Review Article

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A review of defect formation, detection, and effect on mechanical properties of three-dimensional braided composites

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Abstract: Three-dimensional (3D) braided composites have received much attention in the fields of aerospace, the automotive industry, *etc.*, due to their unique structure and excellent performance. However, due to the complexity of their preparation process, the generation of defects is almost inevitable. With its wide application, it has become crucial to understand and control its defects. This article reviews the research progress on the defects of braided composites. First, it analyses the connection between the molding process parameters and the formation of void defects. It also introduces some nondestructive testing methods and principles for defects in 3D braided composites. Second, for the yarn deformation defects caused by the extrusion of component materials, the relevant assumptions about cross-sectional deformation and uniform yarn orientation are summarized, and the law of the influence of yarn distortion randomness on the material properties is summarized. For void defects, the differences and connections between the matrix porosity model and the matrix/yarn porosity model are discussed. In addition, the effects of other types of defects on the material are summarized. Finally, based on the summary of existing results, the prospect of future research directions is proposed.

Keywords: 3D braided composites, defect, mechanical properties

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1 Introduction

In recent decades, with the rapid development of science and technology, composite materials have gradually become the focus of engineering applications with their unique structure and superior performance and are the preferred materials in many fields such as aerospace, automotive, energy, and other fields [1,2]. However, with the increasing popularity in industries, the defects during its manufacturing and application have attracted extensive attention. The local non-uniformity caused by defects greatly reduces the overall performance of the composite materials. As common defects in traditional composite structures, delamination and debonding can be divided into manufacturing delamination, impact damage delamination, fatigue damage delamination, and nail hole delamination according to different causes, which seriously affect the strength and service life of materials [3]. This poses a new challenge to the reliability and performance of materials. Three-dimensional (3D) braided composites, due to their unique preparation process and structural design, are textile composites made by impregnating and solidifying braided preforms with resin materials. By winding and braiding yarns, a spatial near-net-shaped structure is formed, which successfully overcomes the severe defects of traditional laminated composites in interlayer strength and anti-delamination properties [4,5]. It has a wide range of applications in medical and aviation fields [6,7]. So far, many scholars have studied the microstructure and mechanical properties of 3D braided composites [8–10]. However, since 3D braided composites are generally processed by the resin transfer molding (RTM) process, due to initial defects in the material, uneven flow during resin injection, insufficient impregnation, *etc.* [11].

The generation of defects is almost inevitable, including voids, cracks, foreign objects, *etc.* These defects are difficult to observe directly with the naked eye, and most of them exist at the meso-scale and micro-scale [12]. These defects may not only lead to the decline of material properties but also have a noticeable impact on the strength and reliability of the structure.

With the continuous improvement of the performance requirements of engineering materials to ensure safety and reliability in practical application, it is an inevitable development trend to deeply study the defects of 3D braided composites. It is of great significance to understand the formation mechanism of these defects, the specific morphological characteristics of defects, their specific effects on material properties, and the optimization and improvement of nondestructive testing methods for solving the application problems of 3D braided composites.

This article starts with the relationship between molding processes and defect formation and improvement strategies. It reviews the NDT methods applicable to 3D braided composites and summarizes the effects of yarn deformation, void, and other specific defects on material properties. The entire text is organized and elaborated along this line of thought. By reviewing and summarizing the current state of research on defects in 3D braided composites, this article aims to provide valuable references and guidance for the design, fabrication, and engineering application of these materials. Through an in-depth summary of existing research findings, we hope to offer new ideas and insights for future research directions and practical applications.

2 Forming process of composite materials

The unique structure and excellent performance of 3D braided composites have attracted much attention in many engineering fields. However, while pursuing the superior properties of materials, the defects introduced in the molding process have become one of the challenges that restrict their wide application. Understanding and controlling the defects in the molding process is very important to ensure the performance and reliability of the final product.

The preparation process of 3D braided composites usually involves key steps such as fiber lamination, resin infiltration, and curing. In this series of complex processes, many factors may lead to the formation of defects. Given the connection between molding process and void defect formation, Ya *et al.* [13] used CT scanning technology to characterize the internal structure and porosity of 3D full five-directional (3DF5D) braided composites nondestructively. Glass fiber yarn was added to the carbon fiber specimen as a tracer, and a tracer model was developed using the 3D reconstruction method, which indicated that during the RTM molding process, there were elongated large voids at the top and bottom of the sample at the inlet and outlet of the epoxy resin, while the two smaller voids were distributed throughout the sample. Wu and Guo [14] investigated the defect problems of 3D braided preforms/phenolic composites obtained by RTM technology under different conditions using a modified RTM technology. It is found that the porosity of vacuum and compression-assisted RTM process can reach 0.68%. In vacuum-assisted RTM, the cavity shape mainly exists in the resin-rich area, showing many irregular shapes, such as strips, triangles, and ellipses. With the assistance of vacuum and compression, voids are mostly distributed in yarns. And the equivalent large-size holes mostly appear in vacuum-assisted RTM, and the medium-size and small-size holes mainly appear in compression-assisted and vacuum-and compression-assisted RTM. Ge *et al.* [15] to characterize the void features of 3D braided composites with void defects, the NDT method micro-computed tomography (micro-CT) was used for cross-scale damage analysis. The results of the experiment are shown in Figure 1(a). In the RTM process, holes are more likely to occur inside yarns than between yarns.

Ruiz *et al.* [16] simultaneously investigated the link between injection flow rate and void formation using numerical simulation based on a two-scale flow model and capillary number, as in Figure 1(b). An injection optimization algorithm is proposed to minimize the percentage of voids formed within the fiber reinforcement to improve the performance of the finished product, as in Figure 1(c) and (d). Fu *et al.* [11] derived the governing equations for void generation, compression, and migration in 3D braided composites using finite-element simulation, as shown in Figure 1(e), introduced energy and mass equations to outline the relationship between resin properties and curing process, and thus established a numerical model for void formation during RTM molding. It was concluded that the void content in 3D braided composites could be controlled by adjusting the resin injection volume per unit time, and the lower the outlet pressure, the lower the void content. Jeffrey *et al.* [17] improved the existing numerical simulations with the effects of capillary pressure and air entrainment situations generated during the molding process at the level of the fiber strand and on the formation of micro-voids. It is proposed that both capillary effects and air entrainment should be considered for the perfusion of dual-scale fabrics and that methods such as slowing down the flow or allowing the resin to flow out through the vents can be considered in reducing the formation of micropores. Patel and Lee [18,19] visualized the flow behavior of resins in various glass-fiber-reinforced materials and developed an optical image analysis and processing technique to help quantify/reduce void formation by associating microscopic flow patterns, void formation, movement, and removal with the microstructure of the fiber preformance. Combined with the multiphase Darcy's law, a phenomenological model was established to predict the macroscopic void fraction with flow rate and fluid properties, and a criterion for the movement of trapped voids was also developed.

In summary, it can be seen that the composite molding process has a great connection with the formation of defects, and the distribution and formation of defects can be obtained through the characterization and visualization of the real molding process. Numerical simulation can be

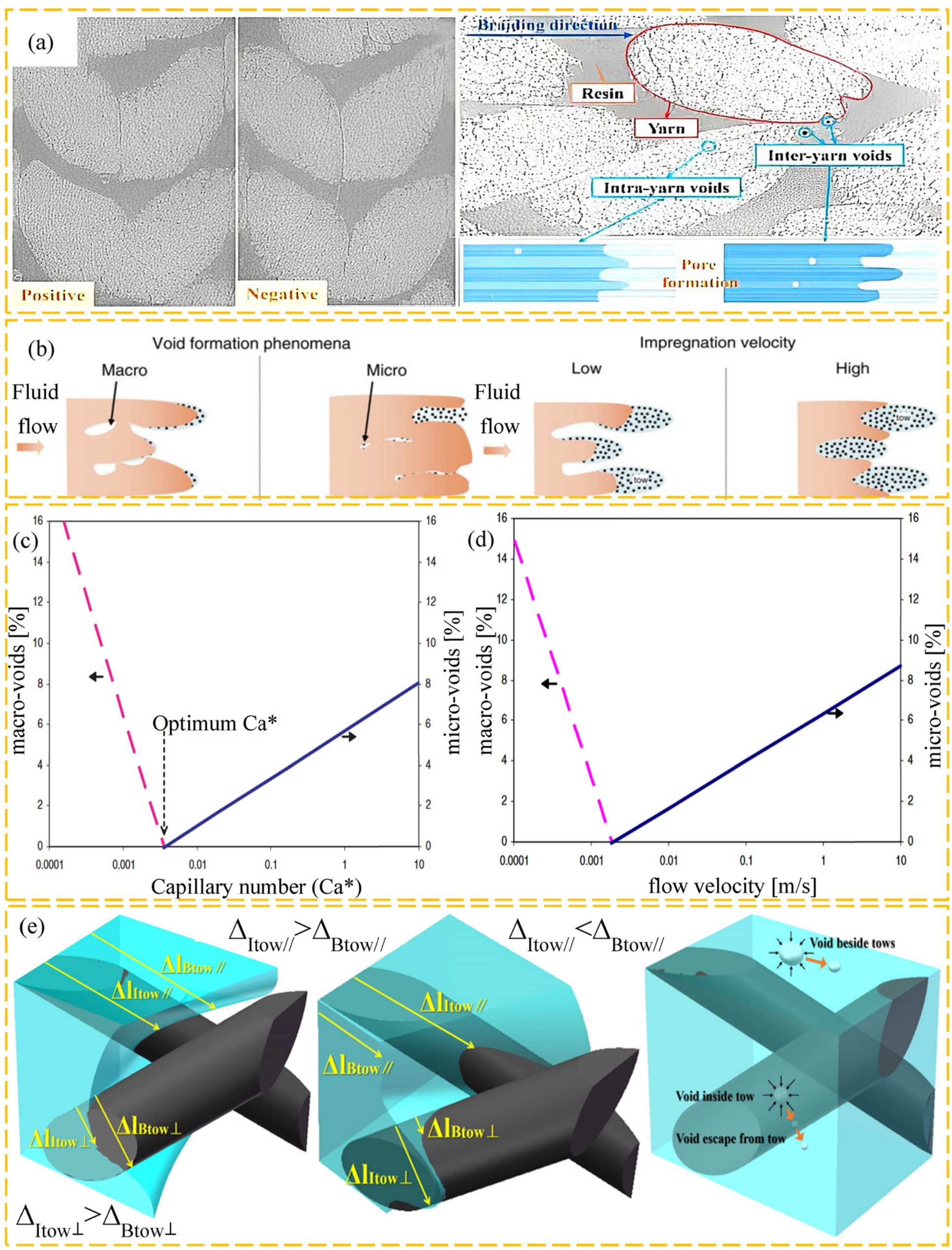

Figure 1: Relationship between forming process and void formation (a) micro-CT pattern indicating inter- and intra-yarn void formation [15]; (b) infiltration mechanism in a two-scale porous medium [16]; (c) variation of void content with capillary number and Ca* [16]; (d) macro/micro-void fractions as a function of the axial flow velocity [16]; and (e) relationship between void location and resin flow [11].

used to study and improve the process parameters affecting defect formation, such as air entrainment, capillary pressure, and resin flow behavior, in order to obtain optimized algorithms and processes to reduce the void content and achieve the objectives of improving material properties, reducing costs, and increasing productivity.

3 Detection method

Compared to two-dimensional laminated composites, the multi-directional braiding of fibers in 3D braided structures increases the complexity and diversity of defects. Therefore, in the process of preparation and application, the defects in these materials often show more changeable and hidden characteristics. The introduction of NDT methods is very important for understanding the formation mechanism of defects in 3D braided composites. First of all, these methods can provide in-depth insight into the internal structure without destroying the sample. The non-invasive and high sensitivity of these technologies make them a powerful tool to deeply understand the internal structure of materials. Second, nondestructive testing methods play a key role in quality control in the preparation process. Through real-time monitoring and testing, potential defects can be found in time to avoid further expansion in the preparation process, thus improving the quality and reliability of the final product.

3.1 Ultrasonic testing

Ultrasonic testing, utilizing the differences in reflection, attenuation, and resonance of ultrasonic waves (frequency ≥ 20 kHz) between defective and normal areas, can identify internal structures, defects, and inhomogeneities within materials. It generates images of the material's interior, providing detailed information about its structure. As an NDT method, it ensures the integrity of the material. Due to these advantages of ultrasonic testing, many scholars have used this method to study defects in 3D braided composites.

Qu *et al.* [20] conducted internal defect detection of 3D braided composites using the vertical incidence method of ultrasonic longitudinal waves and conducted a comprehensive comparative analysis of the ultrasonic detection results at different frequencies. The results show that the comprehensive comparative method of multi-frequency ultrasonic waves can be used to judge the distribution of voids in different areas, as shown in Figure 2, but cannot quantitatively detect the distribution of internal voids.

Xiao *et al.* [21] performed a quantitative inspection of 3D braided composites with artificial defects using ultrasonic C-scan technology. The results prove that ultrasonic C-scan detection can accurately identify the location and size of various defects, including voids, inclusions, and resin particles, but the identification and differentiation of voids and metal inclusions is still insufficient. Tian *et al.* [22] proposed a multi-mode excitation method to eliminate the standing wave problem in ultrasonic infrared thermography detection for the detection of composite materials with crack defects. The results show that the multi-mode excitation method can not only effectively eliminate standing waves, but also make the subharmonic and higher harmonics in the response waveform more abundant, thereby improving the detection capability of ultrasonic thermography technology and avoiding secondary damage to the material. Morbidini and Cawley [23] proposed an ultrasonic infrared calibration method to determine the threshold health index (HI) that must be reached in industrial testing. The study showed that the maximum temperature rise and the

Figure 2: Schematic diagram of abnormal area identification of samples at different frequencies [20].

maximum heating index of the continuous testing of the specimens have a high correlation, which can increase the accuracy of defect size detection.

Wan and Wang [24] used the back propagation (BP) neural network to classify and identify void and microcracking defects and to automatically identify defects in 3D braided composites. The experiment found that the defect location will cause the ultrasonic signal energy to fluctuate at a certain frequency, and the signal energy of different frequency bands can describe the defect characteristics, while the signal frequency energy change can describe the defect type. However, for materials with complex shapes, the error caused by human factors is large. Guo *et al.* [25] proposed a new detection baseline model based on a fully convolutional network (FCN) and gated recurrent unit to classify ultrasonic signals for 3D braided composites with delamination defects. The results show that the model can classify ultrasonic defect signals and shows certain advantages when competing with other models. Guo *et al.* [26] employed semantic segmentation technology to characterize defects in 3D braided composites using phased array ultrasonic testing. They implemented semantic segmentation pyramid scene parsing network to analyze ultrasonic B-scan images obtained from flaw detection experiments. They established a comprehensive database containing over 1,000 processed images and conducted a comparative evaluation with four established segmentation models: U-Net, SegNet, FCN, and pyramid scene parsing network. The results demonstrate that the addition of the SE module enables small sample recognition and reduces the phenomenon of classification errors.

3.2 Magnetic flux change imaging method

Magnetic flux change imaging method, based on the quantum effect of superconducting materials (SQUID), is an NDT method that uses a sensor to scan for tiny magnetic field changes at a certain height above the surface of a magnetic specimen or a conductor specimen excited by a magnetic field, in order to detect internal defects and heterogeneities. It has the advantages of high sensitivity, good detection depth, and being by the surface condition of the material.

Wan *et al.* [27] utilized the high magnetic field sensitivity of quantum perturbation superconducting detection sensors to apply the quantum perturbation superconducting detection NDT technology to the NDT of internal defects in 3D braided composites plate specimens and established a theoretical model suitable for the eddy current distribution of thin-plate circular defects. The results show that this method can accurately identify the location and size of hidden defects that are invisible to the naked eye and has good detection and positioning capabilities. It is an advanced NDT technology for 3D braided composites. Wang *et al.* [28] used a SQUID NDT system to study the electromagnetic properties of 3D braided composites and compared the results with those of defect-free samples. The results show that SQUID-based flux imaging can accurately display the location and size of defects and can also distinguish different internal structures caused by different braiding methods in 3D braided composites based on the high sensitivity of SQUID to weak magnetic fields, which provides a basis for the application of SQUID in the NDT of 3D braided composites.

3.3 CT scanning technology

Computed tomography (CT) uses X-rays to scan the specimen in multiple directions, combines with computer algorithms and synthesizes the collected data to construct a 3D graph of the sample, to analyze and study the internal structure, defects, and foreign bodies of the sample. It is a nondestructive testing technology with high resolution and wide practicability.

Ge *et al.* [15] in order to characterize the void characteristics and tensile behavior of 3D braided composites with voids, a cross-scale analysis was made based on micro-CT. The results show that this method can well characterize the characteristics of voids, and then predict the tensile behavior of 3D braided composites with void defects. Ya *et al.* [13] characterized the porosity and internal structure of 3D five-way braided composites using micro-CT at yarn scale. The results showed that small voids were distributed inside the samples and large ones were distributed at the top and bottom, and the voids appeared centrally in the matrix and between the yarns, with almost none inside the yarns. Feng *et al.* [29] used micro-CT technology to investigate the relationship between the yarn shape and porosity of 3D C_f/SiC_m composites and gas transmission during the chemical vapor infiltration (CVI) process, as shown in Figure 3(a). The study showed that the reconstructed porosity images illustrate that the nucleation and growth rates of CVI and chemical vapor deposition (CVD) are different, but the processes are similar.

Qian *et al.* [30] used micro-XCT to scan 3D braided C/C composites and trained image intelligent recognition using a deep learning algorithm. Finally, it was found that micro-XCT can quantitatively characterize the defect distribution and morphology of 3D braided C/C with high precision, as shown in Figure 3(b), and combined with the deep learning algorithm, it can accurately and efficiently characterize and segment the internal microstructure of 3D braided C/C composites. Gao *et al.* [31] investigated the microstructural characteristics of reinforced composites of 3D braided preforms using synchrotron radiation X-CT scanning technology. The scanning results revealed information about the fibers, matrix, and voids between and within the layers, as well as the relevant structural changes and porosity. At the same time, the mechanism of the influence of different preforms on the microstructure was revealed to a certain extent. Zhou *et al.* [32] adopted an NDT technology combining X-ray micro-computed tomography (micro-CT) and acoustic emission to comprehensively analyze the signal parameters, mechanical properties, and internal damage morphology of 3D braided composites. The results show that the two complementary techniques have a good detection effect, providing a certain foundation for structural health monitoring.

3.4 Carbon nanotube thread (CNT) sensor

CNT sensor, because of the excellent electrical properties of carbon nanowires, can achieve the detection purpose by monitoring the changes of electrical signals caused by changes in the surrounding environment and converting them into corresponding physical quantities. Because of its high sensitivity and fast response, carbon nanowire sensors are more widely used in real-time nondestructive monitoring, which is different from traditional nondestructive testing technology.

Wan *et al.* [33,34] analyzed the mechanical properties of CNTs and methods for embedding them into 3D braided composite preforms, as well as the mechanical properties of CNT sensors, measuring the change in resistance using a traditional strain amplifier and using the change in resistance to analyze defects as shown in Figure 4. The data show that CNT sensors have advantages such as easy embedding in 3D braided composite specimens, good linearity during the loading process, and little influence on the mechanical properties of the materials. Finally, the size and location of defects can be accurately identified using the resistance response surface theory.

In addition to defect detection, carbon nanowires also have outstanding advantages in structural health detection applications. Wan and Ying [35] proposed the application of CNTs in the health monitoring of 3D braided composites and proposed an algorithm based on a sliding window to detect anomalies in data streams. The data show that information on the strain, stress, and damage location in the material can be obtained, and the model can also reduce the amount of data processing and difficulty. Jia [36] based on the four-step 3D six-directional (3D6D) braiding process, analyzed the maximum embedded amount and position of

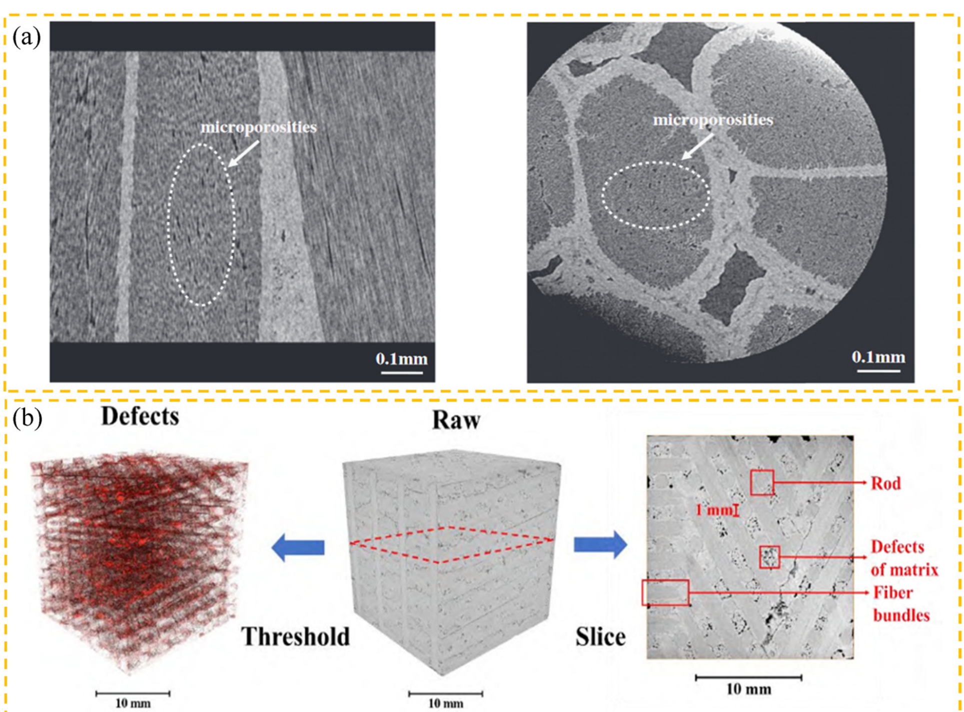

Figure 3: 3D braided composites CT image with defects: (a) local enlargement of sample reconstruction image at high resolution [29] and (b) 3D braided C/C composites XCT original image [30].

the CNT yarn sensor and verified the correctness of the optimized configuration of the embedded CNT yarn sensor through tensile and compressive stress experiments on undamaged specimens. It was found that the maximum error in damage source location was less than 0.6 mm, indicating that the optimized configuration principle of CNT yarn sensors can be used for damage detection of 3D braided composites.

In general, all kinds of existing nondestructive testing methods have their unique advantages and detection capabilities, but there are also some shortcomings. For example, ultrasonic testing has limited flaw detection depth and requires coupling agents in some cases; magnetic flux change imaging method has high cost and high environmental requirements. Therefore, in practical application, it is necessary to choose the appropriate detection system and operating parameters according to specific requirements to balance its economy and accuracy of results. In the future, it is necessary to develop nondestructive testing technology in the direction of intelligence, multi-mode, digitalization, and environmental adaptability to meet the increasingly complex and demanding testing needs in different fields.

4 Waviness-section deformation

The unique braiding structure of 3D braided composites and the complex interlacing of yarns, as well as the mutual extrusion between yarns and external stress loading, will lead to yarn deformation defects, which are non-uniform in most cases and will have a certain impact on the properties of materials.

4.1 Randomness is not considered

For the deformation defects of yarns in 3D braided composites, in some articles, scholars have studied the waviness and used the method of assuming the cross-sectional shape of the yarn to simulate and explore.

Lei *et al.* [37] used numerical methods to investigate the effect of defects on the compressive properties of 3D multiaxial braided composites (3DMBCs) fabricated by a novel five-step braiding process. The results showed that a 7° waviness defect led to a 27% decrease in the compression modulus, and the waviness defect had a significant effect on the mechanical properties of 3DMBCs. Shen *et al.* [38] explored the effect of on the mechanical properties of 3D braided SiC_f/SiC materials, as shown in Figure 5(a), by assuming the yarn cross-section shape to be hexagonal in conjunction with the realities observed by scanning electron microscopy in the development of the representative volume element (RVE) model. Li *et al.* [39] through the electron microscope scanning map, found that the

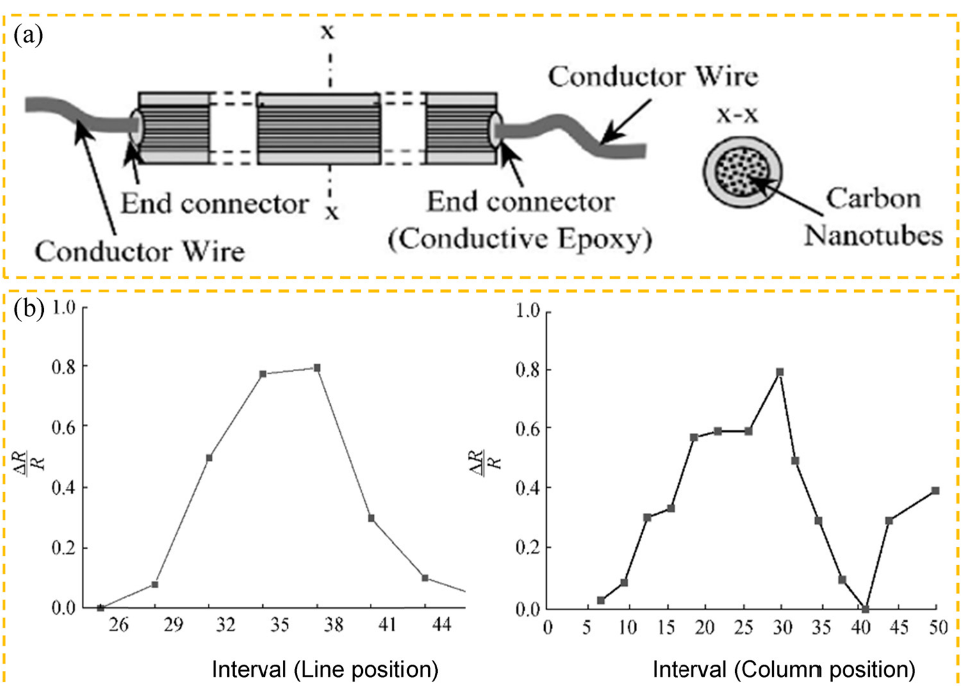

Figure 4: (a) Carbon nanowire sensor connection diagram [33] and (b) resistance change of carbon nanowire sensor [34].

braided yarn axis was in a flat state, and the yarn cross-sectional area was assumed to be hexagonal considering the mutual extrusion of the yarns during the braiding process. Thereby, a new parametric 3D finite element model was established based on the fine structure. Zhang *et al.* [40] based on microscopic image analysis, assumed the cross-sections of the braided yarn and axial yarn to be hexagons and quadrilaterals, as shown in Figure 5(b), and established a finite-element model from the mesoscale scale to evaluate the uniaxial and biaxial strength characteristics of 3D braided composites. Huang *et al.* [41] assumed the cross-sectional shape of the yarn to be an octagon, as shown in Figure 5(c), and assumed that the major and minor axes of the inscribed ellipse in the octagon represent the width of the compressed yarn, and established a multi-scale finite-element model to predict the elastic properties of three-dimensional four-directional (3D4D) rotational braided composites containing voids defects.

Liu *et al.* [42] considered the different cross-sections and lengths of 3D braided composites, assumed the yarn cross-section to be hexagonal, and gave representative yarn graphics of internal, surface, and corner defects, as shown in Figure 6(a), and studied the compression behavior of the material along the braiding direction under high strain rates. Zhu *et al.* [43] considered the change in the cross-sectional shape of the yarns along the axial direction, as shown in Figure 6(b), from an initial ellipse to becoming circular due to the mutual extrusion of the yarns, and the degree of extrusion decreases and then increases, while assuming that the deformation state of the yarns extruded inside all the transverse and vertical cross-sections is the same, and the cross-sectional areas are equal. A fine-scale structural model was developed to predict the stiffness of the 3D braided composite. Ya *et al.* [13] used micro-CT to nondestructively characterize the internal structure of 3DF5D braided composites from the yarn scale. The study found that due to the special internal structure, the yarn cross-section has rectangles and fillets and will change with height. The cross-sectional shape of the interior, surface, and corner regions will alternate between a square with rounded corners and a sector, as shown in Figure 6(c).

Li and Liu [44] studied the cross-section of yarns in 3D braided composites and found that the cross-sectional shape of the bundles at the edge of the material is triangular, while the cross-sectional shape at the corner is a right triangle, and the cross-sectional shape of the inner yarns is a rhombus with four rounded corners. In addition, the yarns undergo periodic cross-sectional deformation due to squeezing in the preform, resulting in a decrease in the cross-sectional area. Xu and Qian [45] considered that the squeezing conditions of the inner yarn are different from those of the surface and corners and assumed

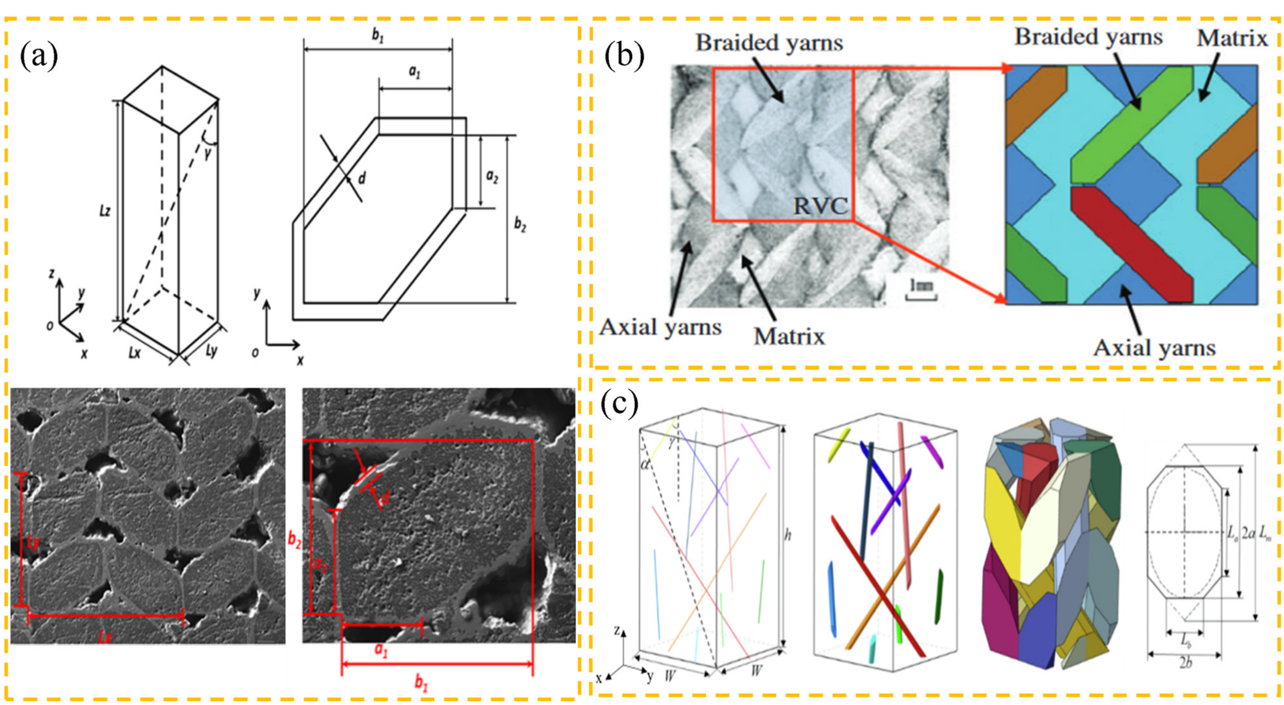

Figure 5: Yarn cross-sectional shape: (a) scanning electron microscope (SEM) images of yarn cross-sections and RVE model parameters [38]; (b) real yarn cross-sections of 3D five-directional composites (3D5D) [40]; and (c) RVE model of 3D4D rotationally braided composites [41].

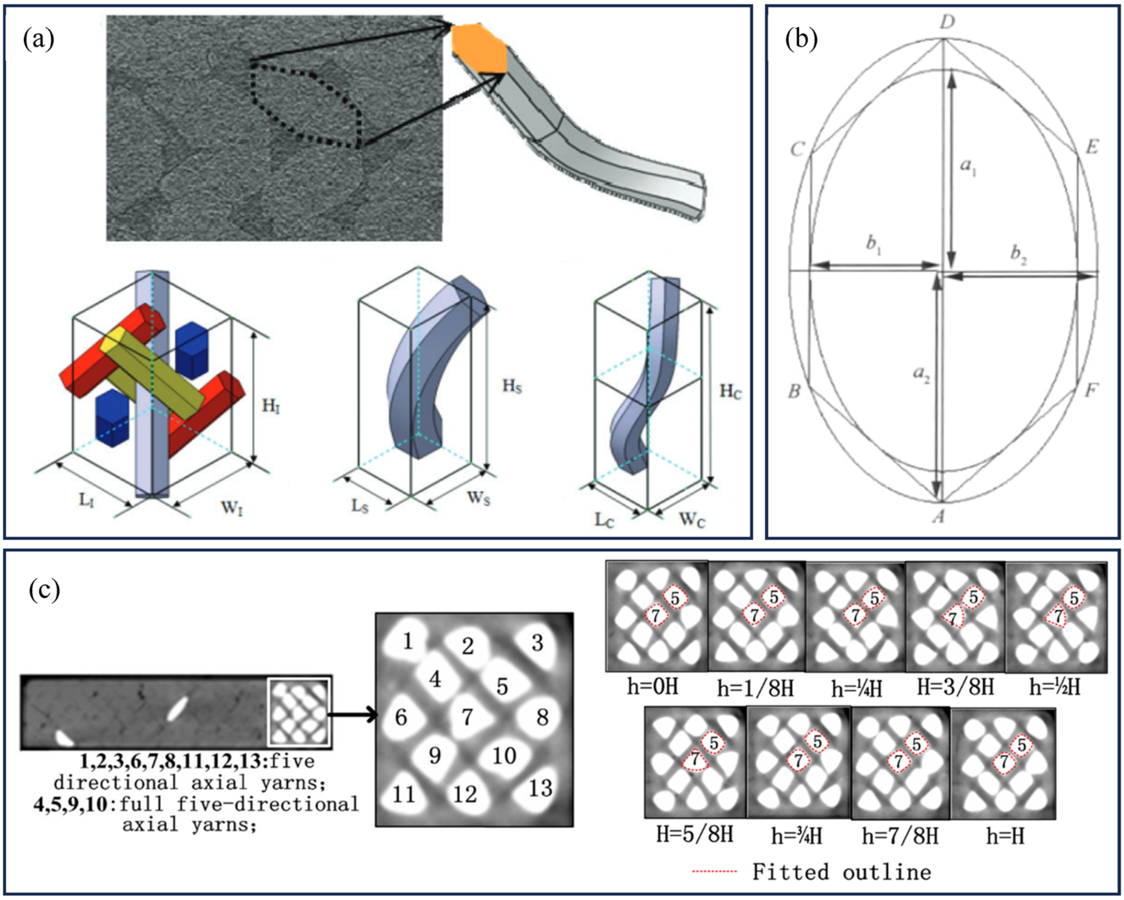

Figure 6: Continuous variation of yarn cross-section. (a) Yarn cross-section shape and three basic types of representative yarns: internal, surface, and corner [42]. (b) Schematic diagram of yarn cross-sectional shape inside [43]. (c) Axial yarn types and axial yarn sections [13].

that the cross-section of the inner yarn is an octagon, the cross-section of the outer yarn is an ellipse, the inner yarn is straight, and the surface corner yarn is straight and divided into several sections. Then, a multi-unit cell model was established, and the fiber volume fraction obtained from the experiment was compared to verify its reliability in the design and mechanical property research of 3D braided composites. Zhang and Xu [46] considered the spatial structure of the braided yarn and the different squeezing conditions in different regions. It was assumed that the yarn cross-section was elliptical, but the cross-sectional area was different in different unit cell models. At the same time, the braided yarn cross-sectional shape of the surface and corner regions gradually changed inward. Three-unit cell models were established to predict the elastic properties of 3D braided composites. Wang *et al.* [47] assumed that the yarn had a circular cross-section before being squeezed, and the squeezed part underwent a transition from a circular to an elliptical shape, which in turn caused the fiber trajectory to bend. An improved unit cell model was established for the continuous change of the yarn cross-section shape from a circle to an ellipse, which was used to predict the macroscopic elastic constants of 3D4D braided composites. Jiang *et al.* [48] combined existing research to introduce yarn curvature into the model, established a geometric unit cell model for 3D braided composites, and simulated the elastic mechanical properties. It was found that Young's modulus and shear modulus obtained based on the spiral geometric model were higher than those of traditional unit cell models, which were more consistent with experimental results.

From the above results, it can be seen that when predicting the properties of 3D braided composites by simulation, the yarn cross-section is usually simplified into polygonal, circular, elliptical, and circular/elliptical gradual changes. These assumptions reduce the error from the real situation to some extent, but there is still a certain gap between the simplified model and the real structure of the material. In the future, the research on the assumption of cross-section deformation shape should be more detailed, comprehensive, and adaptable, so as to better simulate and predict the properties of 3D braided composites.

4.2 Consider randomness

3D braided composites are usually made up of a variety of different fibers. Due to the influence of the preparation process and material properties, yarns will be randomly deformed due to extrusion. Therefore, it is very important to consider the random effect to deeply understand the performance changes and variability of these materials.

Yushanov *et al.* [49] developed a general stochastic theory for the elastic properties of continuous randomly curved spatially reinforced composites, as shown in Figure 7(a), to assess the elastic response of randomly corrugated multi-directional reinforced composites. The results show that even small local

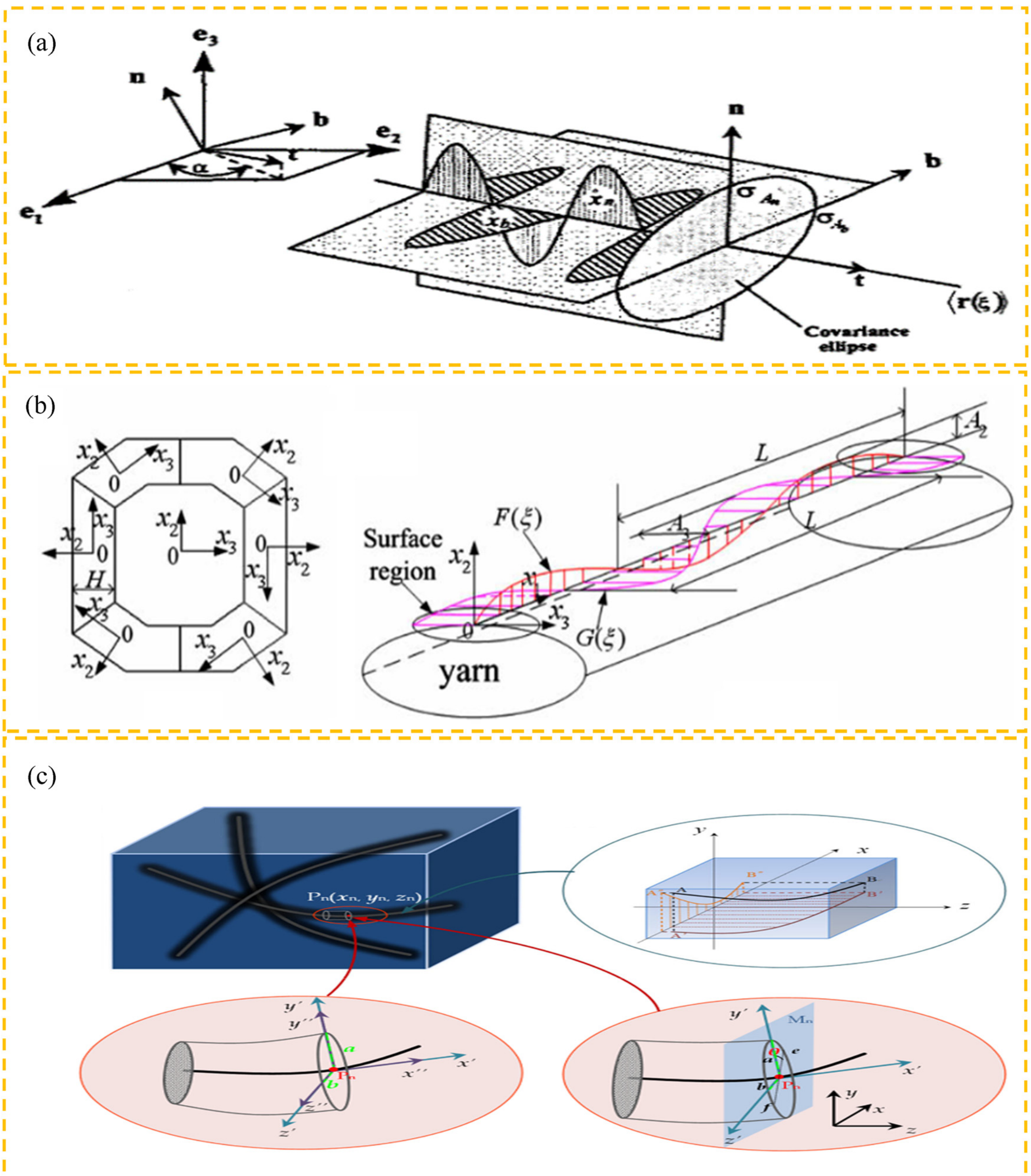

Figure 7: Random characterization of yarn deformation: (a) orthogonal decomposition of random fluctuation of yarn path [49]; (b) cross-section and action of surface fiber path of yarn [51]; and (c) characteristic parameters and coordinate system of deformed yarn [52].

waviness on the reinforcement path can have a significant effect on the elastic response of the material. Bogdanovich Yushanov and Bogdanovich [50] developed a general stochastic theory for fiber-reinforced composites with continuous, random curvature to quantify the effect of fiber deviation from the assumed ideal path and used a random extension of random function theory and the method of directional averaging to evaluate the mean and standard deviation of the full tensor anisotropic stiffness properties.

Fang *et al.* [51] assumed that the cross-section of the yarn was octagonal and that the surfaces of adjacent yarns were in contact with each other. Each braided yarn in the inner layer of the braided composite is divided into several regions, and random variables are introduced to describe the path of the fibers in the twisted yarn, as shown in Figure 7(b). The effect of yarn deformation on the elasticity and strength of 3D4D braided composites was considered using the theory of random functions. Zhai *et al.* [52] provided an explanation based on the stochastic theory for the factors influencing the distortion characteristics of multiple types of yarn, including path, cross-sectional shape, and cross-sectional torsion effects. Meanwhile, the cross-sectional shape is assumed to be elliptical and used to describe the distorted characteristics of the yarn cross-sectional shape. The elastic properties of yarns in 3D braided composite materials were studied, as shown in Figure 7(c). Kang *et al.* [53] divided the yarn cross-section into five regions and introduced random theory to describe the twist characteristics of interlaced yarns and obtain the compliance of each region of the twisted yarn using random function theory. The influence of yarn deformation on the elastic properties of 3D braided reinforced fiber rod composites was studied. Zhang *et al.* [54] reconstructed the real yarn cross-sections and fiber shape deviations of the molded composites by combining micro-CT. The macroscopic and microscopic mechanical properties of the 3D tubular braided composites were simulated at different temperatures. It was found that the transverse and shear properties of the yarns were affected by the fiber shape, and the yarn RVEs with elliptical fiber shapes exhibited better mechanical properties than those with circular ones.

To sum up, the 3D braided composites model considering random effect can effectively simulate the yarn deformation defects caused by braiding arrangement and other factors in the actual situation. At the same time, it also reduces the error in evaluating the properties of the material to some extent. However, there is still a lack of unified standards and models, and it is difficult to compare different experiments. In addition to this, the nature of randomness and the high computational cost make it a pressing issue to consider random effects. Therefore, it is necessary to carry out more in-depth theoretical research, model verification, and experimental design. At the same time, randomness research needs to be combined with practical application to ensure that the research results have practical guiding significance for engineering practice.

5 Void defects

Void, as one of the most common defects in 3D braided composites, refers to the voids or bubbles formed inside the materials, which are mainly caused by gas release, poor resin flow, or braided structure during preparation. Therefore, it is an important subject to accurately understand and control the void defects in 3D braided composites to improve their performance and reliability.

5.1 Dry spots in the bundle are not considered

Due to the diversity and complexity of void-forming factors, the formation of voids is particularly complicated in 3D braided structures, and voids may be formed in yarns, matrix, or interface areas. Some scholars have studied the properties of 3D braided composites with void defects without considering the dry spots in yarns.

Yang *et al.* [55] studied the off-axis tensile mechanical properties of 3D5D braided composites and the axial mechanical properties of two braided angle specimens by introducing randomly distributed void defects in the microscopic model. The results showed that the porosity had a greater effect on reducing the tensile strength of the large-braided-angle specimens than that of the small-braided-angle specimens, but different porosities had less effect on the tensile strength. Lu *et al.* [56] investigated the longitudinal tensile behavior of 3DF5D braided composites by conducting multi-scale simulations grounded on a novel 3D damage model that applies the Linde failure criterion. It is found that the void defects lead to a slight decrease in modulus and strength, but increase the failure strain, which indicates that a proper amount of void defects can improve the ductility of composites. Shen *et al.* [38] developed an RVE model to investigate the effects of defect location, size, and shape on the mechanical properties of 3D braided SiC_f/SiC-ceramic matrix composite. The results showed that the tensile properties of the material decrease with increasing porosity, and the decrease is insignificant at low porosity, as shown in Figure 8.

Gong *et al.* [57] considered the effects of void and interface defects on the effective stiffness of 3D braided composites. The experiments showed that when the voids were located in the matrix, the reduction in yarn stiffness was much greater than when they were located at the interface. When the void shape was spherical, the reduction in yarn stiffness was the smallest, and when it was cylindrical, the yarn stiffness decreased slightly, while when it was a disk, the yarn stiffness decreased significantly. The interface properties did not change the effect of void shape on stiffness, and the yarn modulus decreased linearly with increasing porosity at different interface thicknesses, as shown in Figure 9.

Shi *et al.* [58] simulated voids by introducing voids into the unit cell model to investigate the effect of porosity on the elastic constants of 3D braided ceramic matrix composites. It was concluded that the porosity had a significant effect on the elastic constants, and the elastic modulus in the direction of the yarn decreased with increasing porosity. Gao *et al.* [59] proposed a 3D constitutive model of braided composites with void based on the microstructure, and the elastic properties of materials with different porosities were predicted theoretically. Finally, it was concluded that when the porosity increased by 1%, the material strength decreased by 6.5% and the modulus decreased by 2.04% at the same volume content. At the same porosity, the mechanical properties were positively related to the fiber volume and tended to converge. The strength is more easily influenced by the matrix voids than the modulus. Wang *et al.* [60] took yarn extrusion and matrix void defects into account to develop a realistic fine-scale RVE model for 3D6D braided SiC_f/SiC composites to test the elastic modulus in comparison with the ideal model. The data show that the ideal model I without defects and the predicted model data modulus were compared to obtain a prediction error of 3.67% for the initial modulus when $\xi_f = 0.3$. For the G model with $\xi_f = 0.8$, the computational error of the initial modulus is 2.36% and the voids have a large effect on the elastic properties of the material. Dong and Gong [61] established a microscopic model of 3D braided composites with random void defects to simulate the progressive damage process of tensile and proposed a stiffness degradation method to generate random delamination defect units and discussed the influence of void defects on material damage extension and strength, as shown in Figure 10. The results show that the random voids in the matrix will lead to the redistribution of micro-stress and reduce the strength and ductility of the material, and the reduction effect is related to porosity. Initial porosity increases almost every type of damage, especially the longitudinal damage propagation of yarn.

At present, simulating the mechanical properties of defective materials through microscopic models is an effective method. As can be seen from the above studies, the characteristic parameters such as shape, size, location, and content of void defects between yarns will lead to changes in the effective stiffness reduction effect of 3D braided composites. As an important characteristic parameter, the porosity between yarns will lead to a certain decrease in the tensile and elastic properties of the material as it increases. Moreover, the elastic strength is more easily affected by the matrix void than the modulus, but a moderate amount of porosity has a beneficial effect on the ductility of the material. In addition, void can also aggravate almost all types of damage.

5.2 Considering dry spots in yarns

As microscopic defects, in-beam dry spots have a significant influence on the properties of materials. In order to

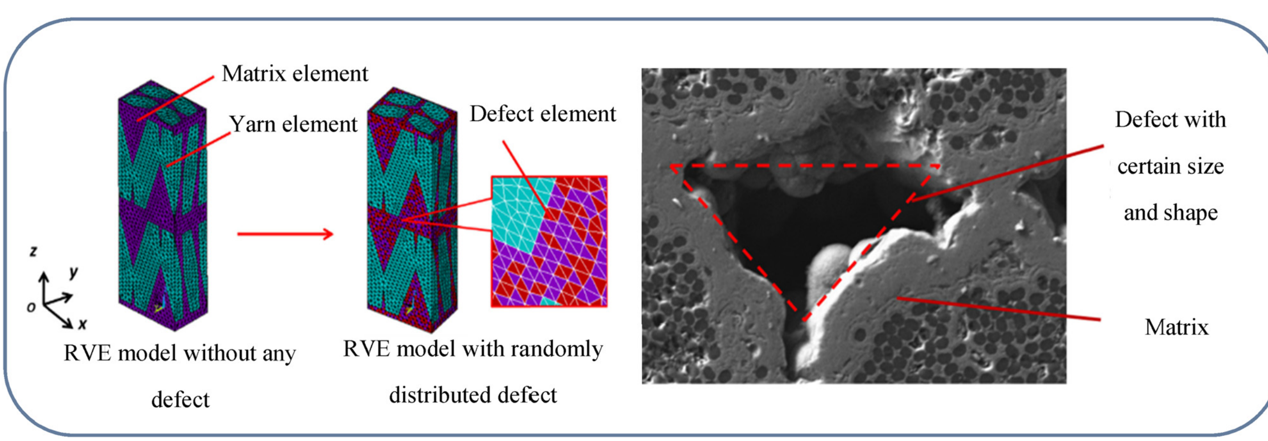

Figure 8: RVE modeling method of randomly distributed defects [38].

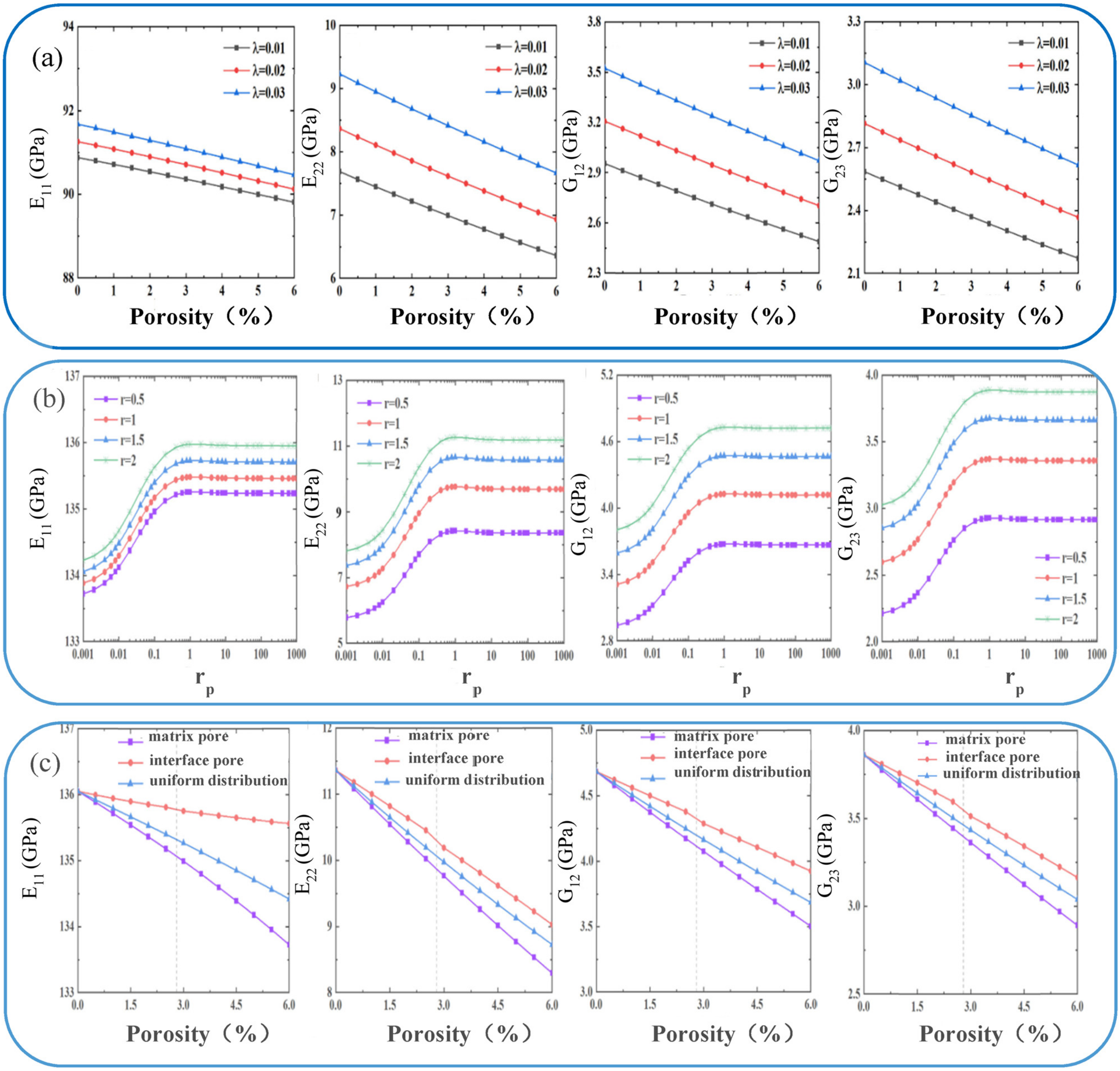

Figure 9: Performance study of 3D braided composites with void defects: (a) effect of porosity and interface thickness (λ) on effective yarn modulus (E_{11}, E_{22}, G_{12}, G_{23}) [57]; (b) effect of porosity (r) and void shape (r_p, the ratio of the lengths of the two main axes determines the shape of the ellipsoid) on effective yarn modulus (E_{11}, E_{22}, G_{12}, G_{23}) [57]; and (c) effect of porosity and void location on effective yarn modulus (E_{11}, E_{22}, G_{12}, G_{23}) [57].

more accurately predict the influence of void defects on the properties of 3D braided composites, many scholars have taken both in-beam dry spots and matrix voids into consideration.

Ge *et al.* [62] established a multi-scale modeling to predict failure modes and strength properties in 3D braided composites containing void defects. According to the periodic characteristics of the material across different length scales, they developed a unit cell model based on selective element formulation, and an explicit void morphology model, as shown in Figure 11(a). The results show that the two-scale damage failure analysis method based on the void model is feasible. The void model is better than the element model in predicting the mechanical properties of 3D braided composites. Xu and Qian [63] established a microscopic unit cell model based on the causes of void defects in the RTM process and combined probabilistic statistical methods to analyze the influence of porosity and random distribution of defects on the equivalent elastic properties of the material. The results show that the elasticity of materials is more sensitive to porosity than the random distribution of porosity to some extent.

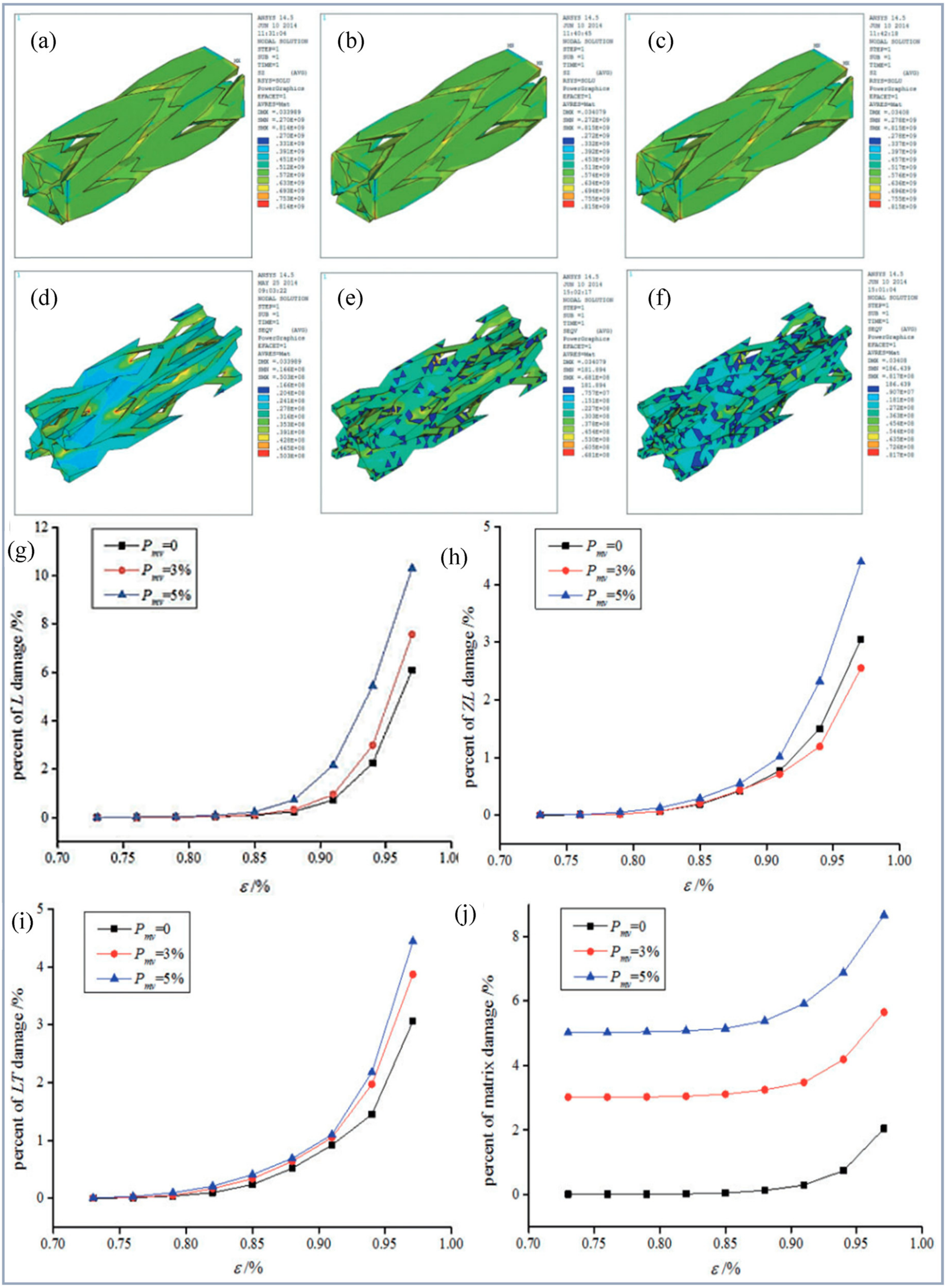

Figure 10: Effect of defects on damage expansion and stress distribution in different materials (a)–(f) Stress distribution in yarns and matrices containing void defects: (a) yarn (P_{mv} = 0); (b) yarn (P_{mv} = 3%); (c) yarn (P_{mv} = 5%); (d) matrix (P_{mv} = 0); (e) matrix (P_{mv} = 3%); (f) matrix (P_{mv} = 5%); (g)–(j) damage propagation curves for different porosity; (g) yarn L-type damage; (h) yarn ZL-type damage; (i) yarn LT-type damage; and (j) matrix damage [61].

The increase of porosity leads to the linear decrease of material modulus, and the braiding angle will lead to the change of the influence of defects on modulus. Song *et al.* [64] developed an analysis method combining micro-CT imaging, unsupervised machine learning, and progressive damage analysis methods in order to cross-scale analyze 3D braided composite damage. It was shown that the volume of voids in the interior is larger compared to the surface of the material. An increase in porosity results in a linear decrease in the strength and modulus of the material, and the stress concentration generated by the voids results in an increase in the strength reduction of the material as the porosity increases. The presence of voids also increases the damage to the material to some extent. Ge *et al.* [65] developed a multi-scale viscoelastic analysis method to characterize the viscoelastic behavior of porous 3D braided composites and established a semi-theoretical model using the generalized unit method to calculate the viscoelasticity of the yarn. The experimental results show that the transverse viscoelastic behavior of 3D braided composites with void defects is obviously reduced, but the longitudinal long-term properties have little change. Huang *et al.* [41] for the first time, created a multi-scale finite-element model and an agent model for predicting the elastic properties of 3D, four-way, void-containing rotary braided composites and also proposed a BP neural network model optimized by a genetic algorithm. The results show that the maximum error of the predicted homogeneous elastic constant is 9.4% compared with the experimental results, and the porosity has a great influence on the transverse and shear properties, but little influence on the axial properties of yarns.

Xu and Qian [66], employed a finite element model based on RVE and periodic unit cell to predict the finite elastic properties of composites, while accounting for matrix voids and yarn dry spots. The results show that the void volume

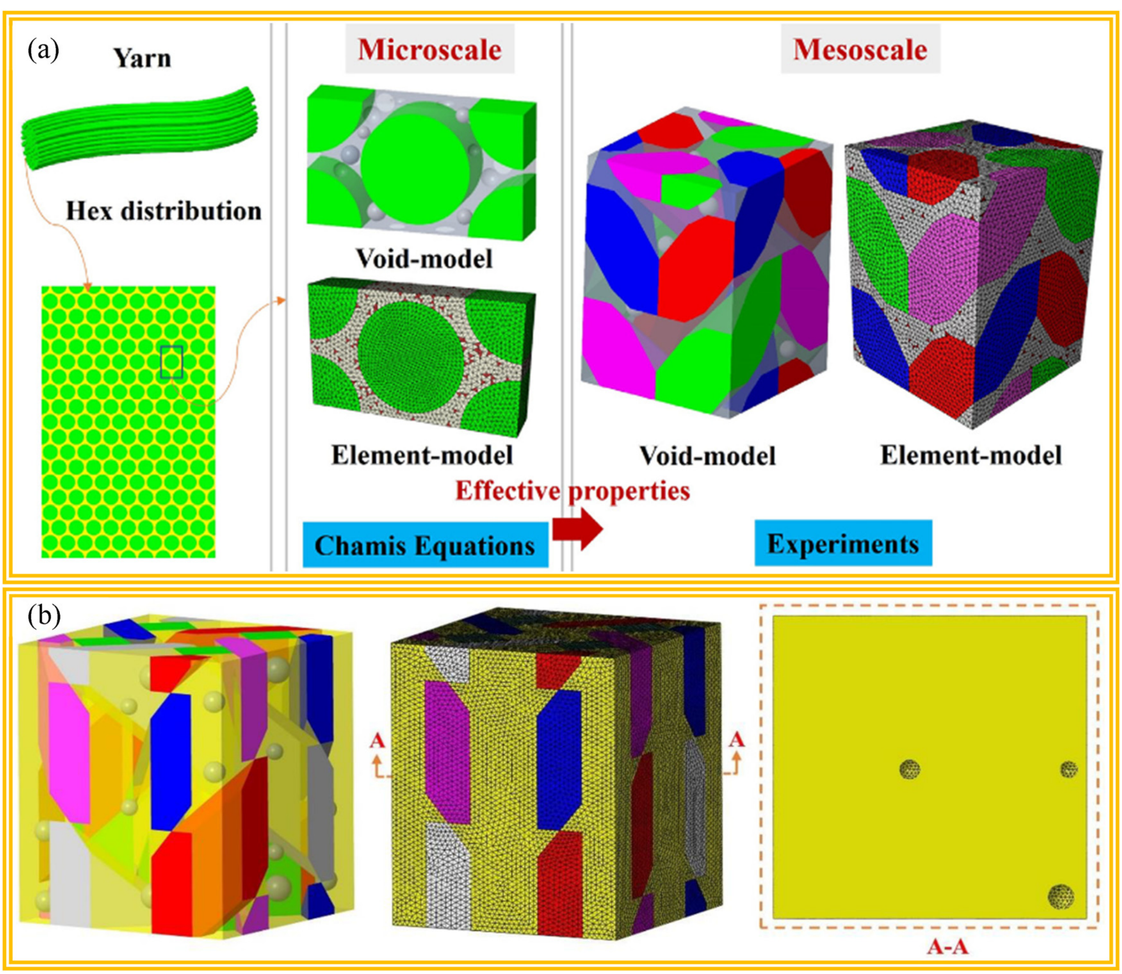

Figure 11: Modeling of composite materials considering yarn dry points: (a) bi-scale analysis algorithm for 3D4D composites with void defects [62] and (b) microscopic void model with spherical defects [67].

fraction has a great influence on the 3D braided composites, and it is influenced by the braiding angle. Except for Poisson's ratio *XZ* and *YZ* directions, other elastic moduli are negatively correlated with void volume. Ge *et al.* [67] used multi-scale modeling to predict the elastic behavior of porous 3D5D, as shown in Figure 11(b), and homogenized the defective matrix to simplify the experiment. The results show that fiber distributions, void types, and void distributions have little effect on the effective elastic constant of yarn, and fiber content is negatively correlated with porosity. The increase of porosity will lead to the decrease of the elastic constant of yarn. For 3D5D, elastic modulus and shear modulus will decrease with the increase of porosity, but Poisson's ratio is opposite, as shown in Figure 12.

Ge *et al.* [68] proposed an improved Chamis model and established a RVE with void defects to predict the elastic constants of 3D braided composites and also established a homogenized full-size model. It is found that the elastic modulus and shear modulus decrease with the increase of void content, while Poisson's ratio changes inversely. The sensitivity of elastic constants in different directions to defects is different, and the full-scale homogenization model can improve the economic and time problems of evaluating material properties, as shown in Figure 13.

Wei *et al.* [69] considered the void defects of fiber-reinforced phase, matrix phase, and interface phase and studied the influence of void on the elastic properties of 3D braided C/C composites from a multi-scale perspective. The

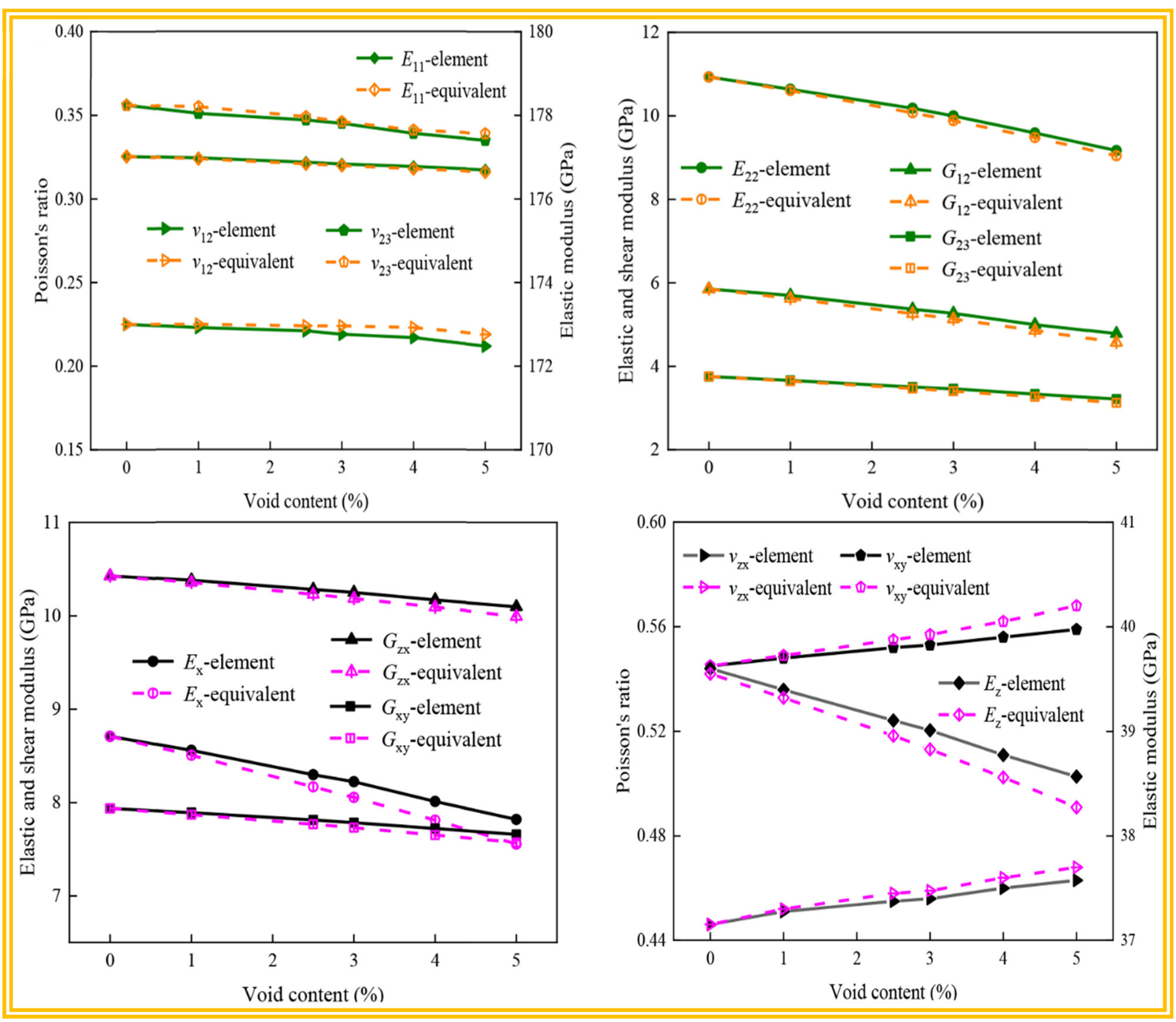

Figure 12: Effect of porosity on micro- and meso-scale unit models and response equivalent models [67].

results show that the porosity has a great influence on the elastic constant. For example, when the porosity is 10%, the axial and radial tensile modulus of the material decrease by 11.7 and 12.3%, respectively; the in-plane and out-of-plane shear modulus decrease by 11.28 and 29.74%, respectively; and the out-of-plane Poisson ratio decrease by 29.32%, while the in-plane Poisson ratio increases by 0.26%. The influence of porosity of each phase is fiber-reinforced phase > matrix phase > interface direction. Zhang *et al.* [70] introduced units to simulate dry spots and inter-bundle porosity within yarns at micro and fine scales, respectively, and established a macroscopic homogeneous model for the prediction of macroscopic elastic constants. The results indicated that the dry spots have a greater effect on the macroscopic elastic properties than the inter-bundle porosity, and the increase in dry spot porosity leads to a decrease in the longitudinal Poisson's ratio, and the opposite is true for the inter-bundle porosity. Qi *et al.* [71] introduced voids into the model to simulate dry spots and voids in the matrix and yarns and discussed the effect of defects

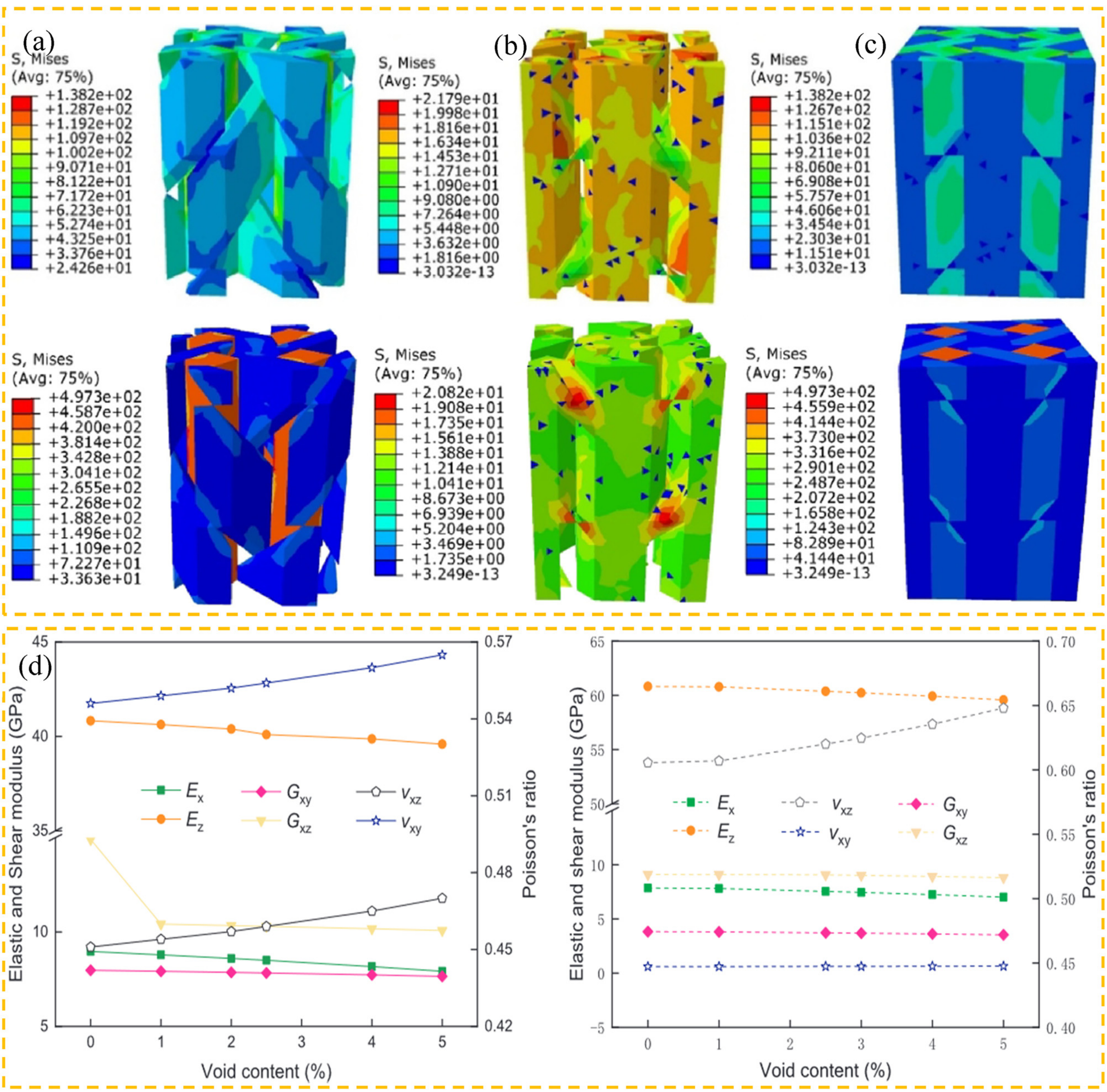

Figure 13: In-beam dry spot effects on material stresses and properties (a)–(c) stress distribution of RVC under *X*-direction and *Z*-direction loading [68]. (a) Yarn, (b) matrix and (c) whole cell; and (d) effect of porosity content on the properties of 3D5D composites with α as 40° and 23° [68].

on the mechanical properties of the material. The data show that when the porosity is constant, the influence of the void position on the elastic modulus along the knitting direction can be ignored. The increase of porosity leads to a downward trend in all mechanical properties except transverse Poisson's ratio, and the influence of defects in yarns is greater than that in the matrix. Dong and Chen [72] established models from both the mesoscopic and microscopic scales to study the macro-mechanical properties of 3D braided composites with voids and dry spots. The experiments found that all engineering elastic constants decreased with increasing porosity, except for the longitudinal and transverse Poisson's ratios. The compressive elastic modulus and shear elastic modulus were more affected by the porosity of the yarns. In addition, the main reason for the reduced stiffness of the material was the dry spots in the yarns. Dong and Huo [12] based on a dual-scale model, considered matrix voids and dry spots in yarns to predict the effective elastic properties and microscopic stress of 3D braided composites. The calculation results showed that the void volume fraction had different effects on each elastic constant. The void volume fraction of the yarn had a greater effect on the elastic constant than that in the matrix. The presence of voids increased the transverse deformation of the material under longitudinal loading.

Zhang *et al.* [73] constructed a cross-scale plastic damage constitutive model that includes plastic effects and damage accumulation to analyze the nonlinear behavior of 3D tubular braided composites with defects. The experiment shows that interfacial or void defects greatly affect the transverse or shear strength of yarns. The calculated longitudinal tensile strength of uncoupled void defects and collective plasticity is 613.21 MPa, with an error of 14.09% from the experimental results, and the calculated result of the coupled model is 499.19 MPa, with an error of 7.13% from the experimental results as in Figure 14.

Liu *et al.* [74] established a full-scale microstructure finite-element analysis model to study the impact compression properties of 3D carbon fiber/epoxy resin ring-braided composite tubes under the influence of defects based on the numerical method, as shown in Figure 15(a). The experiments found that with the change of defect content and braiding angle, the compression properties, initial modulus, and failure strain of the material will change to a certain extent. A smaller braiding angle will lead to earlier failure and a greater decreasing trend in some of the elastic constants and defects in the yarns. It will have a greater impact on the compressive properties and initial modulus than those in the matrix. Liu *et al.* [75] used a finite-element method and introduced random defects into fiber tows using the Monte Carlo method to numerically investigate the effect of random defects on the compressive behavior of 3D braided composites. It is found that random defects have a certain influence on the compressive modulus and strength of materials along the in-plane direction but have no obvious influence on the compressive properties under out-of-plane impact, as shown in Figure 15(b)–(e). Liu *et al.* [42] studied the size effect of the compressive behavior of 3D braided composites with and without defects under high strain rates through numerical simulation. According to the results, the defects in yarns have

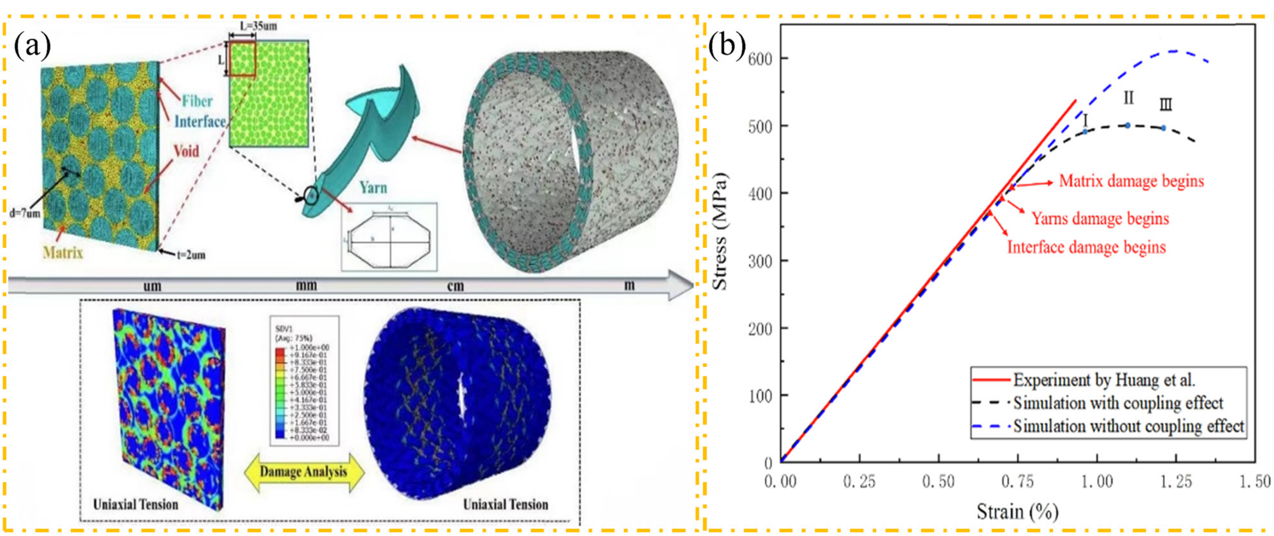

Figure 14: Effect of void defects on the tensile properties of 3D woven composites: (a) cross-scale analysis framework for 3D tubular braided composites and (b) macroscopic stress–strain curve [73].

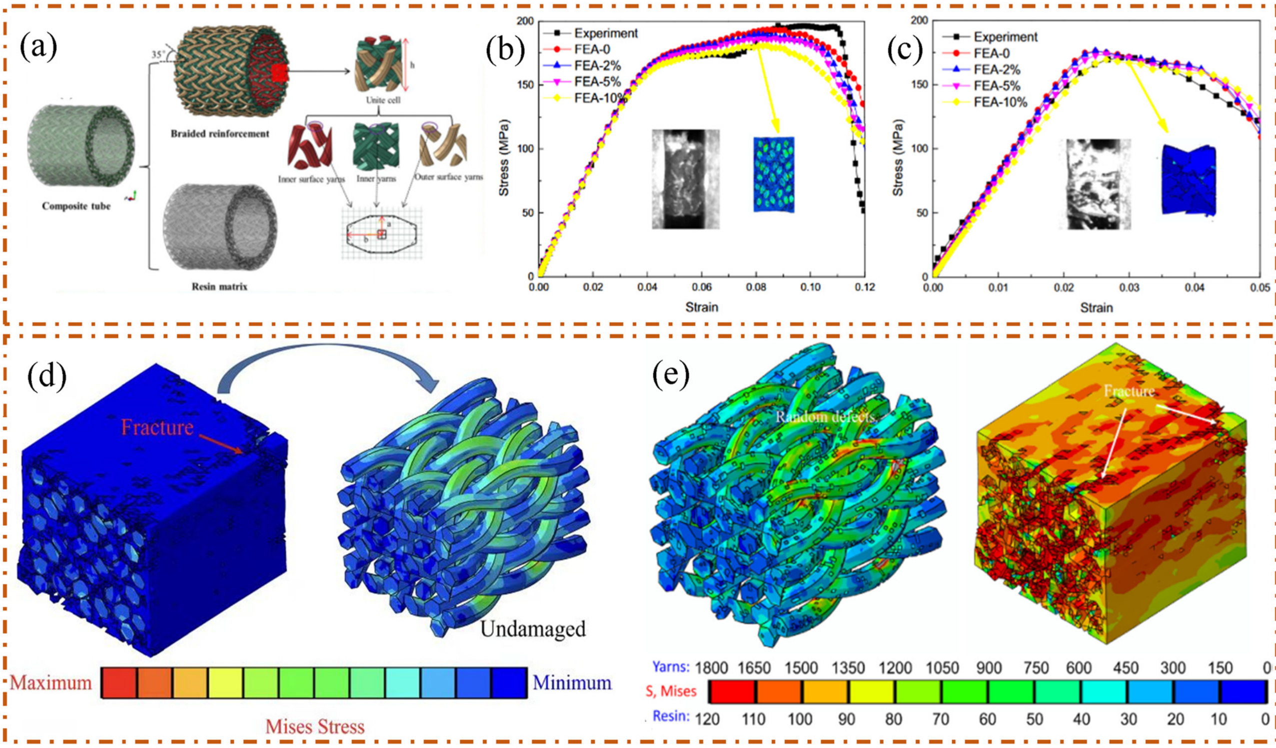

Figure 15: Effect of void defects on the compressive properties of 3D woven composites: (a) geometrical model of 3D braided composites tube [74]; (b) stress–strain curves of BCs under impact in out-of-plane direction; (c) stress–strain curves of BCs under impact in the in-plane direction; (d) fracture modes of defect-free composites in fiber tows under impact in the out-of-plane direction; and (e) fracture modes of defective BCs in fiber tows under impact in the out-of-plane direction [75].

great influence on the compressive properties of materials. The increase of defect volume fraction will lead to the decrease of modulus and strength, and the fracture strain will also increase.

Zhang *et al.* [54], based on the micro-CT multi-scale modeling framework, reconstructed the real yarn cross-section, fiber deformation, and defects inside the matrix of the molded 3D braided composites and simulated the multi-scale mechanical properties of the materials at different temperatures using the elastic–plastic damage model and the traction-separation eigenstructure model. It was found that the internal porosity of the yarns was higher than that between the yarns due to the low permeability property of the resin, and the increase in temperature resulted in a significant decrease in the yield strength, breaking strength, and stiffness of the defect-containing materials under tensile or compressive loading, as shown in Figure 16(a), but the longitudinal mechanical properties were basically unaffected by the temperature. The overall mechanical response of the matrix was negatively correlated with porosity, independent of the location of the voids. Wei *et al.* [76] considered the void defects of fiber reinforcements, yarns, and interfaces and predicted the effective thermal conductivity of the material from the fiber scale and yarn scale based on the AH method. The experiments found that the random distribution of voids had little effect on the effective thermal conductivity, while the finite thermal conductivity decreased linearly with increasing porosity volume fraction. The effect of matrix porosity volume fraction on thermal conductivity was greater than that of fiber reinforcement porosity volume fraction. Increasing the interface thermal conductivity would lead to the effect of interface porosity volume fraction on effective thermal conductivity. The porosity volume fraction in yarns had a greater effect on transverse thermal conductivity than longitudinal thermal conductivity. Wang *et al.* [77] generated a RVE with detailed geometric features to reconstruct the microstructure of SiC_f/SiC. Combined with the Markworth and parallel models, the effect of porosity on the effective thermal conductivity of SiC_f/SiC was investigated. The results showed that when the porosity was 5%, the thermal conductivity in the transverse and longitudinal directions was reduced by 20 and 10%, respectively. The longitudinal thermal conductivity decreased linearly with increasing porosity, while the transverse thermal conductivity decreased nonlinearly as in Figure 16(b), and an improved Markworth model was proposed.

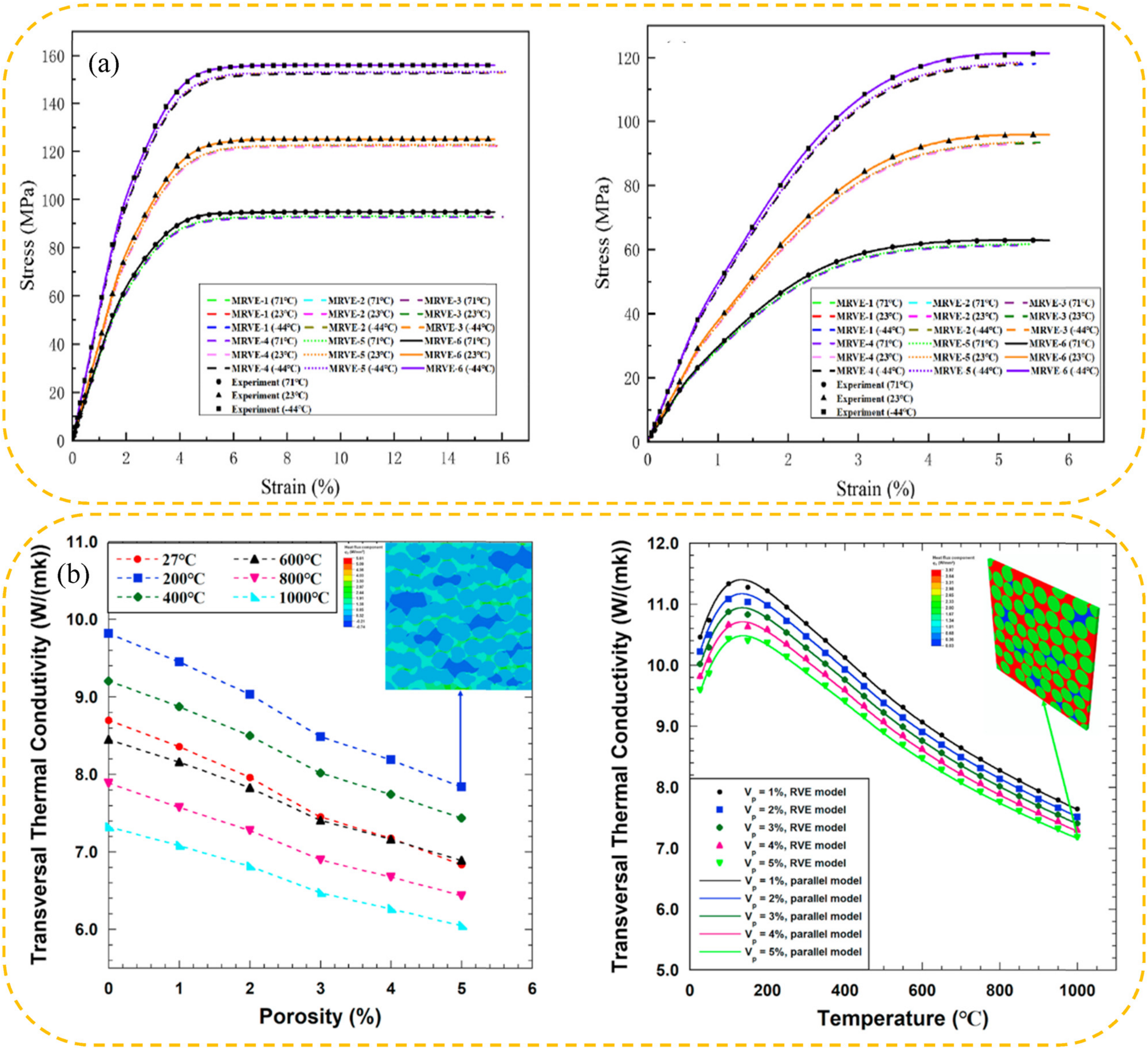

Figure 16: Temperature effects of 3D braided composites under the influence of defects: (a) compressive and tensile stress–strain curves of epoxy resin matrix at different temperatures. (MRVE1-3 are matrices with the same void radius and a random distribution of voids at 2.0% porosity; MRVE-4 are matrices with different void radii and a random distribution of voids at 2.0% porosity; MRVE-5 are matrices with different void radii and a random distribution of voids at 1.6% porosity; and MRVE-6 are non-voids matrices.) [54]; (b) subplots of the distribution of the heat flow component Q2 when 65% fiber fraction RVE model (V_p = 5%) is used in the thermal conductivity calculations at 200°C and a comparison between the RVE model and the modified parallel model in the thermal conductivity calculations at 1,000°C as well as a comparison of the distribution of the heat flow component q when 65% fiber fraction RVE model (V_p = 5%) subplots of heat flow component q distribution [77].

In summary, the multi-scale modeling method takes into account the voids in the yarns. It is found that porosity has a greater influence on the elastic constants of the material than the void type and distribution, and the voids in the yarns have a greater influence on the elastic constants of the material than the voids between the yarns. The elastic constants all decrease to varying degrees with increasing porosity, except for Poisson's ratio. The presence of void defects also leads to a certain decrease in tensile properties, compressive properties, and effective thermal conductivity, and the effect on tensile strength is much greater than that on tensile modulus. In summary, choosing whether or not to consider dry spots in the bundles, based on the research purpose, model complexity, and computability, helps to gain a deeper understanding of the effect of porosity on composites.

6 Other defects

In addition to void defects, there are many other complex and diverse defects, such as cracks and fiber dislocation. The existence of these defects may reduce the strength, toughness, and fatigue properties of materials and affect their reliability in practical applications. Therefore, it is very important to study the formation mechanism of these

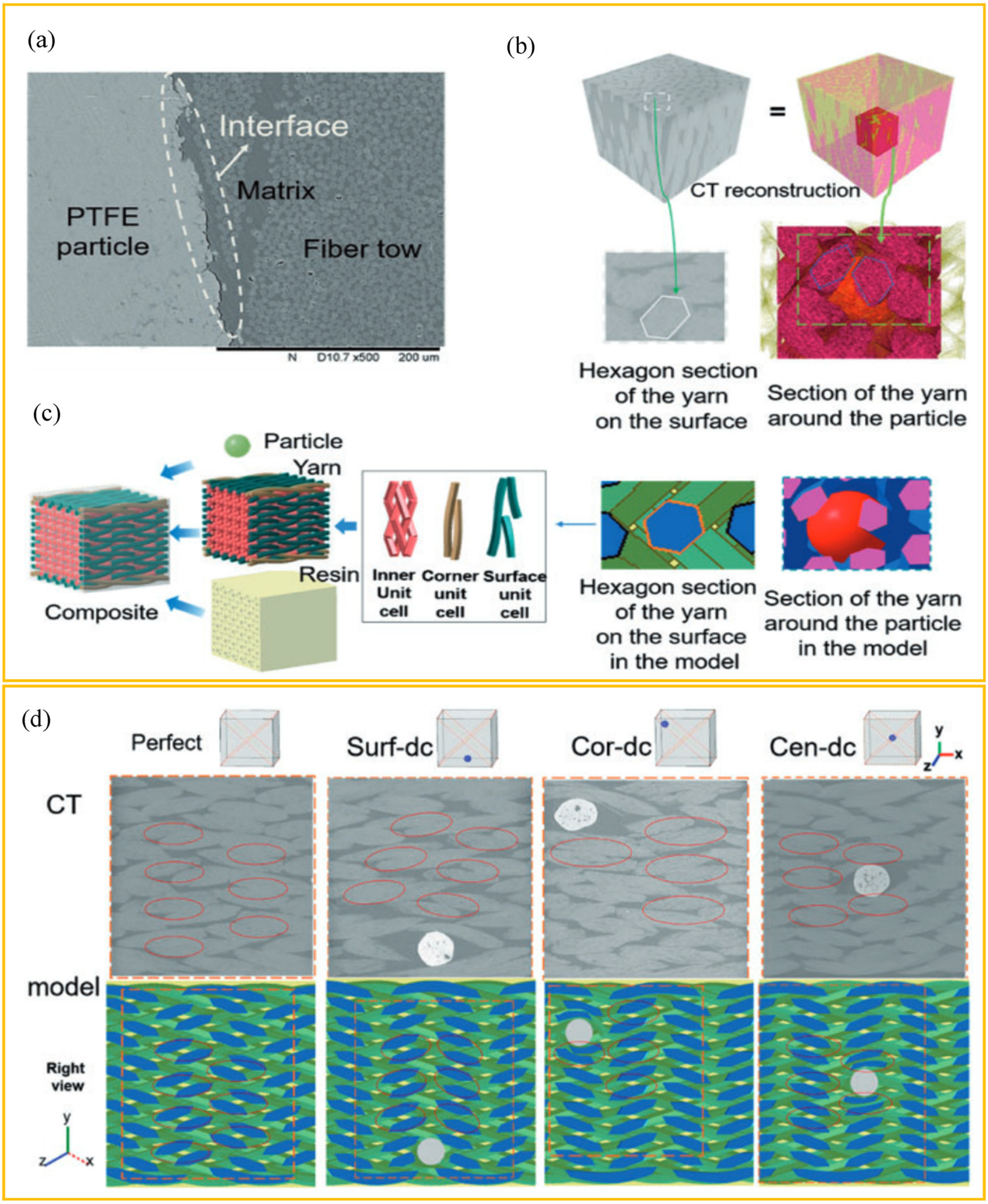

Figure 17: Modeling of 3D braided composites with embedded defects: (a) scanning electron microscopy observation of the interface between 3DMBCs particles and matrix in 3D braided composites; (b) 3D micro-CT reconstruction of Cen-dc to observe the shape of the yarns; (c) geometrical model of 3D braided composites with defects; (d) comparison of the geometrical model and cross-section photographs from micro-CT images between the cross-section photographs of the test samples. (The cross-sectional view is of the composite at the 1/2 particle cross-section.) Surf-dc, surface defective composite; Cor-dc, corner defective composite; and Cen-dc center defective composite [79].

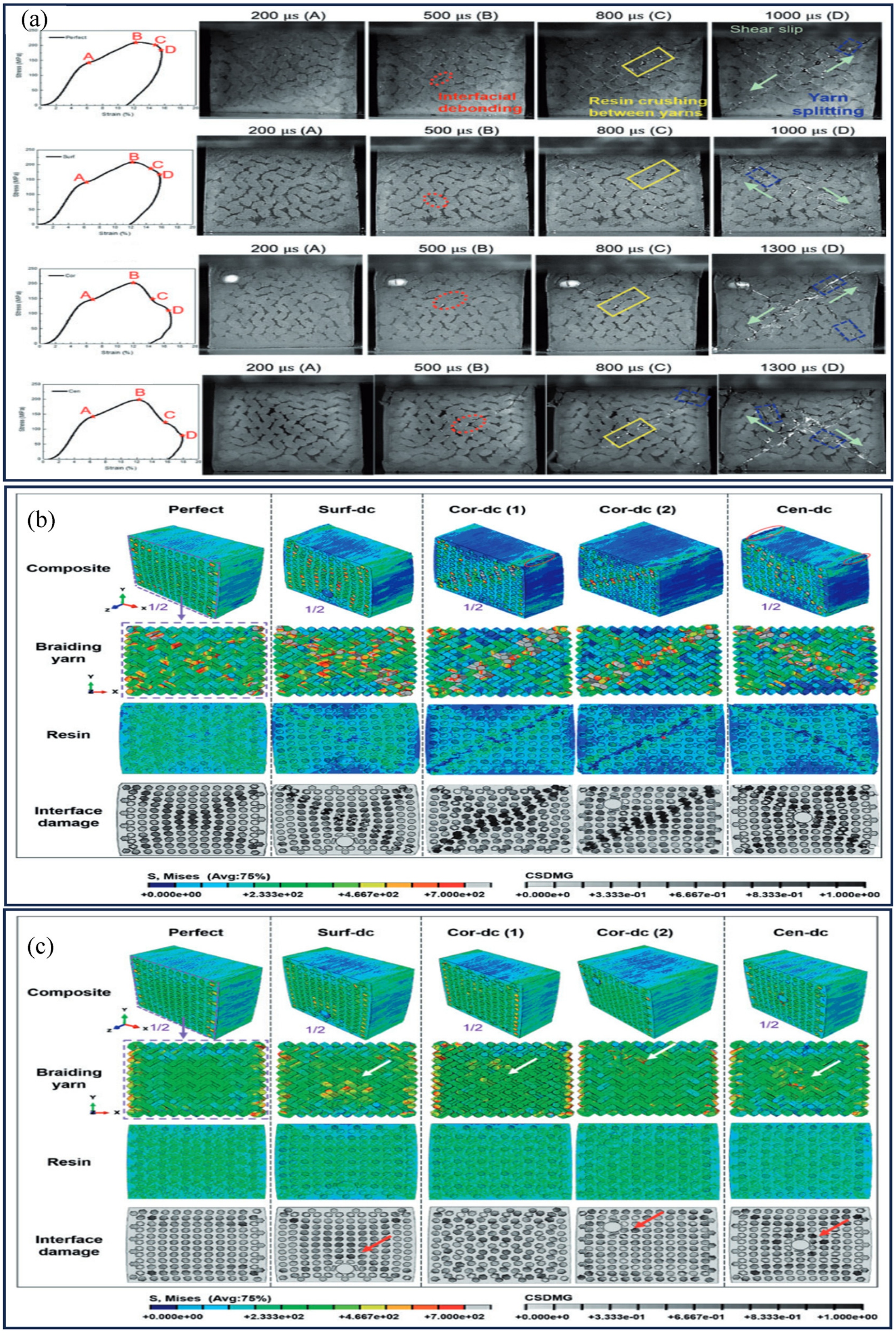

Figure 18: Failure evolution, stress distribution, and interfacial damage of composites containing defects at different locations under low-velocity impacts. (a) Failure evolutions of composites under low-velocity impact compression: perfect composite, Surf-dc, Cor-dc, and Cen-dc. (b) Stress distribution and interfacial damage of the composite and its components at the peak stress point (point B); and (c) the stress distribution and interfacial failure of the composite and its components at the point of maximum deformation (point D) [79].

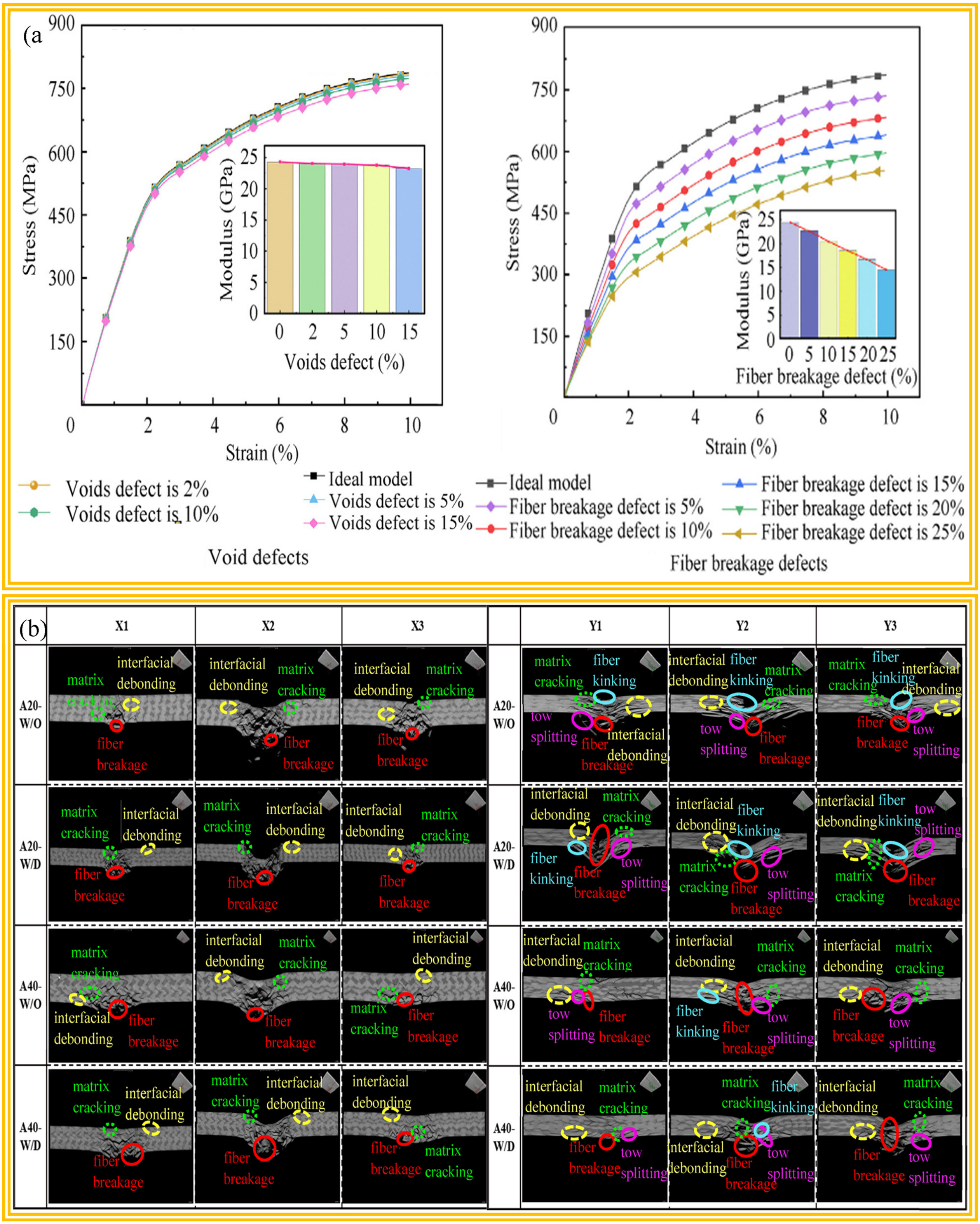

Figure 19: Internal damage morphology of four samples (a) along the *X* direction and along the *y* direction [82]; and (b) numerical simulation results of RUC with different fiber breakage defect contents [37].

defects and their relationship with material properties for formulating effective defect repair and prevention strategies. These research results can not only improve the overall quality of 3D braided composites but also provide powerful guidance for material engineers and designers so that they can make better use of the excellent properties of these materials.

Guo *et al.* [78] investigate the influence of defect size at different locations on the compressive behavior of 3D braided composites, embedded polytetrafluoroethylene (PTFE) particles to form defects, conducted low-velocity impact compression tests, and analyzed the results using high-speed photography and micro-CT. The results show that the increase of defect size will lead to the decrease of compressive strength and the deterioration of damage. Compared with the surface area, the defect will have a greater size effect in the central area. There is stress concentration around the defect, and the change of stress is positively related to the size of the defect. The stress change in the shear zone caused by defects is considered to be the main reason for the decrease of tensile strength. Guo *et al.* [79] placed PTFE particles at different locations and modeled the material morphology obtained using scanning electron microscopy and micro-CT, as shown in Figure 17(a)–(c). By comparing the perfect sample with the defective sample, as depicted in Figure 17(d), they investigated the influence of defect location on the transverse compression behavior of the material under low-velocity impact. It was found that defects in the corner and center regions have a more significant effect on the compressive behavior of 3D woven composites than defects in the bottom position, leading to a reduction in the peak stress of the material and an increase in damage deformation. Defects also lead to localized stress concentrations in the surrounding yarns, as shown in Figure 18.

Zeng *et al.* [80] proposed a simplified model of 3D braided composites containing transverse and longitudinal cracks and used the homogenization theorem to calculate the effective Young's modulus and Poisson's ratio of the material to predict its mechanical properties. The calculation results show that the braiding angle and the composition of braided composites largely determine the degree of reduction of Young's modulus and Poisson's ratio caused by transverse and longitudinal cracks. Liang *et al.* [81] performed theoretical calculations on the thermal expansion coefficient of 3D braided composites with oriented matrix microcracks and analyzed the effect of microcrack density on the thermal expansion coefficient. The experiments showed that the presence of micro-defects such as microcracks greatly affects the properties of the material, causing a reduction in both the stiffness and thermal expansion coefficient of the composites. Sun *et al.* [82] used micro-CT technology to investigate the influence of braiding defects and braiding angles on the behavior and failure mechanisms of 3D braided carbon/epoxy composites under low-velocity impact conditions. The results showed that structural defects significantly affect the impact mechanical properties of 3D braided composites. Materials with yarn missing defects have lower loads and smaller deformations than defect-free specimens, as shown in Figure 19(a). Lei *et al.* [37] numerically investigated the effect of defects on the compressive properties and failure mechanisms of 3DMBCs fabricated by a novel five-step braiding process in different directions. The results showed that one of the main defects produced during the fabrication of 3DMBCs is fiber breakage, and a defect containing 25% fiber breakage decreases the compressive modulus of the composites by 40%, as shown in Figure 19(b).

It can be seen that it is an effective method to simulate the influence of impurity defects on the mechanical properties of 3D braided composites by embedding PTFE particles. It is found that the position and size of impurity defects have different effects on the compression and tensile properties of materials. However, crack defects will lead to the attenuation of elastic properties and thermal expansion coefficient of materials, yarn loss (structural defects) will have a serious impact on the impact mechanical properties of materials, and fiber fracture will lead to the reduction of compression modulus. However, in generally, the research on other defects of 3D braided composites is still insufficient. In order to promote the overall development and application of 3D braided composites, the research on other defects needs to be further deepened.

7 Conclusion and prospect

3D braided composites have excellent mechanical properties and shape adaptability due to their unique fiber mesh interlocked structure, and they are widely used in many fields. Defects, as an important factor affecting the performance of practical applications, restrict the further development of 3D braided composites. Numerous scholars have conducted extensive research on defects in 3D braided composites and have achieved fruitful results. This article provides a comprehensive review of the research progress on various aspects of defects in 3D braided composites, including the relationship between the molding process and defect formation, nondestructive testing methods for defects, and the effects of yarn deformation, void, and other defects. This review aims to summarize and systematize the relatively scattered research findings, forming a comprehensive knowledge system of defects in 3D braided composites, in order to provide some assistance for future research in related fields.

1) The stage from resin flow behavior in the mold to final curing is critical for void generation. Air entrainment, capillary pressure, resin flow behavior, and auxiliary processes used during this stage can all influence void formation. To reduce void defects, it is necessary to optimize and improve relevant parameters using methods such as visualization analysis and numerical simulation. Regarding nondestructive testing methods, existing techniques like ultrasonic testing, CT scanning, and magnetic flux leakage imaging each have their advantages and disadvantages in defect detection. At the same time, for nondestructive testing methods, it is necessary to select appropriate testing systems and operating parameters in combination with actual application needs to ensure accurate results while minimizing costs. To meet the increasing demands for 3D braided composites, future research should focus on developing real-time monitoring and control systems with higher precision. Using low-viscosity, high-flow resins is essential for controlling and minimizing defect generation. Additionally, nondestructive testing techniques should evolve toward intelligence, automation, and multimodality to enhance the accuracy and comprehensiveness of defect identification.
2) It is of great significance to study the deformation defects of yarns in 3D braided composites for the optimization of overall properties. Yarn orientation change and cross-section deformation caused by external pressure and mutual extrusion during the braiding process will directly affect the mechanical properties of the material. When establishing the simulation model, how to be closer to the real structure inside the material is a problem that researchers need to consider. Therefore, it is an inevitable trend to combine microscopic XCT scanning with deep learning algorithms to carry out imaging and characterization of material microstructure and statistical analysis of characteristic parameters, so as to solve the problem that it is difficult to introduce real microstructure characteristics changes into the calculation model. This enables more efficient and accurate prediction of yarn deformation behavior and reduces the impact of yarn deformation defects on material properties.
3) As one of the most common defects, void can lead to varying degrees of degradation in elastic properties, tensile properties, compressive properties, and effective thermal conductivity. It can also increase material damage, particularly by significantly accelerating yarn longitudinal damage propagation. However, it is worth noting that Poisson's ratio does not decrease with increasing porosity, and a moderate amount of porosity can even improve the ductility of the material. The influence of void defects on 3D braided composites is related to the characteristic parameters, but it usually seems that the porosity has the greatest influence, and the void defects in yarns have a greater influence on the elastic properties than those in the matrix. However, most of the existing research studies are focused on the elastic properties of 3D braided composites due to void defects, but few studies have been made on tensile, compressive, and thermal conductivity properties, and the research on other types of defects (impurities, cracks, fiber breakage, *etc.*) is still insufficient. In the future, numerical simulation, theoretical, and experimental verification can be combined to further quantify the influence of different types of defects on the strength, stiffness, and fatigue life of materials and provide scientific basis for designing more durable and reliable 3D braided composites. The development of efficient techniques for repairing void defects is also crucial for material usage and cost reduction.

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References

[1] Zhang, W. and J. Xu. Advanced lightweight materials for Automobiles: A review. *Materials & Design*, Vol. 221, 2022, id. 110994.

[2] Tiwary, A., R. Kumar, and J. S. Chohan. A review on characteristics of composite and advanced materials used for aerospace applications. *Materials Today: Proceedings*, Vol. 51, 2022, pp. 865–870.

[3] Senthil, K., A. Arockiarajan, R. Palaninathan, B. Santhosh, and K. M. Usha. Defects in composite structures: Its effects and prediction methods A comprehensive review. *Composite Structures*, Vol. 106, 2013, pp. 139–149.

[4] Zhang, C., J. L. Curiel-Sosa, and T. Q. Bui. A novel interface constitutive model for prediction of stiffness and strength in 3D braided composites. *Composite Structures*, Vol. 163, 2017, pp. 32–43.

[5] Bilisik, K. Three-dimensional braiding for composites: A review. *Textile Research Journal*, Vol. 83, No. 13, 2013, pp. 1414–1436.

[6] Wielhorski, Y., A. Mendoza, M. Rubino, and R. Stephane. Numerical modeling of 3D woven composite reinforcements: A review. *Composites Part A: Applied Science and Manufacturing*, Vol. 154, 2022, id. 106129.

[7] Huang, T., Y. L. Wang, and G. Wang. Review of the mechanical properties of a 3D woven composite and its applications. *Polymer-Plastics Technology and Engineering*, Vol. 57, No. 8, 2018, pp. 740–756.

[8] Li, D. S., Z. X. Lu, and J. L. Li. Microstructure and mechanical properties of three-dimensional five-directional braided composites. *International Journal of Solids and Structures*, Vol. 46, No. 18–19, 2009, pp. 3422–3432.

[9] Yang, J. M., C. L. Ma, and T. W. Chou. Fiber inclination model of three-dimensional textile structural composites. *Journal of Composite Materials*, Vol. 20, No. 5, 1986, pp. 472–484.

[10] Chen, L., X. M. Tao, and C. L. Choy. Mechanical analysis of 3-D braided composites by the finite multiphase element method. *Composites Science and Technology*, Vol. 59, 1999, pp. 2383–2391.

[11] Fu, Y. T., X. F. Yao, and X. H. Gao. Micro-mesoscopic prediction of void defect in 3D braided composites. *Composites Part A: Applied Science and Manufacturing*, Vol. 147, 2021, id. 106450.

[12] Dong, J. W. and N. F. Huo. A two-scale method for predicting the mechanical properties of 3D braided composites with internal defects. *Composite Structures*, Vol. 152, 2016, pp. 1–10.

[13] Ya, J. X., Z. G. Liu, and Y. H. Wang. Micro-CT characterization on the meso-structure of three-dimensional full five-directional braided composite. *Applied Composite Materials*, Vol. 24, No. 3, 2017, pp. 593–610.

[14] Wu, X. Q. and Q. W. Guo. Void morphology in 3-D braided preform/phenolic composites. *Journal of Donghua University*, Vol. 26, No. 5, 2009, pp. 539–543.

[15] Ge, L., H. M. Li, J. H. Zhong, C. Zhang, and D. N. Fang. Micro-CT based trans-scale damage analysis of 3D braided composites with pore defects. *Composites Science and Technology*, Vol. 211, 2021, id. 108830.

[16] Ruiz, E., V. Achim, S. Soukane, F. Trochu, and J. Bréard. Optimization of injection flow rate to minimize micro/macro-voids formation in resin transfer molded composites. *Composites Science and Technology*, Vol. 66, No. 3–4, 2006, pp. 475–486.

[17] Jeffrey, M. L., N. Valentin, and G. A. Suresh. Modeling the impact of capillary pressure and air entrapment on fiber tow saturation during resin infusion in LCM. *Composites Part A: Applied Science and Manufacturing*, Vol. 40, No. 8, 2009, pp. 1053–1064.

[18] Patel, N. and L. J. Lee. Effects of fiber mat architecture on void formation and removal in liquid composite molding. *Polymer Composites*, Vol. 16, No. 5, 1995, pp. 386–399.

[19] Patel, N. and L. J. Lee. Modeling of void formation and removal in liquid composite molding. Part II: Model development and implementation. *Polymer Composites*, Vol. 17, No. 1, 1996, pp. 104–114.

[20] Qu, Y. L., N. Ning, and S. Z. Zhan. 3D braided composites testing based on multi-frequency ultrasonic comprehensive comparison method. *Non-Destructive Testing*, Vol. 45, No. 6, 2023, pp. 71–74.

[21] Xiao, Z. T., Y. M. Guo, L. Geng, J. Wu, F. Zhang, W. Wang, et al. Analysis of internal defects in 3D braided composites based on ultrasonic C-scan technique. *Insight - Non-Destructive Testing and Condition Monitoring*, Vol. 62, No. 6, 2020, pp. 323–330.

[22] Tian, G., W. Zhang, G. F. Jin, Z. W. Yang, and Y. J. Song. Numerical simulation of multi-mode excitation of ultrasonic infrared thermal wave detection. *Journal of Jiangsu University (Natural Science Edition)*, Vol. 35, No. 2, 2014, pp. 171–175.

[23] Morbidini, M. and P. Cawley. A calibration procedure for sonic infrared nondestructive evaluation. *Journal of Applied Physics*, Vol. 106, No. 2, 2009, id. 023504.

[24] Wan, Z. K. and Z. G. Wang. Research on flaw detection for composite material using ultrasonic testing based on neural network. *Journal of Textile*, Vol. 31, No. 2, 2010, pp. 54–59.

[25] Guo, Y. M., Z. T. Xiao, L. Geng, J. Wu, F. Zhang, Y. B. Liu, et al. Fully convolutional neural network with GRU for 3D braided composite material flaw detection. *IEEE Access*, Vol. 7, 2019, pp. 151180–151188.

[26] Guo, Y. M., Z. T. Xiao, and L. Geng. Defect detection of 3D braided composites based on semantic segmentation. *The Journal of The Textile Institute*, Vol. 114, No. 4, 2023, pp. 574–583.

[27] Wan, Z. K. and M. R. Jia. Flux image-based internal defect detection for flat test pieces of three-dimensional braided composites. *Journal of Textile*, Vol. 36, No. 8, 2015, pp. 49–55.

[28] Wang, Z. G., S. Y. Zhang, Z. K. Wan, and M. L. Zhang. Analysis of non-destructive testing of three-dimensional braided composites based on SQUID. *Nondestructive Testing and Evaluation*, Vol. 32, No. 1, 2017, pp. 21–35.

[29] Feng, Y. J., Z. D. Feng, S. W. Li, W. H. Zhang, X. G. Luan, Y. S. Liu, et al. Micro-CT characterization on porosity structure of 3D C_f/SiC_m composite. *Composites Part A: Applied Science and Manufacturing*, Vol. 42, No. 11, 2011, pp. 1645–1650.

[30] Qian, Q. W., X. Zhang, Z. J. Yang, Z. Shen, and J. Y. Jiao. Intelligent identification of micro components and defects of 3D braided C/C composites based on deep learning of X-ray CT images. *Acta Materiae Compositae Sinica*, Vol. 41, No. 7, 2014, pp. 1–8.

[31] Gao, Y. T., Y. D. Wang, X. M. Yang, M. Liu, H. H. Xiao, P. Huai, et al. Synchrotron X-ray tomographic characterization of CVI engineered 2D-woven and 3D-braided SiC_f/SiC composites. *Ceramics International*, Vol. 42, No. 15, 2016, pp. 17137–17147.

[32] Zhou, W., R. Qin, K. N. Han, Z. Y. Wei, and L. H. Ma. Progressive damage visualization and tensile failure analysis of three-

dimensional braided composites by acoustic emission and micro-CT. *Polymer Testing*, Vol. 93, 2021, id. 106881.
[33] Wan, L., Y. J. Ma, and J. D. Li. Measurement and error estimation of internal defects for three-dimensional braided composites based on carbon nanotube thread sensor. *Synthetic Materials Aging and Application*, Vol. 44, No. 1, 2015, pp. 88–95.
[34] Wan, L., Y. J. Ma, and J. D. Li. The research on internal defect detection of 3D braided composite materials based carbon nanotube thread. *Industrial Textiles*, Vol. 33, No. 11, 2015, pp. 36–42.
[35] Wan, Z. K. and G. L. Ying. The data anomaly diagnosis research of three-dimensional braided composite material based on structural health monitoring system. *Material Guide B: Research Articles*, Vol. 27, No. 20, 2013, pp. 74–77+89.
[36] Jia, M. R. *Research on optimal configuration of 3D braided composite health monitoring sensors*, Tianjin University of Technology, Tianjin, 2022.
[37] Lei, R. X., H. Dou, Y. Sun, T. Liu, W. Fan, C. Y. Song, et al. A novel numerical simulation method for predicting compressive properties of 3D multiaxial braided composites considering various defects. *Chinese Journal of Aeronautics*, Vol. 36, No. 9, 2023, pp. 369–379.
[38] Shen, X. L., X. Liu, S. J. Dong, and L. D. Gong. RVE model with shape and position defects for predicting mechanical properties of 3D braided CVI-SiC_f/SiC composites. *Composite Structures*, Vol. 195, 2018, pp. 325–334.
[39] Li, D. S., J. L. Li, L. Chen, Z. Xing, and D. N. Fang. Finite element analysis of mechanical properties of 3D four-directional rectangular braided composites part 1: Microgeometry and 3D finite element model. *Applied Composite Materials*, Vol. 17, No. 4, 2010, pp. 373–387.
[40] Zhang, D. T., Y. Sun, X. M. Wang, and C. Li. Meso-scale finite element analyses of three-dimensional five-directional braided composites subjected to uniaxial and biaxial loading. *Journal of Reinforced Plastics and Composites*, Vol. 34, No. 24, 2015, pp. 1989–2005.
[41] Huang, H., Z. T. Guo, Z. D. Shan, Z. Sun, J. H. Liu, D. Wang, et al. Prediction of elastic properties of 3D4D rotary braided composites with voids using multi-scale finite element and surrogate models. *Composite Structures*, Vol. 328, 2023, id. 117519.
[42] Liu, T., B. Z. Sun, and B. H. Gu. Size effects on compressive behaviors of three-dimensional braided composites under high strain rates. *Journal of Composite Material*, Vol. 5228, 2018, pp. 3895–3908.
[43] Zhu, Y. L., H. T. Cui, W. D. Wen, Y. Xu, and H. J. Zhang. Microstructure model and stiffness prediction of 3D braided composites considering yarns' cross-section variation material based on structural health monitoring system. *Acta Materiae Compositae Sinica*, Vol. 29, No. 6, 2012, pp. 187–196.
[44] Li, J. L. and Q. Liu. Study on fiber tows' cross-section in 3-D braided composites. *Acta Materiae Compositae Sinica*, Vol. 18, No. 2, 2001, pp. 9–13.
[45] Xu, K. and X. M. Qian. Microstructure analysis and multi-unit cell model of three dimensionally four-directional braided composites. *Applied Composite Materials*, Vol. 22, No. 1, 2015, pp. 29–50.
[46] Zhang, C. and X. W. Xu. Finite element analysis of 3D braided composites based on three unit-cells models. *Composite Structures*, Vol. 98, 2013, pp. 130–142.
[47] Wang, W. Q., Q. Liu, D. Y. Hu, L. Zhang, and X. L. Shen. Improved unit cell model and elastic constant prediction method of 3D four-directional braided composites material based on structural health monitoring system. *Acta Materiae Compositae Sinica*, Vol. 34, No. 9, 2017, pp. 1973–1981.
[48] Jiang, L. L., T. Zeng, S. Ya, D. N. Fang, and Y. Gu. Predicting mechanical properties of 3D braided composites using a helix geometry model. *Polymers and Polymer Composites*, Vol. 19, No. 4-5, 2011, pp. 397–400.
[49] Yushanov, S. P. and A. E. Bogdanovich. Stochastic theory of composite materials with random waviness of the reinforcements. *International Journal of Solids and Structures*, Vol. 35, No. 22, 1998, pp. 2901–2930.
[50] Yushanov, S. P. and A. E. Bogdanovich. Fiber waviness in textile composites and its stochastic modeling. *Mechanics of Composite Materials*, Vol. 36, No. 4, 2000, pp. 297–318.
[51] Fang, G. D., J. Liang, Y. Wang, and B. L. Wang. The effect of yarn distortion on the mechanical properties of 3D four-directional braided composites. *Composites Part A: Applied Science and Manufacturing*, Vol. 40, No. 4, 2009, pp. 343–350.
[52] Zhai, J. J., X. X. Kong, L. C. Wang, S. Yan, L. L. Jiang, and Z. W. Cai. Nonlinear mechanical property of 3D braided composites with multi-types micro-distortion: A quantitative evaluation. *Polymers*, Vol. 15, No. 6, 2023, id. 1428.
[53] Kang, H., Z. D. Shan, Y. Zang, and F. Liu. Effect of yarn distortion on the mechanical properties of fiber-bar composites reinforced by three-dimensional weaving. *Applied Composite Materials*, Vol. 23, No. 2, 2016, pp. 119–138.
[54] Zhang, Y. Y., H. M. Li, X. Liu, Y. H. Chen, C. W. Qin, and D. N. Fang. Prediction of mechanical properties of 3D tubular braided composites at different temperatures using a multi-scale modeling framework based on micro-CT. *Composites Science and Technology*, Vol. 245, 2024, id. 110349.
[55] Yang, Z. X., M. Zhang, A. Li, and C. Zhang. Off-axis tensile mechanical properties of 3D five-directional braided composites with void defects material based on structural health monitoring system. *Journal of Beijing University of Aeronautics and Astronautics*, Vol. 48, No. 4, 2022, pp. 569–577.
[56] Lu, Z. X., B. Xiao, and Z. Y. Yang. Investigation on the tensile properties of three-dimensional full five-directional braided composites. *Computational Materials Science*, Vol. 77, 2013, pp. 445–455.
[57] Gong, J. J., Z. Q. Yang, R. Z. Huang, J. Zhou, and Y. Z. Liu. An effective multiscale analysis for the mechanical properties of 3D braided composites considering pore defects. *Acta Mechanica*, Vol. 234, No. 12, 2023, pp. 6629–6647.
[58] Shi, D. Q., H. W. Niu, X. Jing, X. G. Zhou, and X. G. Yang. Prediction method of elastic constants of 3-D braided ceramic matrix composites considering pores. *Journal of Aerodynamics*, Vol. 29, No. 12, 2014, pp. 2891–2897.
[59] Gao, X. H., L. Yuan, Y. T. Fu, X. F. Yao, and H. Yang. Prediction of mechanical properties on 3D braided composites with void defects. *Composites Part B: Engineering*, Vol. 197, 2020, id. 108164.
[60] Wang, Z. Q., Q. Yuan, X. X. Wang, and D. T. Zhang. Real meso-scale model reconstruction and tensile failure prediction of 3D braided PIP-SiC_f/SiC composites considering pore defects. *Composite Structures*, Vol. 305, 2023, id. 116478.
[61] Dong, J. W. and Y. H. Gong. Influence of void defects on progressive tensile damage of three-dimensional braided composites. *Journal of Composite Materials*, Vol. 52, No. 15, 2018, pp. 2033–2045.
[62] Ge, L., H. M. Li, H. Y. Zheng, C. Zhang, and D. N. Fang. Two-scale damage failure analysis of 3D braided composites considering pore defects. *Composite Structures*, Vol. 260, 2021, id. 113556.

[63] Xu, K. and X. M. Qian. Effect of random void defects on the mechanical properties of 3D braided composites. *Journal of Solid Mechanics*, Vol. 34, No. 4, 2013, pp. 396–400.
[64] Song, X. Y., J. Zhou, D. Zhang, S. H. Zhang, P. Li, L. T. Bai, et al. Trans-scale analysis of 3D braided composites with voids based on micro-CT imaging and unsupervised machine learning. *Composites Science and Technology*, Vol. 249, 2024, id. 110494.
[65] Ge, L., H. M. Li, Y. Y. Zhang, J. H. Zhong, Y. Chen, and D. N. Fang. Multiscale viscoelastic behavior of 3D braided composites with pore defects. *Composites Science and Technology*, Vol. 217, 2022, pp. 109–114.
[66] Xu, K. and X. M. Qian. An FEM analysis with consideration of random void defects for predicting the mechanical properties of 3D braided composites. *Advances in Materials Science and Engineering*, Vol. 2014, 2014, pp. 1–12.
[67] Ge, L., H. M. Li, Y. H. Gao, R. S. Lou, K. Liu, J. H. Zhong, et al. Parametric analyses on multiscale elastic behavior of 3D braided composites with pore defects. *Composite Structures*, Vol. 287, 2022, id. 115332.
[68] Ge, L., H. M. Lia, B. S. Liu, and D. N. Fang. Multi-scale elastic property prediction of 3D five-directional braided composites considering pore defects. *Composite Structures*, Vol. 244, 2020, id. 112287.
[69] Wei, K. L., H. B. Shi, J. Li, and M. Tang. Effect of porosity on effective elastic properties of three-dimensional woven C/C composites. *Journal of Materials Science and Engineering*, Vol. 39, No. 2, pp. 186–192.
[70] Zhang, H., C. Li, L. Liu, and G. L. Gong. Multi-scale mechanical properties analysis of three-dimensional four-direction braided composites considering pore defects based on improved three-cell model. *Composites Science and Engineering*, Vol. 2, 2023, pp. 14–23.
[71] Qi, Z. W., D. Y. Hu, L. Zhang, Y. Q. Zeng, and R. Q. Wang. Two-scale analysis for mechanical properties of 3D four directional braided composites with pore defects. *Advancing Technology*, Vol. 39, No. 8, 2018, pp. 1873–1879.
[72] Dong, J. W. and P. J. Chen. A double scale analysis for mechanical properties of 3D braided composites with defects. *Chinese Mechanics Society*, 2016, id. 118.
[73] Zhang, Y. Y., H. M. Li, X. Li, Y. H. Gao, and C. Y. Guan. Trans-scale elastic–plastic damage analysis of 3D tubular braided composites with void defects. *International Journal of Solids and Structures*, Vol. 274, 2023, id. 112288.
[74] Liu, T., X. Y. Wu, B. Z. Sun, W. Fan, W. L. Han, and H. L. Yi. Investigations of defect effect on dynamic compressive failure of 3D circular braided composite tubes with numerical simulation method. *Thin-Walled Structures*, Vol. 160, 2021, id. 107381.
[75] Liu, T., W. Fan, and X. Y. Wu. Comparisons of influence of random defects on the impact compressive behavior of three different textile structural composites. *Materials & Design*, Vol. 181, 2019, id. 108073.
[76] Wei, K. L., J. Li, H. B. Shi, and M. Tang. Two-scale prediction of effective thermal conductivity of 3D braided C/C composites considering void defects by asymptotic homogenization method. *Applied Composite Materials*, Vol. 26, No. 5, 2019, pp. 1367–1387.
[77] Wang, J., Y. S. Chen, Y. J. Feng, G. Zhao, X. G. Jian, Q. Huang, et al. Influence of porosity on anisotropic thermal conductivity of SiC fiber reinforced SiC matrix composite: A microscopic modeling study. *Ceramics International*, Vol. 46, No. 18, 2020, pp. 28693–28700.
[78] Guo, J. H., W. N. Ke, Y. Y. Wu, B. H. Gu, and B. Z. Sun. Effects of defect sizes at different locations on compressive behaviors of 3D braided composites. *Thin-Walled Structures*, Vol. 179, 2022, id. 109563.
[79] Guo, J. H., B. Z. Sun, B. H. Gu, and W. Zhang. Failure behaviors of 3D braided composites with defects in different locations under low-velocity impact compression. *Textile Research Journal*, Vol. 92, No. 1–2, 2022, pp. 196–209.
[80] Zeng, T., D. N. Fang, L. C. Guo, and L. Ma. A mechanical model of 3D braided composites with transverse and longitudinal cracks. *Composite Structures*, Vol. 39, No. 1, 2005, pp. 117–125.
[81] Liang, J., S. Y. Du, J. C. Han, L. Y. Liu, and J. Wan. Thermal expansion coefficients of three-dimension woven composites with matrix microcracks. *Astronautical Journal*, Vol. 19, No. 1, 1998, pp. 91–94.
[82] Sun, M., X. D. Liu, D. T. Zhang, J. Sun, and K. Qian. Effects of structural defects on low-velocity impact damage mechanisms of three-dimensional braided composites based on X-ray micro-computed tomography. *Polymer Testing*, Vol. 104, 2021, id. 10743.