

Research Article

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The effect of temperature on the tensile properties and failure mechanisms of two-dimensional braided composites

<https://doi.org/10.1515/secm-2022-0191>

received November 10, 2022; accepted February 22, 2023

Abstract: Two-dimensional (2D) braided composites have excellent structural integrity and damage tolerance. Currently, there are few researches focused on the effect of temperature on tensile failure behaviors of 2D braided composites. In this study, 2D biaxial braided composites with different fiber materials were prepared, and the tensile properties and failure mechanisms of these braided composites at different temperatures were studied by means of the tensile test and the high-definition charge coupled device optical microscope. The results show that temperature has significant effects on the tensile properties and fracture damage of 2D braided composites. As the temperature increases, the tensile properties of the two braided composites decrease obviously, and their external fracture failure becomes subtle, while their internal deformation damage becomes significant. Moreover, the differences between the two fibers in tensile fracture behaviors of composites can be more conspicuously observed at higher temperatures.

Keywords: 2D biaxial braided composites, hybrid composites, temperature, mechanical properties, failure mechanisms

1 Introduction

Fiber-reinforced composites have the characteristics of high specific strength, high specific modulus, impact resistance, fatigue resistance, corrosion resistance, aging resistance, lightweight, and so on. Two-dimensional (2D)

braided composites are composites made of 2D braided preform reinforcements and resin matrix through the molding process, and the composites have attracted public attention because of their excellent structural integrity and damage tolerance. With the development of the composite materials industry, 2D braided composites, as important structural materials, have gradually been widely used in aerospace, transportation manufacturing, industrial engineering, sports equipment, biomedicine, and other fields [1].

Currently, scholars have conducted a large number of studies on the structures and mechanical properties of 2D braided composites, and most of them focus on 2D triaxial braided composites. These studies include tensile properties, compressive properties, bending properties, shear properties, torsional properties, elastic properties, and impact properties [2–18]. At the same time, Li et al. studied the high-temperature tensile properties and failure mechanisms of 3D six-directional braided composites, while Zuo et al. studied the transverse bending fatigue behaviors and failure mechanisms of 3D five-directional braided composites at different temperatures [19,20]. In addition, scholars' studies on the theoretical modeling of braided composites are also helpful to analyze and verify the structures and mechanical properties of braided composites. Dell'Isola et al. selected an effective nonlinear model to study the microstructures, displacements, deformations, and damage behaviors of “scaled structure” metamaterials [21,22]. Tornabene et al. studied the vibration behaviors of anisogrid composite lattice cylindrical shell structures, as well as the buckling behaviors of the lattice shells under axial compression, transverse bending, pure bending, and torsion [23,24]. So far, there are few reports about the influence of temperature on tensile properties and failure mechanisms of 2D braided composites. In various applications, 2D braided composites are needed to work at complex ambient temperatures, so it is of great significance to study the structures and properties of braided composites at different temperatures.

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2D braided structures can be classified as biaxial braided structure and triaxial braided structure. 2D biaxial braided structures can be classified as diamond braid (1/1 repeat), regular braid (2/2 repeat), and Hercules braid (3/3 repeat) based on the weave pattern. The triaxial braided structure can be made by introducing axial fiber bundles during the manufacturing process of the biaxial braided structure [25–27]. The above mentioned 2D braided structures are shown in Figure 1.

The term “hybrid composite” is generally used to describe materials containing two or more different types of fibers, and hybrid composites mainly include interlayer (or layer-by-layer) hybrid, intralayer (or yarn-by-yarn) hybrid, and intra-yarn (or fiber-by-fiber) hybrid [28,29].

In this article, we aim to analyze the effect of temperature and carbon/glass fiber hybrid braiding on tensile properties and failure mechanisms of 2D braided composites. First, the pure fiber 2D biaxial braided composites and 2D biaxial hybrid braided composites were prepared, and the tensile tests of these materials were carried out at different temperatures. Subsequently, the failure and fracture morphology after failure of the 2D braided composites were observed with the assistance of high-definition charge coupled device (CCD) optical microscope, and the failure mechanisms of the composites were clarified. Furthermore, the effects of temperature and different fibers on tensile properties and damage were analyzed. It is predicted that this article can provide an experimental basis for the design and application of two-dimensional braided composites in future.

2 Materials and samples

The braided preform reinforcements of 2D braided composites are the main bearing parts of the composites when they are subjected to external forces, so the fiber raw materials with high strength and high modulus, low density, and good thermal stability are generally used. The properties of 2D braided composites also depend on the resin selected, the proportion of each component, and the forming process used. This section describes in detail the preparation processes of 2D braided preforms and 2D braided composites, as well as the parameter determination of 2D braided composite samples.

2.1 2D braided preforms preparation

In this article, glass fiber 2D biaxial braid preforms (diamond braid (1/1 repeat) structure) and carbon fiber-glass fiber 2D biaxial hybrid braid preforms were prepared. The carbon fiber and glass fiber are hybrid braided at a ratio of 1:1. The yarn arrangements of the above mentioned two braided preforms are shown in Figure 2.

The carbon fiber used in braiding is T300B-3000-40B carbon fiber multifilament (linear density is 198tex and volume density is 1.76 g/cm^3) produced by Japan Toray Company, and the glass fiber is EDR17-1200-398 alkali-free glass fiber direct yarn (linear density is 1200tex) produced by China Jushi Group. The braiding machine

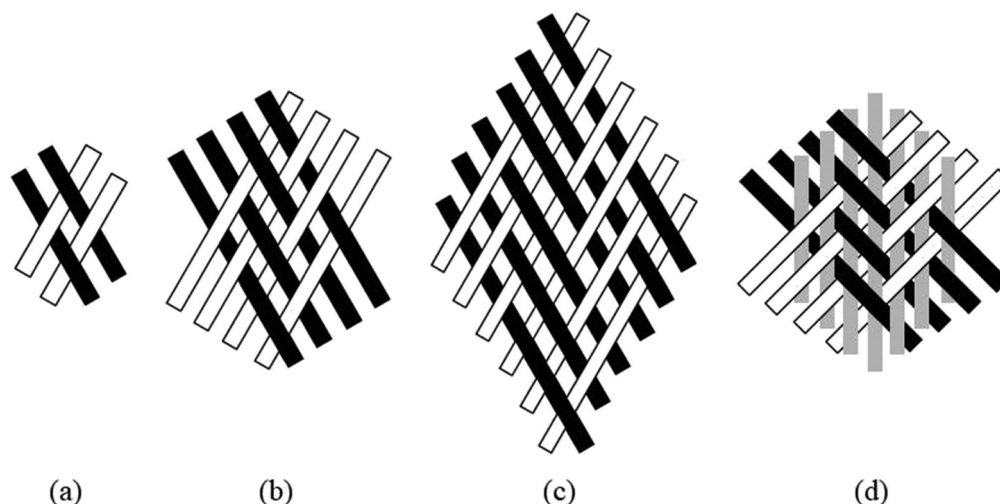


Figure 1: Braiding patterns: (a) diamond biaxial braid (1/1 repeat), (b) regular biaxial braid (2/2 repeat), (c) Hercules biaxial braid (3/3 repeat), and (d) regular triaxial braid (2/2 repeat).

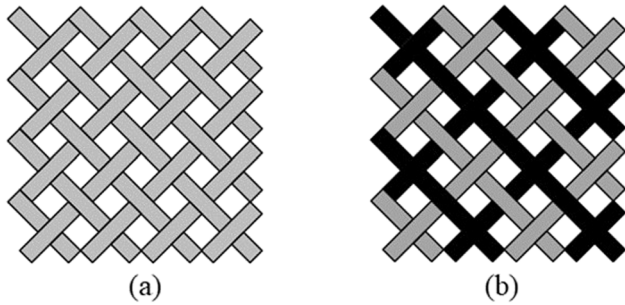


Figure 2: Two yarn arrangements: (a) pure glass fiber and (b) carbon fiber/glass fiber ratio = 1:1. (Black is carbon fiber yarn and gray is glass fiber yarn).

adopts a 32-spindles vertical 2D braiding machine independently constructed, with a braiding angle of 33.9° , as shown in Figure 3.

2.2 2D braided composites preparation

The two kinds of 2D biaxial braided preforms mentioned earlier are used as reinforcements for the 2D braided composites. For testing, the preforms are flattened into the flat type to make plate-type composites.

2D braided composites were prepared according to GB/T 1446-2005 “General Rules for Performance Test Methods of Fiber Reinforced Plastics” and GB/T 2567-2021 “Test Method for Tensile Properties of Fiber Reinforced Plastics” [30,31].

Epoxy resin was selected as the matrix, and two-dimensional braided composites were produced by vacuum-assisted resin transfer molding process, after curing and other processing procedures, the composites

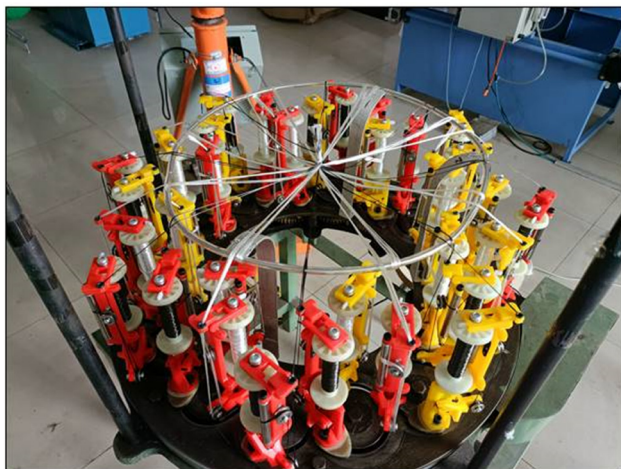


Figure 3: Two-dimensional braiding machine with 32 spindles.

obtained are shown in Figure 4(a). Then, we processed the 2D braided composites into dumbbell-shaped samples with the cutting machine, as shown in Figure 4(b). The sample specifications are summarized in Table 1, and there are six samples of the two kinds of braided composites. GFT1, GFT2, and GFT3, respectively, stand for pure glass fiber braided composites at the test temperature of 25, 45, and 60°C , while CF-GFT1, CF-GFT2, and CF-GFT3, respectively, stand for carbon fiber-glass fiber hybrid braided composites whose test temperatures are 25, 45, and 60°C . The thickness in Table 1 refers to the thickness of the 2D braided composite sample in the direction of cross-section.

3 Experimental procedures

The tensile mechanical properties of 2D braided composites reflect the ability to withstand the tension of the composites under the action of external tensile forces. This section mainly introduces the process of axial tensile test process of 2D braided composites under different temperature conditions, as well as the optical microscope measurement process of surface topography of braided composites after the tensile fracture.

3.1 Tensile test

Sample configurations and test procedures were performed according to the standards of GB/T 1446-2005 “General Rules for Performance Test Methods of Fiber Reinforced Plastics,” GB/T 2567-2021 “Test Method for Tensile Properties of Fiber Reinforced Plastics,” and GB/T 1447-2005 “Test Method for Properties of Resin Castings” [30–32]. Tensile tests were carried out at different temperatures (25, 45, and 60°C) by using XS(08) F2 series electronic fabric strength machine equipped with custom-made tensile fixture. The heating and insulating device was independently built; when the temperature reached the set temperature, heating was stopped and the samples were kept at this temperature for 20 minutes before the tensile test was carried out. Tensile velocity was 2 mm/min, and the load direction was along the axial braiding direction. The database of XS(08) series electronic fabric strength measurement and control system records the tensile time, displacement, load, and other test data in the form of Access file. Figure 5 shows the tensile test procedure.

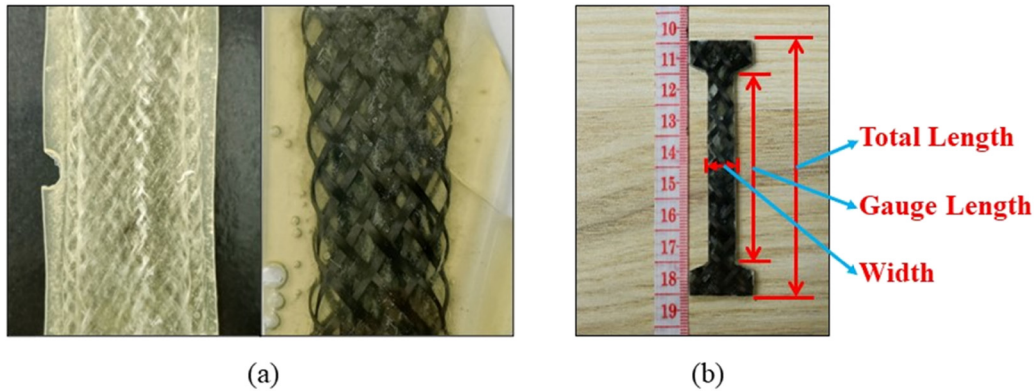


Figure 4: Materials and samples: (a) 2D braided composites and (b) dumbbell-shaped samples.

Table 1: Details of tensile samples

Samples	Braiding angle (°)	Total length (mm)	Gauge length (mm)	Width (mm)	Thickness (mm)	Test temperature (°C)
GFT1	33.9	80.00	60.00	8.08	2.82	25
GFT2	33.9	80.00	60.00	8.56	2.86	45
GFT3	33.9	80.00	60.00	8.44	2.76	60
CF-GFT1	33.9	80.00	60.00	8.62	2.76	25
CF-GFT2	33.9	80.00	60.00	8.48	2.90	45
CF-GFT3	33.9	80.00	60.00	8.74	2.72	60

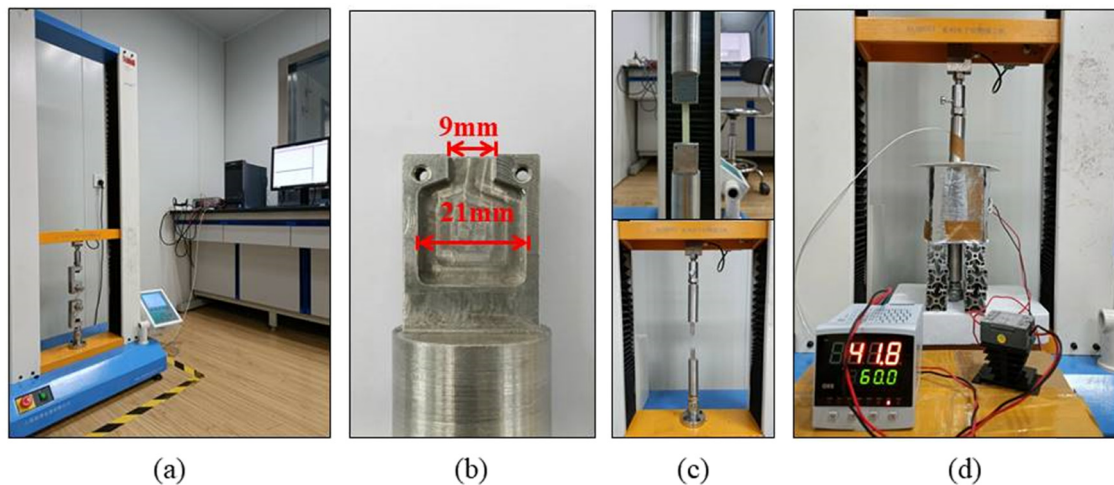


Figure 5: Tensile test procedure: (a) electronic fabric strength machine, (b) tensile fixture, (c) tensile test at room temperature, and (d) tensile test at different temperatures.

3.2 High-definition CCD optical microscope measurement

The surface morphology of the composite specimens after the tensile test was characterized by using the GP-300C high-definition CCD optical measuring microscope at the

condition of 14 million pixels. The lens magnification of the objective lens is 1×, the electronic magnification is 30×, the working distance is 95 mm, and the field of view (length multiplied by width) is 17 mm by 9 mm. Figure 6 shows the characterization process of high-definition CCD optical microscopy.



Figure 6: Characterization by high-definition CCD optical microscopy.

4 Results and discussion

It is beneficial to improve the preparation technology of 2D braided structural composites to study the response forms and damage mechanisms of 2D braided composites under external loads at different temperatures. In this section, the results of tensile tests at each temperature, as well as the tensile fracture morphology and failure mechanisms of 2D braided composites, are discussed and analyzed.

4.1 Tensile test results and analysis

Through the tensile test of 2D biaxial braided composites, the stress–strain relationships of composites were obtained by using the cross-sectional area of each specimen. The mechanical properties of the composites obtained from the stress–strain curves, including elastic modulus, ultimate tensile strength, and strain rate at fracture, are presented in Table 2. Figure 7 shows the stress–strain curves of 2D braided composites at different temperatures. Figure 8 shows the stress–strain curves of the two braided composites at the same temperature. All curves have a relatively consistent trend, showing sudden failures without any visible warning, and there is no clearly defined yield point in the curves. The stress–strain curves of 2D braided composites show nonlinear characteristics before fracture and are similar to a gradual yielding.

From Table 2 and Figure 7, it can be observed that the tensile properties of 2D braided composites decrease with the increase in temperature. For the pure glass fiber

Table 2: Tensile properties of 2D braided composite test specimens

Samples	Ultimate tensile strength (MPa)	Strain rate at fracture (%)	Elastic modulus (MPa)	Test temperature (°C)
GFT1	8.6974	8.0617	124.15181	25
GFT2	5.2701	10.0367	18.07597	45
GFT3	2.2599	10.0867	11.80930	60
CF-GFT1	7.4778	9.0983	93.60919	25
CF-GFT2	4.1629	11.3117	32.60635	45
CF-GFT3	1.2334	9.9400	9.82987	60

braided composites, the ultimate tensile strength and elastic modulus decrease gradually with the increase in temperature, while the strain rates at fracture increase gradually. For the carbon fiber–glass fiber hybrid braided composites, the ultimate tensile strength and elastic modulus decrease gradually with the increase in temperature, while the strain rates at fracture increase first and then decrease. It is a fact that as the temperature increases, the softened matrix will greatly lose its strength and the interfacial adhesion will be weakened, thereby greatly reducing the tensile properties. It is found that temperature is an important parameter affecting the tensile properties of 2D braided composites. The reason is that as the temperature increases, the internal molecular movements of the composites become active and the resins become soft. In addition, the thermal expansion coefficients of fiber and matrix are different, and the increase in temperature will also lead to the weakening of fiber/matrix interface performance. It is also found that as the temperature increases, after the stress of carbon fiber–glass fiber hybrid braided composites reaches its peak, its decline rate becomes slower, and the fracture strain increases. This is because the internal structure is no longer rigid, and the fibers lose their bearing capacity.

From Table 2 and Figure 8, it can be observed that at the same temperature, compared with pure glass fiber braided composites, carbon fiber–glass fiber hybrid braided composites have lower tensile properties, which is the case at 25, 45, and 60°C. At the same temperature, the ultimate tensile strength of pure glass fiber braided composites is higher than that of carbon fiber–glass fiber hybrid braided composites. At 25 and 60°C, the elastic modulus of pure glass fiber braided composites is higher than that of carbon fiber–glass fiber hybrid braided composites; however, at 45°C, the situation is just the opposite. In brief, with the increase of the carbon fiber volume content and the decrease of the glass fiber volume content, the tensile properties of 2D braided composites decreased. The reason is that carbon fiber is a kind of brittle material

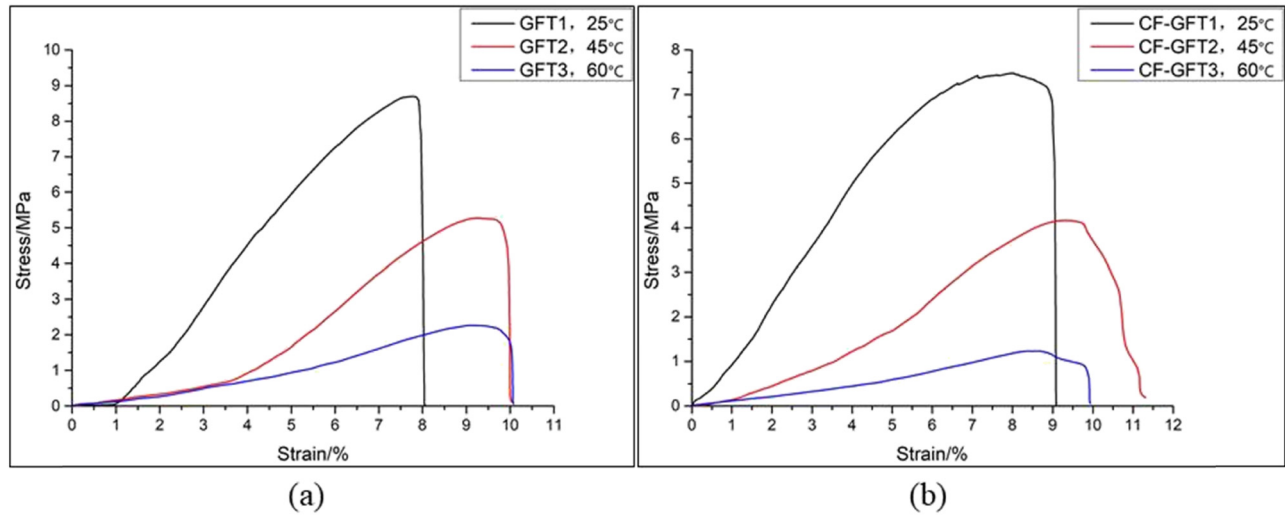


Figure 7: Stress–strain curves of 2D braided composites at different temperatures: (a) pure glass fiber braided composites and (b) carbon fiber-glass fiber hybrid braided composites.

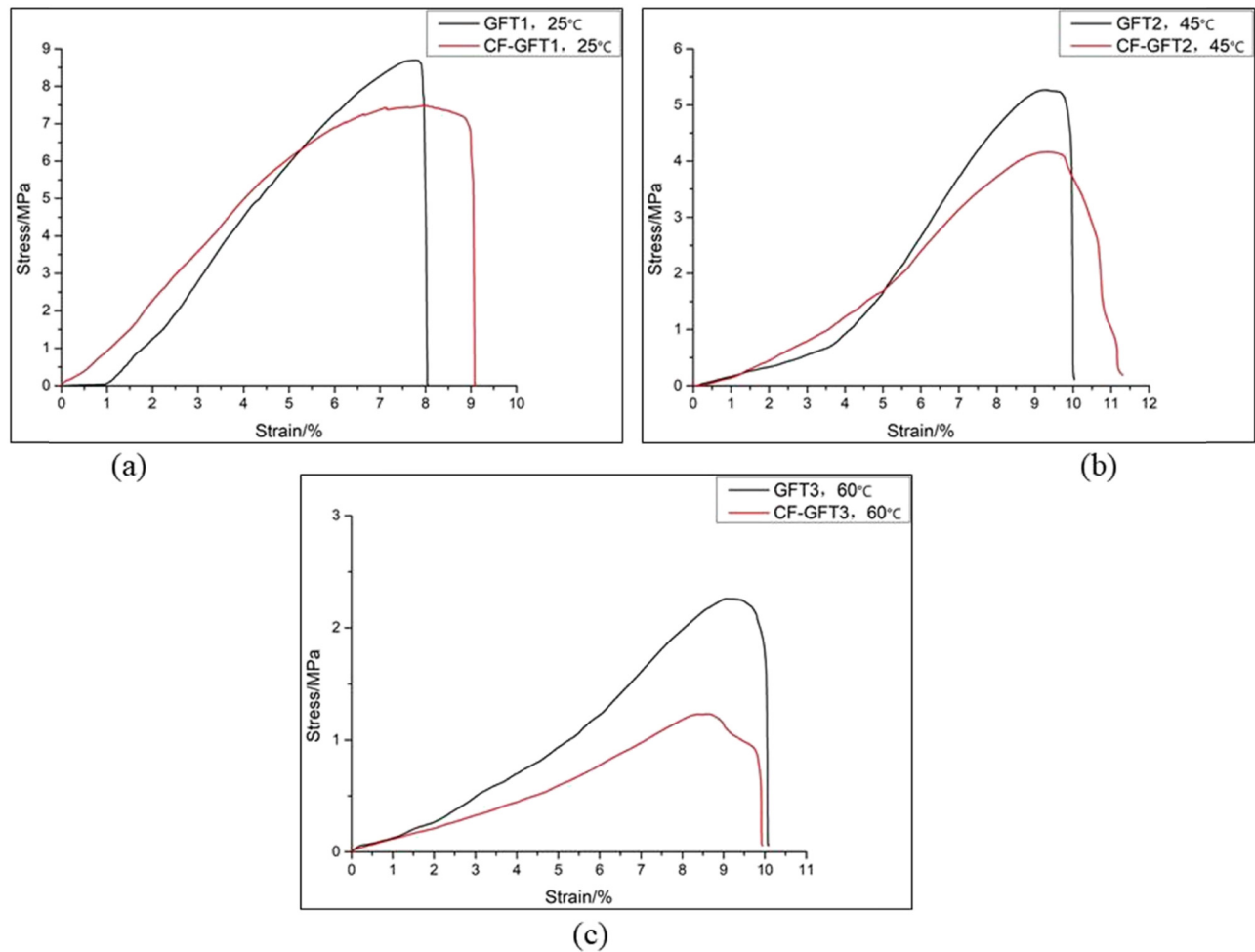


Figure 8: Stress–strain curves of two braided composites at the same temperature: (a) 25°C, (b) 45°C, and (c) 60°C.

with low elongation at break and poor ductility, and composites with more brittle fibers will fail before composites with more ductile fibers during the tensile test.

4.2 Tensile fracture morphology and mechanisms

The composite specimens show the brittle fracture failure mode with a clicking sound during tensile tests, and this sound becomes more pronounced with the increasing load until the composites break. By using high-definition CCD optical microscopy for characterization, the tensile fracture morphologies of 2D braided composites at different temperatures are shown in Figure 9. The appearance morphologies of 2D braided composites captured by an ordinary camera are shown in Figure 10.

It can be seen that the test area of the composite specimens after tensile failure shows noticeable multi-matrix cracking and delamination. The fracture and deformation of the composite specimens are along the braided angle, the white matrix fragments can be seen clearly on the surface of the specimens, and the shear fractures occur in the braiding fibers. Meanwhile, for pure glass fiber braided composites and carbon fiber–glass fiber hybrid braided composites, the matrix cracking at room temperature 25°C is more serious than that at other temperature conditions, the damage area is more significant, and composites can even be easily pulled out by hand. With the increase in temperature, the cracking damage of the matrix at the specimen fracture site becomes subtle, while the fiber–matrix debonding and crack propagation around the fracture site become more significant. It is the fact that the resins become soft with the increase in temperature, which leads to the reduction of the interface bonding strength between the fiber and the matrix, and the internal structures of composites are no longer rigid and internal damage is caused, which is also shown in Section 4.1. Another special finding is that the debonding phenomenon between glass fiber and matrix is more obvious than that of carbon fiber in the tensile fracture process, and this phenomenon can be observed more significantly in the specimens with tensile fracture at higher temperature, which also corresponds to the tensile failure sequence of ductile fiber and brittle fiber mentioned in Section 4.1.

Therefore, after tensile tests at different temperatures, the main failure modes of 2D braided composites are fiber shear fracture, multi-matrix cracking, and fiber–matrix debonding. With the increase in temperature, the

resins become soft and plasticized, the support of the fibers to the matrix is greatly reduced, the fibers fracture, and the interfaces debond seriously, which finally leads to the tensile failure of the composites.

5 Conclusions

In this study, two kinds of two-dimensional biaxial braided composites were prepared successfully, and their tensile properties and failure mechanism were investigated at different temperature conditions. To this end, all the prepared 2D braided composite samples were applied to tensile loads at different temperatures (25, 45, and 60°C) until fracture. Stress–strain curves and high-definition CCD optical microscopy were utilized to access the influences of temperature on tensile properties and damage of composite samples. The results show that temperature has significant effects on the tensile properties and fracture damage of 2D braided composites.

According to the tensile test results, the two kinds of 2D braided composites show the highest ultimate tensile strength and elastic modulus at 25°C, and their ultimate tensile strength and elastic modulus decrease obviously when the temperature increases gradually. The effects of temperature increase on the strain rates at fracture of the two composites are different. The strain rates at fracture of the pure glass fiber braided composites increase obviously, while those of the carbon fiber–glass fiber hybrid braided composites reach the maximum at 45°C. It is also found that under the same temperature conditions, the tensile properties of the carbon fiber–glass fiber hybrid braided composites are lower than those of the pure glass fiber braided composites.

According to the failure behavior research results, the two kinds of 2D braided composites have more serious fracture damage at 25°C, and when the temperature increases gradually, their external fracture failure becomes subtle, while their internal deformation damage becomes significant. At each temperature, the main tensile failure modes of the two composites are fiber shear fracture, multimatrix cracking, and fiber–matrix debonding. In addition, the fracture failure of carbon fiber (a kind of brittle fiber) occurs before that of glass fiber, and the debonding phenomenon of glass fiber and matrix is more obvious than that of carbon fiber, which can be more conspicuously observed at higher temperature.

Further research will focus on the effect of braided angle on tensile properties and fracture damage of two-dimensional biaxial braided composites at different

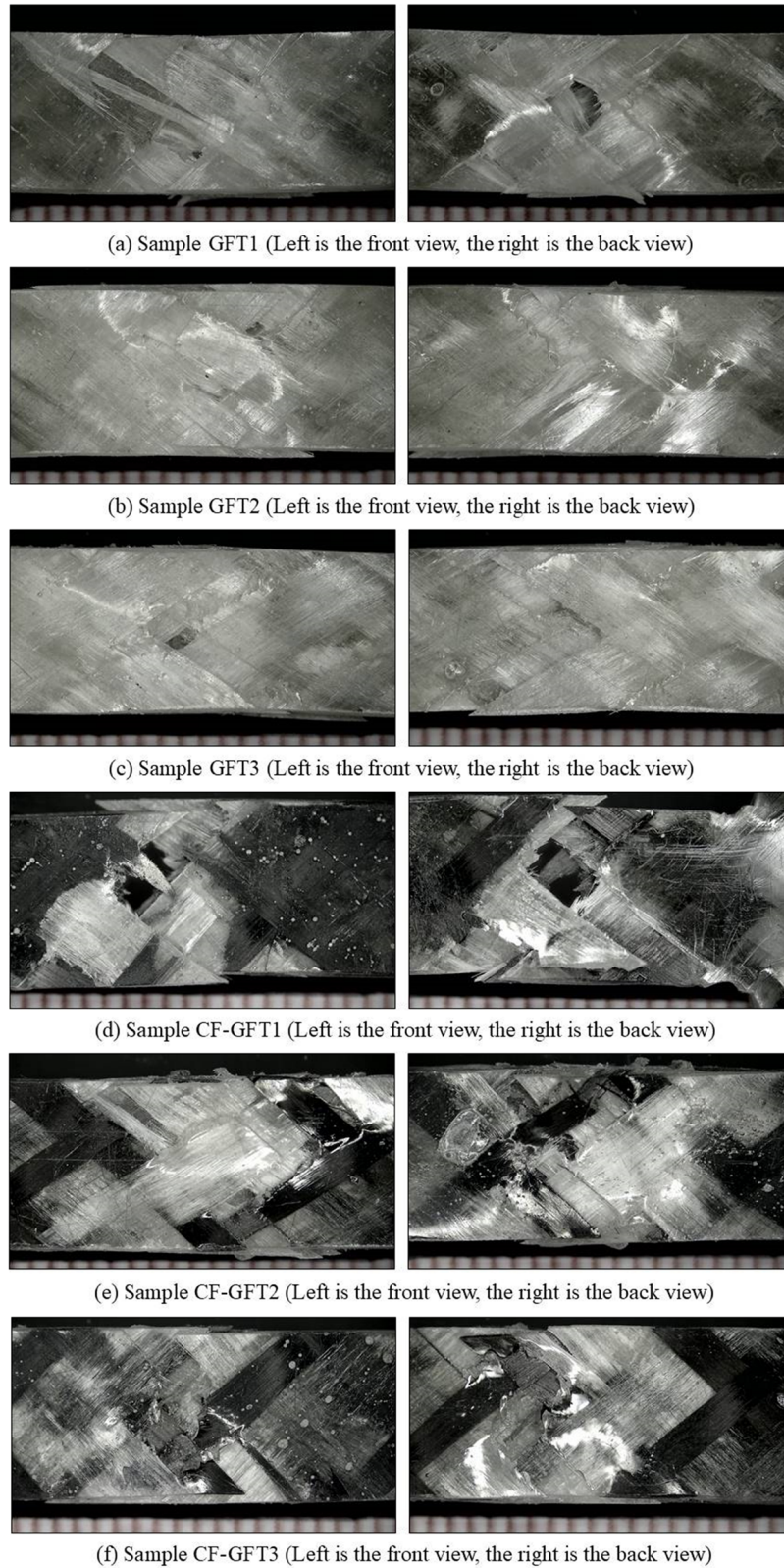


Figure 9: Tensile fracture morphology of 2D braided composites at different temperatures: (a) 25°C, (b) 45°C, (c) 60°C, (d) 25°C, (e) 45°C, and (f) 60°C.

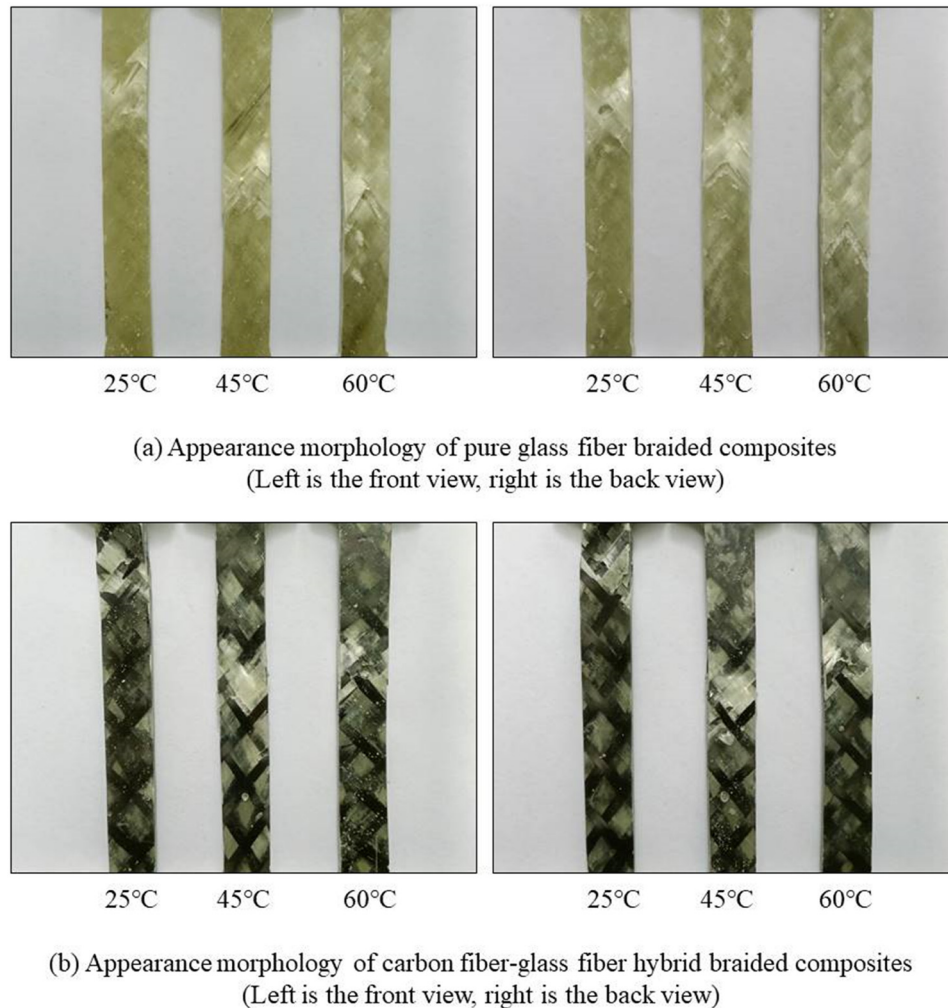


Figure 10: Appearance morphology of 2D braided composites: (a) pure glass fiber braided composites and (b) carbon fiber-glass fiber hybrid braided composites.

temperatures, and may also note the aspects of theoretical modeling of braided composites.

Funding information: The work was financially supported by An Hui Province International Cooperation Research Center of Textile Structure Composites.

Conflict of interest: We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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