Weaknesses
Laminated composites made of natural fibers like flax, hemp, sisal, and ramie providing sustainable features	Could generate weaker interfacial bonding if the fibers are not treated properly in composite systems
Higher stiffness and strengths	Efficient innovations for large scale industrial production are lacking
Larger production volumes	Inhomogeneous characteristics varying on fabric characteristics and design
Bio-based laminates could be recycled	Need to combine two different production plants together like textiles for fabric and composite manufacturing companies for laminated composite productions together
Providing superior strength in terms of hybrid composites made of natural and synthetic fabric reinforcements	Lack of efficient bio-based thermosetting/thermoplastic polymers
Newer marketing potentially is being continuously created	Lack of efficient modeling availability
Opportunities	**Threats**
Manufacturers and researchers are becoming more involved in laminated composites production	Nonhomogeneous quality of developed laminates, especially for natural fiber-based fabric composites
Light weight, sustainable, and economic features	Higher prices of synthetic fabrics like carbon, glass, aramid etc., has made it difficult to ensure availability for reinforcing with bio-based fabrics
Latest technological advancements are being implemented with continuous improvements from scientific methods and facilities	Current extreme dependency on wood particle/flour-based composites instead of laminations
Natural fibers are available throughout the world, which could facilitate bio-based fabric-reinforced laminated composites manufacturing	Lack of specific technological equipment for manufacturing composites

composites would minimize costs and energy consumption. The production of energy efficient products would abate the pressure on the environment. Furthermore, the utilization of state-of-the-art technologies like numerical simulation, advanced bio-based polymeric materials, processing routes, fabric treatments, nanomaterial loading, and naturally originated fabric usage to ensure sustainability could create revolutionary changes in this sector.

Acknowledgements

This work was supported by the "Stipendium Hungaricum" scholarship under the Simonyi Károly Faculty of Engineering, Wood Sciences, and Applied Arts, University of Sopron, Hungary. This article was made in the frame of "EFOP-3.6.1-16-2016-00018-improving the role of research, development, and innovation in the higher education through institutional developments assisting intelligent specialization in Sopron and Szombathely."

Author contributions

KMFH: Writing—original draft, conceptualization, methodology, data curation, investigation. PGH: Drawing, resources, conceptualization, supervision, writing—reviewing and editing. TA: conceptualization, supervision, writing—reviewing and editing.

Funding

Open access funding provided by University of Sopron.

Declarations

Conflict of interest The authors have no conflict of interest for this research.

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