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REVIEW ARTICLE

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# A review of high-velocity impact on fiber-reinforced textile composites: Potential for aero engine applications

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## Abstract

Considerable research has indicated that fiber-reinforced textile composites are significantly beneficial to the aerospace industry, especially aero engines, due to their high specific strength, specific stiffness, corrosion resistance, and fatigue resistance. However, damage caused by high-velocity impacts is a critical limitation factor in a wide range of applications. This paper presents an overview of the development, material characterizations, and applications of fiber-reinforced textile composites for aero engines. These textile composites are classified into four categories including two-dimensional (2D) woven composites, 2D braided composites, 3D woven composites, and 3D braided composites. The complex damage mechanisms of these composite materials due to high-velocity impacts are discussed in detail as well.

KEYWORDS

aero engines, damage mechanism, high-velocity impact, textile composites

## 1 | INTRODUCTION

The addition of high-strength fibers and matrices allows the use of fiber-reinforced polymer textile composites in a wide range of aerospace industry applications, particularly aero engines,[1] due to their excellent material properties, such as high specific strength, specific stiffness, corrosion resistance, and fatigue resistance. Since the first entered service of the commercial jet engine "GE90" equipped with composite fan blades in 1995, as shown in Figure 1,[2] the application of composites in aero engines has been gradually extended to other key components, such as fan casing and triple-shaft architecture. There are many types of textile composites with potential for use in aero engines. Weaving is one such method that interlaces two distinct sets of yarns or threads at right angles to produce fabrics. In another knitting arrangement, yarn feeding and loop formation occur at each needle in succession across the needle bed. Braiding can be designed by arranging the interlaced yarns diagonally about or off an axis.

Woven and braided architectures are the most widely used structures for composites. In particular, woven composites are produced by weaving yarns in warp and weft directions, intersecting each other with different thickness. The position of the yarns highly

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FIGURE 1 A GE90 engine with 22 carbon fiber composite fan blades. Reproduced with permission.[2] Copyright 2012, Elsevier

affects the yarn friction, which has significant influence on the impact resistance of the woven composites. Specifically, two-dimensional (2D) woven textile composites are produced by assembling multiple layers of fabrics and reinforcing with resin in two dimensions. However, this structure cannot produce satisfactory delamination resistance against impact loading. In contrast, 3D woven composites consisting of yarns in the *z*-direction bind the fabric through their thickness, conferring high delamination resistance and interlaminar strength.[3] This structure has been well studied and economically used for composite structures to bear multidirectional loading in recent years.[4]

The braided textile composites are generally manufactured by entangling short fibers through needling, knitting, and/or stitching using thermal and/or chemical production technologies. This 2D short fiber-to-fiber crossing leads to stick–slip motions that increase the resistance to high-speed impact by debris and crashworthiness protection, resulting in a wide range of applications for projectile threats.[5] When yarns are intertwined with each other following a specific predefined placing path, known as four-step (or row-and-column) braiding, a 3D intertwined structure is produced to generate a 3D braided textile composite, with high delamination resistance and impact damage tolerance.[6] As positioned through the fabric thickness, the yarns are biased, resulting in an angle between 10° and 70° of the fabric width. Furthermore, the braider yarns are placed in rows and columns as matrices and intertwined with each other through the thickness direction. This structural characteristic makes these composites excellent candidates for lightweight impact-resistance applications.[7]

It is interesting to note that the textile composites have nonlinear stress–strain responses under off-axis tensile loading conditions. This is due to the high sensitivity to the alignment of the fibers, compared to the case under external loading conditions.[8] The angle between the fiber and loading directions has a significant effect on the nonlinear response, which might be due to the interaction between the tensile and shear stresses.[9] Generally, the on-axis and off-axis failure of textile composites, especially those with large off-axis angles, suggests a noticeable brittle-natural feature.[10] A high local strain gradient could be observed at a meso-scale, and thus the inhomogeneity is enhanced under the off-axis conditions.

High-velocity impact tests have been carried out on textile composites. Specifically, the impact tests at a macro-scale level are normally conducted using gas gun facilities, consisting of a compressed gas reservoir, a breech, a pair of clamps, a barrel, a sabot arrester, and a target support. Experimental tests were performed by Oakley and Nowell[11] using a gas gun with a barrel length of 1.3 m and a bore diameter of 12.5 mm. A cylindrical sabot was introduced to accelerate a projectile with a weight of 0.22 g. The impact tests at a meso-scale are always conducted using a split Hopkinson bar (SHPB) experiment, in which a sample is fixed between an incident bar and a transmission bar. An air compressor was used to inflate an air tank, and the initial speed of the striker bar was controlled by adjusting the air pressure in the air tank to produce different strain rates. Some researchers found that the ballistic performance of the textile composites is significantly affected by their textile structures. For example, the 3D fabric is superior to the 2D fabric in terms of breaking load and energy absorption under the ballistic impact conditions.[12] Moreover, analytical methods have been developed to predict the stiffness and thus investigate the ballistic performance of the textile composites.[13] Experimental and numerical studies on the ballistic impact of the textile composites have identified the main failure modes as fiber shear, tensile failure, and matrix crush failure.[14]

However, fiber-reinforced textile composites, regardless of the structure, are vulnerable to impact damage at high velocity. This drawback has negatively impacted the spacecraft and aircraft design,[15] especially for key components, such as the design of aero engines, containment cell, oil tanks, and airframes.[16] Therefore, it is important to investigate the factors that dominate the mechanisms of impact damage and influence the structural performance of the composites. During the last two decades, research relevant on these issues has been performed and it was concluded that the impact damage of the composites at high velocity is highly complicated because of their natural anisotropy and heterogeneously distributed stresses at the transient loading.[17] In general, the dominant damage/failure mechanisms occur successively in five phases during impact[18–20]: (1) debonding of the fiber/matrix interface, as a result of high transverse shear load on top surfaces; (2) transverse crack of the matrix, as a result of high flexural load on bottom surfaces; (3) delamination of plies, as a result of the cracks being diverted to interlaminar regions; (4) failure of fiber, as a result of the tension, and fiber micro-buckling due to the compression loading, and finally (5) penetration of materials.

According to previous research investigations, it is essential to ascertain the damage and failure modes as well as their time-integrated progression during impact. Therefore, this paper reviews the material characterizations and applications of four main fiber-reinforced textile composites: 2D woven composites, 2D braided composites, 3D woven composites, and 3D braided composites. Subsequently, a review of the damage mechanisms of high-velocity impact is presented. This critical review aims to be a state-of-the-art source of numerous studies for research on the application of fiber-reinforced polymer textile composites in aero engines.

## 2 | 2D WOVEN COMPOSITES

2D woven composites are produced by two sets of yarns that are interwoven along 0° and 90°, leading to the interlacements to form the fabric surface, as shown in Figure 2. Plain, twill, and satin are the main weaving types for 2D woven composites due to their lightweight, impact resistance, specific strength, and specific stiffness. 2D woven composites could be applied in aero engines to increase the thrust–weight ratio as well as to reduce fuel consumption and pollutant emission. Significant efforts have been devoted to the study of the failure behavior and mechanism of 2D woven composites subject to high-speed impact.

Yang and Jia[24] conducted high-speed impact tests to examine the damage mechanisms of 2D woven composites. They suggested that the damage was highly dependent on the curvature and width of the fabrics. Ultrasonic C-scan was used to detect and analyze the damage zone, demonstrating that the whitening area of the glass tows on the distal side corresponded to the C-scanned damage area.[25] Hu et al.[23] experimentally studied the mechanical response of 2D silicon carbide-based composite beams when impacted by a monopolar light air gun, and determined the internal and surficial morphologies of the beams using a scanning electron microscope (SEM, TM4000 Plus; Hitachi), as shown in Figure 3. The crush of the SiC coating and damage of the fiber bundle in different impact stages were therefore illustrated. Yashiro et al.[26] investigated the damage characteristics of a 2D woven composite at elevated temperatures by conducting high-speed impact, thermal-explosion, and thermal-shock tests successively, suggesting that the operating temperature was one of the most important parameters that impacts resistance. Coles et al.[27] tested the resultant ballistic dynamic response of a T300 woven composite in a flat-plate shape by applying a noninvasive analysis technique. It was proven that the solid projectiles led to increasing localized deformation and even penetration, whereas the destroyed fragmenting projectiles led to homogeneously distributed impact load, causing the major front-surface damage that depended on the depth of indentation. A split Hopkinson tensile bar (SHTB) and an ultrahigh-speed camera are other commonly used equipment to test the dynamic material properties of 2D woven composites and thus their progressive failure. This method enabled the identification of crack in different stages from initiation, propagation, accumulation, spreading, and finally to failure.[28]

Additionally, finite element (FE) models have been widely used to simulate the failure behavior of 2D woven composites.[29,30] For example, a multiscale stochastic fracture model was proposed to predict progressive failure of the composite in the form of nonlinearity, and it was found that the failure location depends on the fiber volume fraction and temperature.[31] Chen and Aliabadi[32] proposed a novel method to predict the general behavior of a 2D woven composite, for which a viscoplastic model was used to evaluate its nonlinear and rate-dependent response. It was found that the maximum stress increased with increasing strain rate. However, the failure strain decreased with increasing strain rate, a behavior similar to that of a polymer matrix. Subsequently, the damage/failure of the yarns and deformation of the woven fabrics were studied using Weibull distribution-based formulations. According to previous research, the failure modes for 2D woven composites could be matrix cracking, interface cracking, delamination, matrix fiber shearing, and fiber fracture, which exist in different loading stages, that is, initial damage stage, damage evolution stage, and material final failure stage, respectively.[33] Multiscale models also enable the prediction of the scalable impact response of the composites by parameter-segmented unit cells.[34] Cao et al.[35] developed a meso-scale FE model to investigate the progression of failure of a 2D woven composite on applying tensile and compressive loading. Using a similar method, Zhou et al.[36] researched the failure evolution of a carbon/epoxy composite in two dimensions, proving that the transverse damage, matrix damage, and delamination dominated the mechanical property degradation. In the study of Goda et al.,[37] the perforation and the corresponding failure mode of a 2D woven composite demonstrated that the ejection performance was influenced by the properties of adhesive materials, stacking order, and fabric materials. A 3D

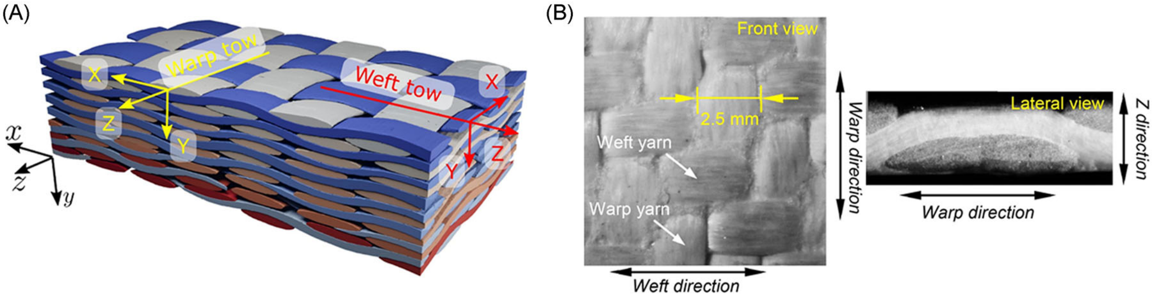

**FIGURE 2** (A) Schematic representations of two-dimensional (2D) woven composites. Reproduced with permission.[21] Copyright 2020, Elsevier and (B) the local structure of a 2D silicon-based woven composite in front and lateral views obtained by a digital image correlation. Reproduced with permission.[22] Copyright 2018, Elsevier

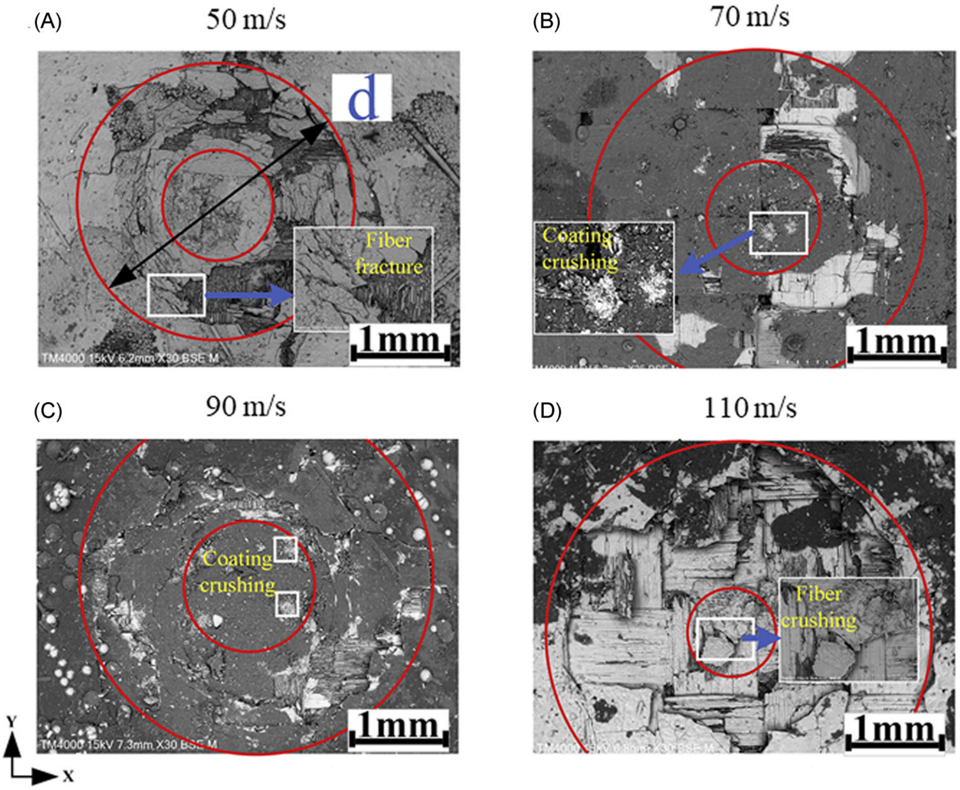

**FIGURE 3** Morphologies observed from the top surfaces of a two-dimensional woven composite after impact at different velocities: (A) 50 m/s, (B) 70 m/s, (C) 90 m/s, and (D) 110 m/s. Reproduced with permission.[23] Copyright 2020, Elsevier

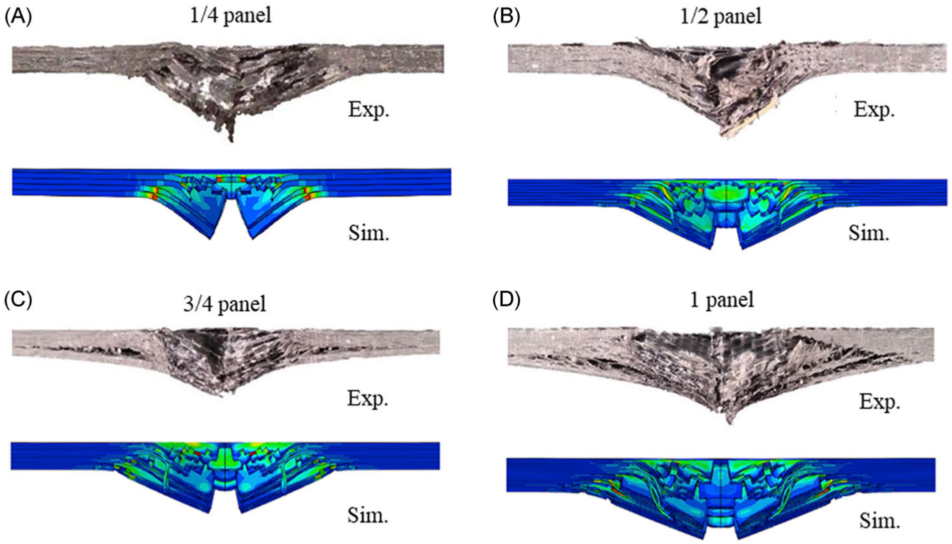

**FIGURE 4** Experimental and modeled damage characteristics of a two-dimensional woven composite with different scaled sizes: (A) 1/4 panel, (B) 1/2 panel, (C) 3/4 panel, and (D) 1 panel. Reproduced under terms of the CC-BY license.[34] Copyright 2020, The Authors, published by Elsevier

multilevel-multisite mesh refinement method was developed by Li et al.[38] to predict the progressive impact response of a 2D woven composite, especially its plastic flow for the gelatin projectile and elastic deformation of the polyethylene projectile. Furthermore, it enabled the prediction of the deformation, location, and extent of the impacted material, which made this study significant for understanding the failure behavior of a 2D woven composite under impact loading, as shown in Figure 4.[34] Based on this study, numerical methods were further improved to study the scaling effect on the impact behavior of 2D woven panels.

The analytical model is another effective tool to investigate the behavior of 2D woven composites subject to high-velocity impact. For example, López-Puente et al.[39] used an analytical model to investigate the penetration of a plain woven composite impacted at high velocity, in which the kinetic energy was absorbed by the crushing of laminar region, transfer of linear momentum, and failure of fibers. Moreover, Alonso et al.[40] reported that the ratio of target thickness to projectile diameter had a significant effect on the laminar damage behavior. Du et al.[41] studied the effects of strain rate and impact position on the impact resistant performance of a 2D woven composite using a viscous stress tensor based on the isotropic Maxwell model. It was found that the strain rate-dependent model of homogeneous material could increase the prediction accuracy on the layered damage area and residual velocity of the impactor.

## 3 | 2D BRAIDED COMPOSITES

Compared to traditional laminated composites, fibers in braided composites are entangled and placed with a braid angle in the material shown in Figure 5. This architecture enhances the shear strength, impact resistance, and damage tolerance of such materials, leading to an excellent performance in the aviation field. The rapid development and wide application of 2D braided composites are therefore markedly increased. For instance, the blade spars are made with Kevlar 2D braided fiber as the reinforcement. However, compared to 2D woven composites, the complex fiber architecture makes strain measurement and characterization more challenging.

Optical strain measurement technologies such as digital image correlation and high-speed imaging are developed to capture the complex deformation as well as monitor the in-service health of 2D braided composites.[5] Microcomputed tomography measurements such as X-ray enable the identification of the geometries and morphologies of the composite structures in detail, which would be beneficial for precisely determining the mechanical properties of the materials. X-ray was applied in the research conducted by Zhao et al.[43] to obtain the failure morphologies and internal damage regions of a 2D triaxially braided composite. Moreover, a nondestructive testing method was used to visualize the penetration and deformation of the laminates, thus determining the energy absorption of a 2D braided composite.[44] Figure 6 shows an X-ray example in the study of Sutcliffe et al.[25] In addition, in situ strain measurements are able to obtain the internal deformation and strain of the braided composites.[45] The damage evolution and failure mechanisms of 2D braided composites at high-speed impact were investigated by conducting tensile, shear, compression, and impact tests, revealing the effects of various structural parameters on the mechanical properties of such materials.[46] Moreover, it was found that the compressive strength of the material was sensitive to the strain rate, leading to a compression failure of the matrix with increasing strain rate.

A meso-structure FE model and other related mathematical methods enable the determination of the mechanical properties of 2D braided composites. For example, Byun[47] developed a structure geometric model combined with a volumetric average method to determine the elastic properties of a 2D braided composite. Miravete et al.[48] developed a different meso-structure model with four boundary lines in the parallel weaving direction. Based on this, two macro- and meso-uniform constitutive models were proposed in the study by Aboudi and Pindear.[49] Classic laminate theory-based inlay models, fiber buckling models, and bridge models were established to determine the macroscopic properties of a 2D braided composite in the study of Dadkhah et al.[50] Additionally, Potluri et al.[51] analyzed the bending and torsion properties of a tubular-shaped 2D braided composite. Subsequently, an improved method was proposed, and the torsion coefficient of the material was predicted based on the classic laminate theory. A 3D analysis model of a 2D braided composite was established to predict its elastic properties by Donadon et al.[52] In their study, the bending of the yarns, the gap between the yarns, and the actual shape of the yarn sections were considered. Furthermore, Tabiei and Yi[53] took the cross-sectional shape and bending of the fiber into consideration and developed a structural geometric model for a 2D braided composite. An analytical prediction model based on the principle of minimum potential energy was developed by Hoa et al.[54] to predict the elastic and flexible stiffness

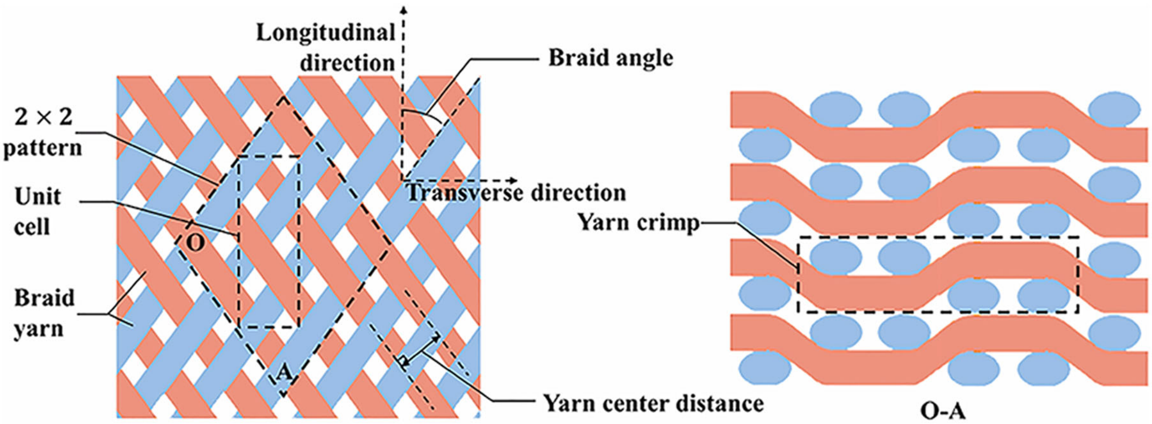

**FIGURE 5** Schematic diagram of a two-dimensional braided composite. Reproduced with permission.[42] Copyright 2021, Elsevier

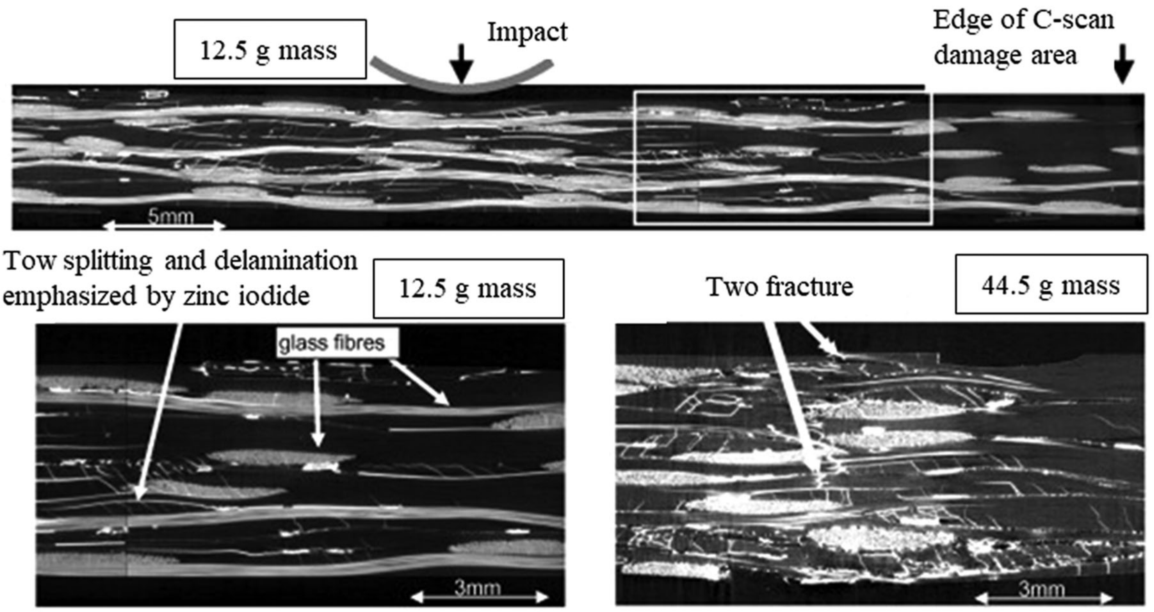

**FIGURE 6** X-ray scanned impact regions of a two-dimensional braided composite subjected to different impact masses. Reproduced under terms of the CC-BY license.[25] Copyright 2012, The Authors, published by Elsevier

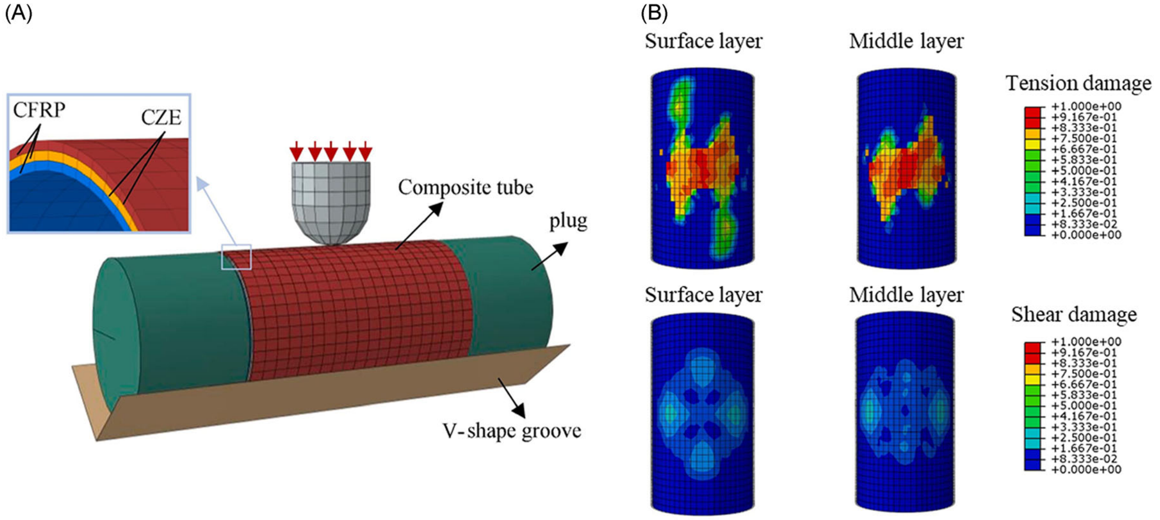

**FIGURE 7** Finite element modeling of damaged patterns of a two-dimensional braided composite impacted by a cylindrical projectile. Reproduced with permission.[57] Copyright 2021, Elsevier

matrix of the material. Taniguchi et al.[55] applied the Hashin–Rotem failure criterion to predict the effect of strain rate on the failure mode by defining an exponential reduction in material stiffness after strain softening, revealing the nonlinear relationship between the tensile fracture and the strain rate. Similarly, nonlinear models and FE codes for predicting the strain rate dependency were reviewed by Qiao et al.[56]

A 2D FE model was developed to analyze the impact behavior of a 2D braided composite under different loading and velocity conditions in the study of Ivanov et al.[58] Figure 7 shows an FE modeling example conducted by Shi et al.[57] A meso-scale framework could enhance the accuracy of the FE results of the evolutionary damage behavior of a 2D braided composite. This was achieved because an explicit solver was able to capture the free edge on the predamage regions after defining translational symmetric boundary conditions.[59] This framework could also be used to predict the elastic module and mechanical strength of a 2D braided composite during progressive failure stages.[60] Xu et al.[61] and Deng et al.[62] improved the FE model by adding a micro-mechanics failure model and a multiscale progressive damage model to further explore the initiation and evolution of 2D braided composite damages under uniaxial loading, in-plane loading, and/or bending conditions. Recently, a concept of stress amplification factor was proposed to couple the constitutive material models, consequently increasing the prediction accuracy as well as enhancing the computational efficiency.[63]

## 4 | 3D WOVEN COMPOSITES

Compared to 2D woven composites, the yarns in the *z*-direction interconnect the warp yarns in the *x*-direction and weft yarns in the *y*-direction in the 3D woven composites, producing the woven composites in three dimensions.[64] Therefore, the addition of the z-yarns tailors the properties of 3D woven composites with higher material strength.[65] For instance, the application of thermoplastic fibers with high stiffness and load-bearing capacity as the *z*-yarns leads to an increase in energy absorption and interlaminar fracture toughness for 3D woven composites.[66] Consequently, they tend to be used in structural components in the aerospace industry, such as turbine blades and landing gear braces.[67,68] 3D woven composites can be divided into angle-interlock composites (3DAWCs) and orthogonal composites (3DOWCs) with respect to the structure of weaves, as shown in Figure 8, which was generated by a textile preprocessor TexGen.

To study its failure mechanisms subject to high-speed impact, experimental research on ballistic impact damage of 3DAWC was conducted by Li et al.[69] and Ren et al.[70] The applied impact velocities were in the ranges of 6–12 and 210–550 m/s, respectively. It was found that the fracture of the kinking yarns was the most prominent type of failure mode for the impacted 3DAWC. Moreover, the compressive and shear failures were identified as the particular modes for the bottom and top surfaces, respectively, by conducting conical–cylindrical projectile tests, which also allowed the analysis of the stress wave propagation and subsequent failure mode for a 3D woven composite.[71] Walter et al.[72] effectively minimized the delamination through the addition of *z*-direction fiber yarns for small-caliber projectiles at a low-impact velocity and load; the effect of *z*-direction fiber yarns was found be to be less at high-impact velocity and load. It was further speculated that the cracking of the matrix and debonding of the fiber–matrix interface were the predominant failure modes at low depths of penetration.

An FE model with a coupled thermomechanical model is able to capture the increases in temperature, strain rate sensitivity, and fragmentation.[69] It was interesting to find that the penetration time of the projectile increased with increasing impact velocity/strain rate. In the study conducted by Zhang et al.,[73] a 3DAWC was simplified in a unit cell model to represent its stiffness changes and thus progressive failure. Using the model, it was found that the damage and deformation of the composite generated considerable heat converted from plastic energy at a high-impact velocity/strain rate, contributing to increasing temperature and thus penetration time. In addition, the impact damage behaviors subjected to transverse impact tests at subzero temperatures were then investigated. It was suggested that the wave propagation of yarns led to concentrated stress and unstable buckling under compressive loading conditions. Furthermore, the failure of kinking yarns and cracking of the matrix occurred, although the delamination resistance was enhanced by interlacing the through-thickness yarns. Figure 9 shows the damage behavior of 3DAWC obtained from experiments and FE modeling in the study by Guo et al.[74] The localized tow splitting, fiber slippage, and interfacial debonding were found to be the primary failure modes of the bias yarns when subjected to the in-plane shear damage at tensile loading.

The warp yarns are oriented longitudinally in 3DOWC structures, while the weft and *z*-yarns are oriented orthogonally, and are interlaced with each other to increase the structural integrity.[75] Different from 3DAWC, the weft yarns in 3DOWC are interwoven between the warp yarns and picks of layers, while the *z*-yarns secure the other two sets of yarns. This noninterlace structure results in high energy-absorbing properties.[76] In the research of Sohail et al.,[77] a pneumatic pressure gas gun was used to investigate the mechanical properties and failure behavior of a 3DOWC impacted at high velocity. Different 3DOWC panels in the forms of non-hybrid and asymmetric hybrid were tested to identify the effects of Kevlar and carbon fibers. It was

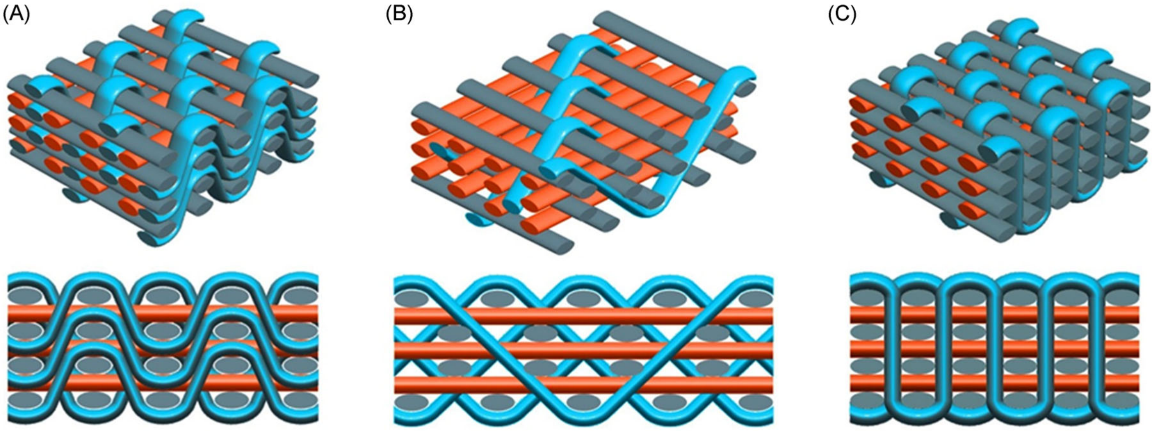

**FIGURE 8** Types of three-dimensional woven composites: (A) layer-to-layer angle-interlock, (B) through-the-thickness angle-interlock, and (C) orthogonal. Reproduced with permission.[3] Copyright 2018, Elsevier

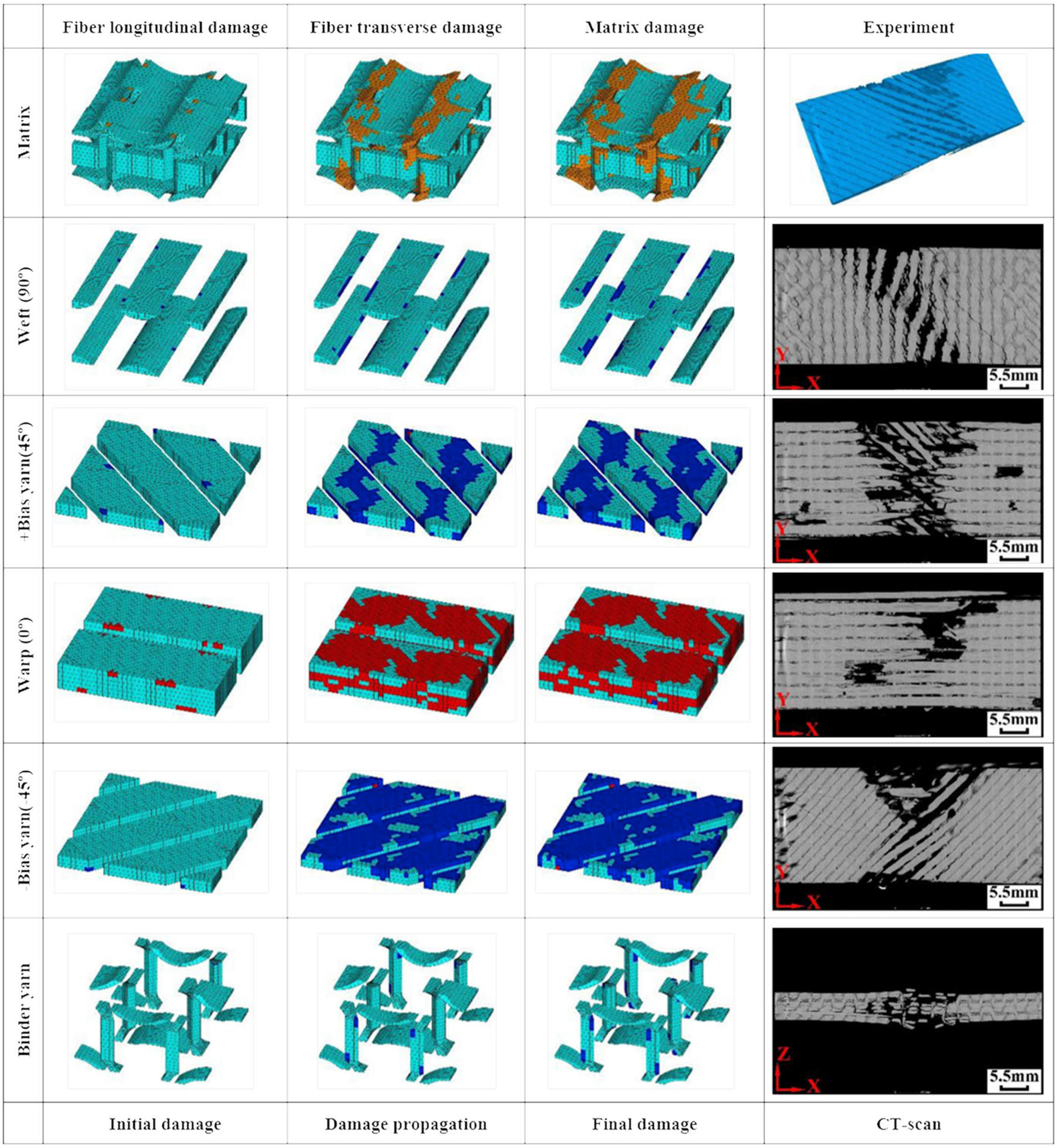

**FIGURE 9** Numerical and experimental evolutionary damage behaviors of a 3DAWC under tension in the warp direction. Reproduced with permission.[74] Copyright 2020, Elsevier

found that the carbon layers diversified impact energy until the cracking of the brittle fiber and matrix, when the Kevlar layers were damaged by fiber rupture. Modified SHPB was utilized to investigate the damage of 3DOWC circular plates under transverse impact in the study of Ji et al.,[78] showing the differences in the deformation behaviors presented by composites subjected to quasi-static and dynamic loadings. Although largely reducing the delamination damage in a low-velocity impact event, the addition of the z-yarns had an insignificant effect on the delamination at high-impact velocity and load, as reported by Walter et al.[72] Microscopic analysis of the damaged 3D glass fiber-reinforced composites proved that the applied 3D weaving scheme intrinsically weakened the fibric planes, increasing the risk of delamination in dynamic indentation and small-caliber ballistic impact. With the aim of studying the effect of z-yarns on the mechanical response of 3DOWC, Ghosh and De[79] suggested that resin-impregnated fibers and bulk resin be used to enhance the viscoplastic characteristics and thus impact resistance. Furthermore, Dewangan and Panigrahi[80] investigated the effect of z-yarns on ballistic resistance, revealing that the uncrimped warp and weft yarns can increase the energy absorption.

For the FEM studies, one possible methodology is to use the continuum shell-based FE model combined with a connector element technique to study the impact response of a 3DOWC.[81] The z-yarns were represented by the connector elements with uniaxial

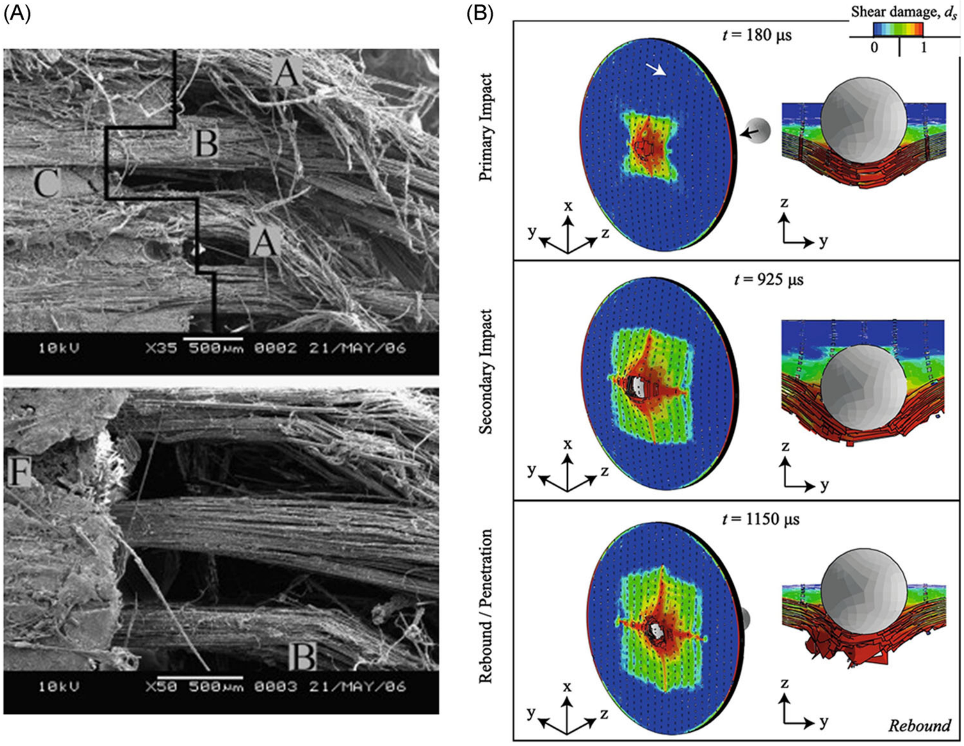

**FIGURE 10** (A) Damage mechanisms between the top and bottom surfaces of 3DOWC. Reproduced with permission.[84] Copyright 2008, Elsevier. (B) Isometric and cross-sectional views of modeled damage and deformed configuration of 3DOWC. Reproduced under terms of the CC-BY license.[85] Copyright 2018, The Authors, published by Elsevier

behavior, considering the stress-based failure criterion. The micro–meso–macro transition approach had been implemented to obtain the complicated weave structure of a 3DOWC. The voxel-based nonconformal meshes were applied to determine the characteristics of the representative volume elements (RVE) during impact.[80] Shi et al.[82] developed an analytical model to simulate the absorption of energy of a 3D woven composite that was impacted by a cylindrical-shaped projectile. The influence of the strain rate on the residual velocity of the projectile and thus fabric deformation was demonstrated. Jia et al.[83] applied the FEA method to study the microstructural damage behavior of 3D woven composites consisting of 60% Twaron and 40% unsaturated polyester resin. Figure 10 shows an example of experimental and modeling of the damage behavior of a 3DOWC impacted at high velocity.

## 5 | 3D BRAIDED COMPOSITES

To achieve variable geometries with high volumes of components, z-yarns are intertwined to form a spatial braided structure. This unique 3D structure increases the stiffness, mechanical strength, and fracture toughness as well as damage resistance and impact tolerance, compared to 2D braided composites.[86] Furthermore, 3D braided composites are found to be advantageous for manufacturing complex-structural components and for reducing the number of fasteners significantly. Therefore, the application of these composites in aeronautics and astronautics industries, such as jet engine stator vanes, is increasing.[87] In some research investigations, different meso-structures of 3D braided composites were produced, which could be divided into four-, five-, six-, and seven-directional arrangements, with respect to the yarn orientations, as shown in Figure 11.[88]

Optical microscopy and field emission gun SEM are two conventional methods to measure and analyze the damage mechanisms of 3D braided composites.[89] Zhang et al.[90] measured the penetration resistance and structural integrity of a 3D spectra braided composite. They subsequently found its failure modes of matrix cracking and fiber crushing in ballistic perforation tests, and summarized the failure modes at different zones based on the load–displacement evolution of the material. By conducting similar tests, Gu and Xu[91] identified the failure modes of a 3D braided composite as indentation, matrix cracking, breaking of axial and braider fiber yarns, and broken fibers pulled outward. An instrumented impact pendulum and a projectile gas gun were applied by Nassir et al.[92] to investigate the damage behavior and thus the failure modes of a graphite/epoxy braided composite. It was found that the total amount of absorbed energy increased with increasing impact velocity, resulted in the cracking of resin, followed by failure of fibers.[93]

Furthermore, Gao et al.[94] demonstrated that the damage resistance increased with increasing braiding angles of a 3D5d braided composite. A failure mode in the form of quasi-static penetration was found from the load-displacement evolution of 3D braided

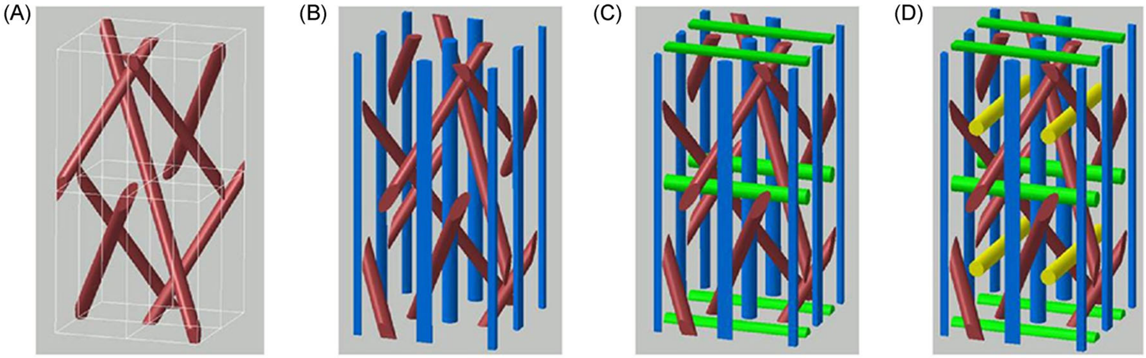

**FIGURE 11** Schematic structures of three-dimensional braided composites: (A) four-directional, (B) five-directional, (C) six-directional, and (D) seven-directional. Reproduced with permission.[88] Copyright 2019, Elsevier

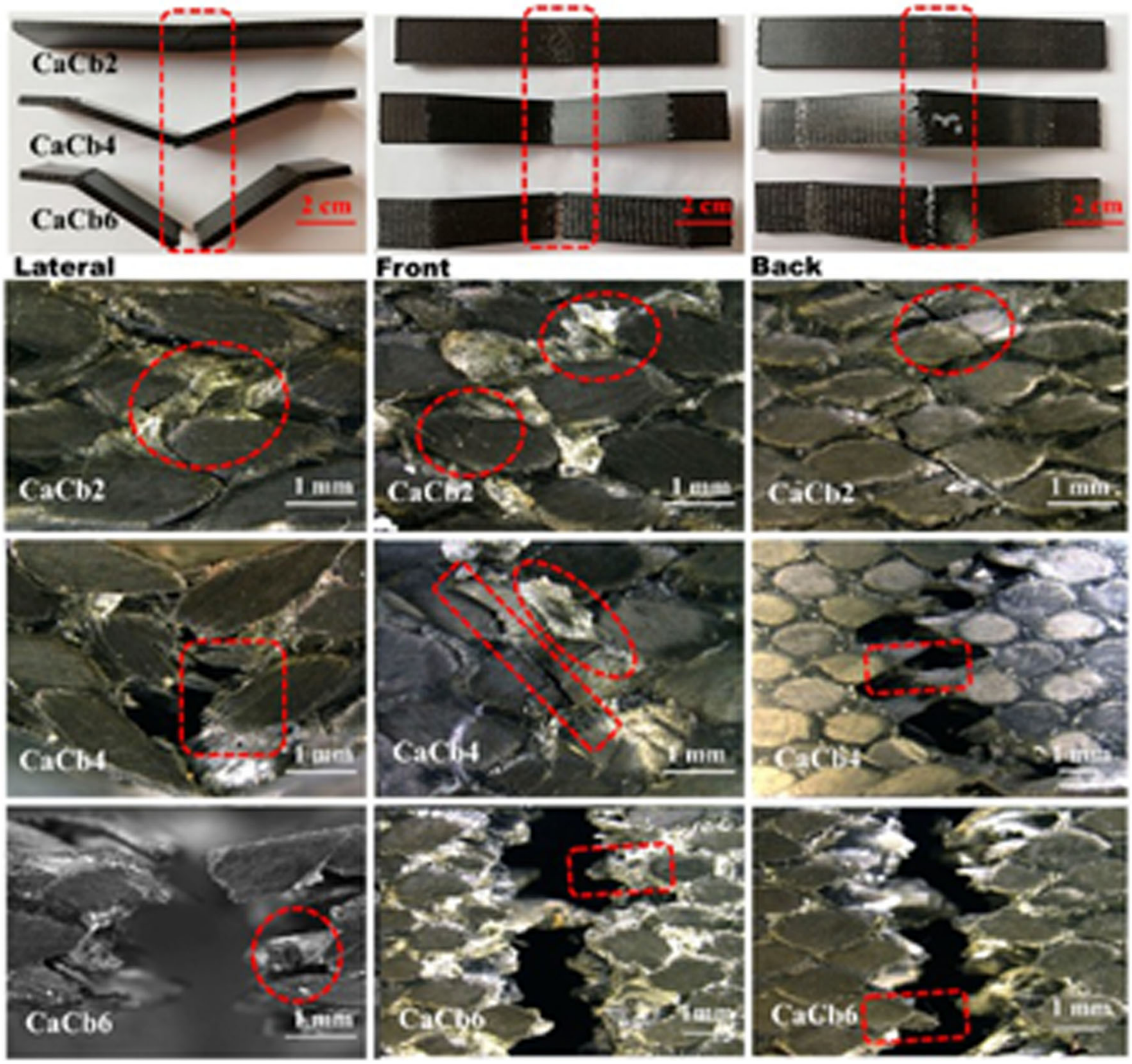

**FIGURE 12** Damage morphologies of a three-dimensional braided composite. Reproduced under terms of the CC-BY license.[98] Copyright 2019, The Authors, published by MDPI

glass/epoxy composites, as reported by Gu.[95] Meanwhile, the respective influences of the projectile velocity on the compressive and shear failure on incident regions, and on the tensile failure on distal regions, were studied during penetration. Li et al.[96] applied an SHPB to conduct compressive tests for a 3DBC along the transverse direction for various braiding factors, such as a strain rate range from 500 to 1500 $s^{-1}$. It was found that the damage and shear failure of the composites occurred earlier at larger braiding angles and fiber volume fractions. The same apparatus and a drop-weight system were applied by Zhang et al.[97] to study impact behaviors of a 3DBC along its transverse direction, where a saw tooth was found in the failure area due to the breakage of the yarns. Figure 12 shows the damage morphologies of a 3D5d composite with three views obtained using an ultrasonic C-scan. It was found that the damage observed on the front view was caused by the compressive resin, while damage observed on the back view was caused by the breakage of fibers, which was due to the fact that a bending surface was generated by the braiding yarns to withstand the tensile load.[98]

Multiscale FE analysis has been widely applied in many studies to simulate the impact damage. For example, a coupled FE—fast Fourier transform (FFT) model was established to study the failure modes of a 3D braided composite.[96] Specifically, it was found that the maximum impact stress markedly increased with increasing strain rate; however, the failure strain and compressive modulus were not sensitive to the strain rate. A multiscale equivalent model was developed in the study of Shi et al.[99] to represent the full scale of a 3D braided composite. Alternatively, an intermediate solving scheme incorporating a fiber inclination model was established to simulate the microstructural damage evolution of 3D4d and 3D5d composites.[91] Figure 13 shows the geometrical models of 3D braided composites by various methods. Based on these models, the evolutionary energy absorption of 3D braided composites could be obtained to analyze their damage mechanisms. Gu and Ding[100] constructed a realistic 3DBC by adding cross-inclined laminae of the braiding yarns, and then proposed a simplified quasi-mesoscale structure model to predict the penetration of the material impacted by a rigid projectile, which supported the previous finding of the strain rate dependence on the impact stress. This quasi-mesoscale structure model was also used to represent the braiding yarns in the preform and how the braiding direction was altered on the same surface.[95] It should be noted that the braiding yarns were meshed by the homogeneous isotropic tetrahedron elements in their study, which was different from the well-accepted yarn modeling approach that assumes transverse isotropy. Zeng et al.[101] developed macroscale homogeneous elements (MAT59) in LS-DYNA to model the impact of 3DBC tubes by axial loading, and obtained accurate energy absorption with different geometrical and braiding factors.

Zhang et al.[107] studied the transverse impact behavior of a 3D braided composite by integrating a user-defined subroutine into an FE model. Meanwhile, the effect of strain rate on the energy absorption was more significant along the out-of-plane direction than that along the in-plane direction. Subsequently, Wan et al.[104] applied a computationally efficient multiscale method to an FE model to predict the compressive properties of a 3D braided composite at quasi-static and high strain-rate loadings, respectively, demonstrating that the damage tends to occur in the corner of the composite rather than on its surface when subjected to a high strain rate compression along the transverse direction. Zhou et al.[108,109] investigated a transverse impact load to a 3D braided composite experimentally and numerically. Specifically, a modified SHPB assembled with high-pressure gas was used to conduct transverse impact tests, which was then simulated using an FE model to demonstrate the meso-scaled 3D braided preform. They also used similar experimental and FE methods to investigate the impact behavior of a 3D braided composite in the form of I-beams along its transverse direction,[110] followed by the analysis of their mechanical

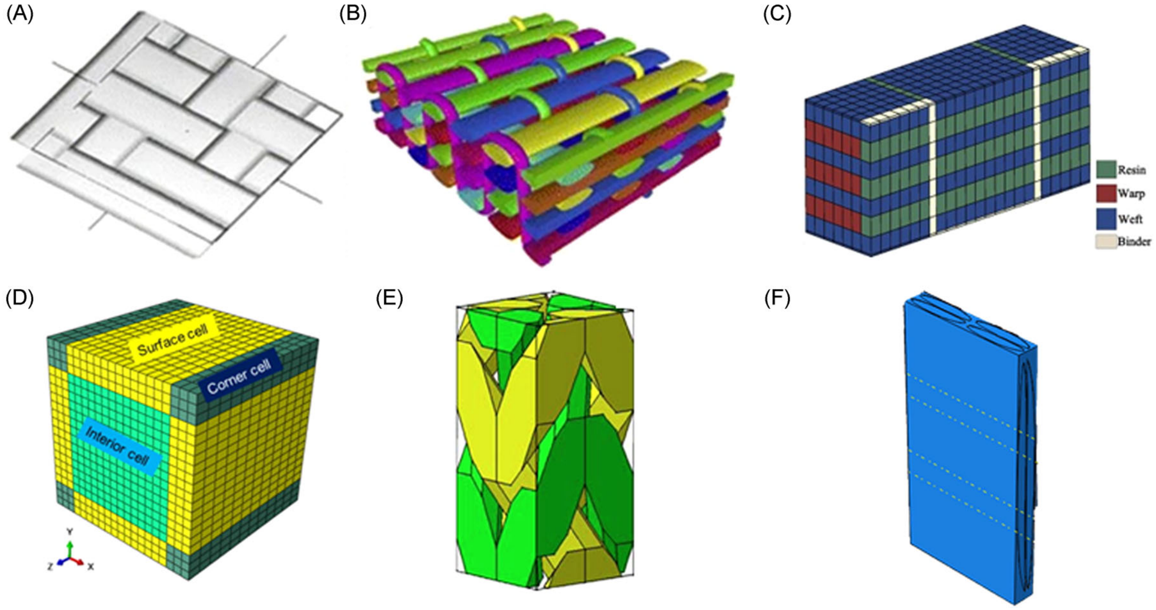

**FIGURE 13** Modeling of three-dimensional braided composites using different methods: (A) WiseTex. Reproduced with permission.[102] Copyright 2015, Elsevier. (B) TexGen. Reproduced with permission.[103] Copyright 2015, Elsevier. (C) The mosaic model. Reproduced with permission.[103] Copyright 2015, Elsevier. (D) The sub-cell model. Reproduced with permission.[104] Copyright 2015, Elsevier. (E) CATIA. Reproduced under terms of the CC-BY license.[105] Copyright 2013, The Authors, published by Hindawi. (F) SolidWorks. Reproduced with permission.[106] Copyright 2016, Elsevier

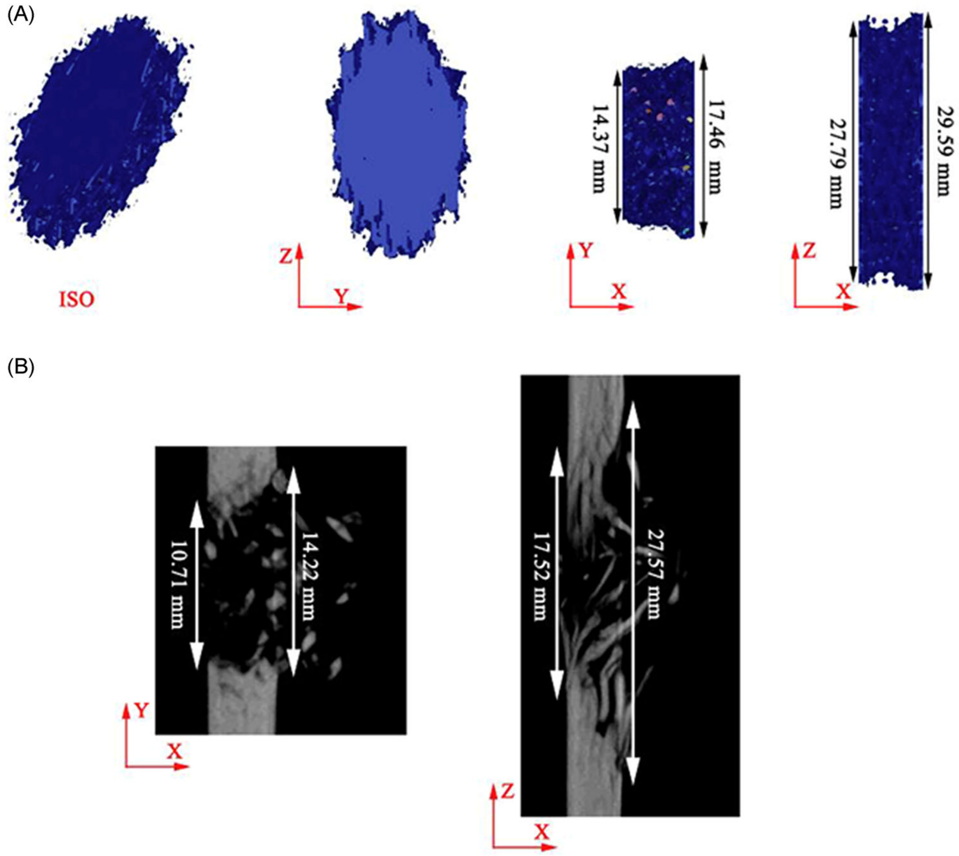

**FIGURE 14** Penetration of a three-dimensional braided plate: (A) numerical results and (B) experimental results. Reproduced with permission.[111] Copyright 2019, Elsevier

responses, such as evolutionary stress, strain, and energy absorption. The full mesoscale model established by Tan et al.[111] in LS-DYNA is shown in Figure 14, showing close agreement between the experimental and predicted damage regions on truncated elliptical cones. In contrast, the homogeneous continuum method is able to model the macro-scale damage with reasonable accuracy and efficiency. However, this method is still unable to predict the complex physical interactions or deformation of the yarns.[112] Although the meso-scale RVE enables the calculation of the yield and fatigue strengths, its function is not able to cover the real-scale composites due to the limitation in size. Moreover, the complexity of the meso-scale geometries makes the simulation of the entire structure more challenging.[113]

## 6 | CONCLUSION

This paper reviews the research focusing on woven and braided composites in both two and three dimensions, including material characterization, applications, impact performance, and damage mechanisms. Five failure modes, debonding of the fiber interface, transverse crack of the matrix, delamination of the fiber, failure of the fiber, and penetration of the fiber, are reviewed.

Compared to laminated composites, the impact energy absorption characteristics and damage tolerance of textile composites, especially the 3D textile composite materials, are generally improved, because of the enhancement in the *z*-direction. In particular, the braided composites show excellent shear performance, impact resistance, and tolerance due to the variability of the braiding angle. However, their preparation processes are too long, imposing constraints on their reproduction. Consequently, they are often used in structures with requirements of shear performance and damage tolerance, such as in the case of transmission shafts. In contrast, preparation processes of the woven preforms lead to better automation and efficiency, and consequently, have a wider application range.

This critical review can serve as a guide for research on the analysis and application of fiber-reinforced polymer textile composites in aero engines as it describes the mechanical performance of woven and braided composites. Nonetheless, more research, directed toward addressing the high cost of assessing the high-velocity impact behavior of these composite materials, is required.

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## CONFLICT OF INTEREST

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no data sets were generated or analyzed during the current study.

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