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Effects of temperature on compression properties of three-dimensional and five-directional braided composites and laminated composites

GANG DING[a,*], HAIJIAO WANG [b], ZHEN KAI WAN, JIALU LI[b,*], LI CHEN[c], XIAOYUAN PEI[b]

School of Textiles, Tianjin Polytechnic University, Tianjin 300160, China

[a]Department of the Management and Construction of Teaching Resources, Tianjin Radio & TV University Tianjin, 300387, China

[b]Composites Research Institute of Tianjin Polytechnic University & Tianjin and Education Ministry Key Laboratory of Advanced Textile Composite Materials, Tianjin 300160, China

[c] Tianjin Key Laboratory of Fiber Modification and Functional Fiber, School of Materials Science and Engineering, Tianjin Polytechnic University, Tianjin 300160, China

The compression properties of three-dimensional (3Dim) and five-directional (5Dir) braided/epoxy resin composites and laminated resin composites at room temperature, 90℃, 120℃, 150℃, and 180℃ and heating for 15 min, 600 min, 1800 min, and 3000 min were studied. The effect rules of different temperature and different heating time on the compression property of these composites were comparatively analyzed. Macro-fracture morphology and SEM micrographs were examined to understand the deformation and failure mechanism. The significant decrease for the compression strength of laminated composites at high temperature is due to the delamination of the laminated composites because of the resin damage, which shows that structures of reinforcements have significant influences on compression property of resin composites at high temperature.

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Keywords: 3-Dimensional reinforcement, Laminated composites, Mechanical properties, Electron microscopy, High temperature

1. Introduction

When the composite is served in the space craft, it is inevitably subjected to the effects of temperature changes. With the expansion of the applied field of the composite, the operating temperature of resin matrix composites is constantly increased [1-2]. Thus, it is necessary to investigate the mechanical properties of the composite at high temperatures [3-5]. Chen Ming et al. [6] tested the mechanical properties of composite T300/AG80 by using temperature measure and control system QBT-70-400x and general experiment machine at different temperature. The effective elastic modulus and tension failure strength of the composite were obtained. Effects of temperature on mechanical properties of the material were analyzed. The numerical simulation and experimental result showed that the decomposition of epoxy was the main reason for the descent of mechanical properties of the composite, but the different fracture morphologies affected by temperature were also important reason. Xue et al. [7] researched the effect of temperature on the fiber bundle/epoxy resin composites. Jia Lixia et al. [8] researched the mechanics and thermal properties of the CF/polyimide composite in different temperature. The result shows that the thermal property of the composite is mainly dependent on the matrix. If the matrix could resist high temperature, its composite could also have high strength under high temperature. The postbuckling analysis of 3Dim textile composite cylindrical shells under axial compression in thermal environments was researched by Zhi-Min Li [9]. The results revealed that when the temperature changed, the fiber volume fraction and the shell geometric parameter had a significant effect on the buckling load and postbuckling behavior of textile composite cylindrical shells. V. K. Rangari et al. [10] researched the microwave curing of CNFs/EPON-862 nanocomposites and their thermal and mechanical properties. Jacques et al. [11] investigated the influence of laminate thickness on composite durability for long-term utilization at intermediate temperature. Aktas et al. [12] researched the compression after impact behavior of laminated composite plates subjected to low velocity impact at room temperature, 40℃, 50℃, 80℃, and 100℃. Results show that the impact experiment temperature has significant effect on the strength of the laminates.

With the expansion of the braided composite application field, the effect of temperature on the performance of braided composites is concerned by more and more scholars. The tensile properties of 3Dim-5Dir braided/epoxy resin composites and laminated resin composites at temperature of room, 80℃, 150℃, and 180℃ were studied by Li Jialu et al. [13], and the effect rules of different temperature on the tensile property of these composites were discussed. Diansen Li et al. [14] studied the effect of temperature on the bending properties and failure mechanism of a 3Dim E-glass/epoxy four-directionally braided composite. The results have shown that the temperature has significant effect on the bending properties of 3D braided composite and its mechanical performance decreases with the increase of the temperature. Song et al. [15] researched the effects of heat-accelerated aging on tensile strength of 3Dim braided/epoxy resin composites. The results of two-way ANOVA indicate that the aging time had a significant effect on tensile strength of these composites. Rapid evaluation of thermal aging of a carbon fiber laminated epoxy composite was researched by Fan et al [16]. The two-way ANOVA results indicate that the aging time had a significant effect on the flexural strength of the composite, and the aging temperature had no significant effect on it. The experimental investigation on the compression properties and failure mechanism of 3Dim braided composites at room and liquid nitrogen temperature was researched by Dian-sen Li et al [17]. The results show that the stress–strain curves and the compression properties were significantly different in the longitudinal, in-plane, and transverse direction.

In this paper, to understand further the effect of the heating temperature and heating time on the compressive properties of different reinforced structure composites, from the time-load curve, compression strength retention rate and fracture morphology were used to analyze the effects of the heating temperature and heating time on compression performance of composites. The data obtained from the compression experiment and fracture surface of the specimen were compared and analyzed. The influence of different temperatures and heating time on the compression property of different reinforced structure composites were researched, and the reasons for these results were discussed. The research of this paper provided the basis for the application of the 3Dim-5Dir braided composites at different temperatures.

2. Materials and experimental procedure

In this experiment, the braided yarn of 3Dim-5Dir braided composite was T700 carbon fiber with the density of 1.76 g/cm^3. 3Dim braided performs were formed by interlacing braid yarns by four-step 1 × 1 braid method [18]. The reinforced structure of the laminated composites was T700 carbon fiber plain weave, the yarn density of which in the warp and woof are 3/cm; the laminate mode was $[0/90]_{13}$. The matrix was TDE-86 epoxy resin with the glass transition temperature of 156°C. The curing agent was 70$^{\#}$ anhydride. All the specimens were consolidated with epoxy resin by resin transfer molding (RTM) process. The catalyst was aniline. Because the cross section of the specimen was square, when it was subjected to the compression action, it was easy to cause the damage of the ends. The photograph of 3Dim-5Dir braided composite and laminated composite specimen is shown in Fig. 1. The specification and parameter of the specimens, which were used for compression experiment, were shown in Table 1.

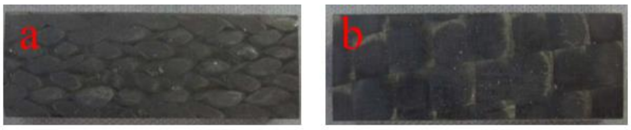

Fig. 1. The specimens of composite: (a) 3Dim-5Dir braid composites, and (b) laminated composites.

Table 1. Specifications of composite specimen.

Composites	Height × wide × thickness/mm × mm × mm	Surface braiding angle / (b)	Fiber volume fraction / %
Three-dimension and five-direction braided composites	30 × 10 × 10	30	55
Laminated composites	30 × 10 × 10	——	55

Because there are no standards of high temperature compression test for 3Dim braided composites, the specimen configuration and test procedure were followed by the ASTM standardD3410-2008 [19]. Three specimens were tested for each temperature and each heating time conditions. Thus, the compression experiment at different temperatures and different heating time needed 42 specimens of 3Dim-5Dir braided composites and 42 specimens of laminated composites. The experiment program of the specimens is shown in Table 2.

Table 2. The testing program of the specimen.

Composites	Heating time /min	Room temperature	90°C	120°C	150°C	180°C
Three-dimension and five-direction braided composites	15	3	3	3	3	3
	600	-	3	3	3	-
	1800	-	3	3	3	-
	3000	-	3	3	3	-
Laminated composites	15	3	3	3	3	3
	600	-	3	3	3	-
	1800	-	3	3	3	-
	3000	-	3	3	3	-

The compressive experiments were performed at AG-250KNE universal testing machine of SHIMADZU Company. When the heating time was 600 min, 1800 min, and 3000 min at high temperature, the specimens were placed in the electric constant temperature drying oven (DL-101) to heat first. All compressive specimens were loaded to failure in stroke mode at a rate of 2 mm/min. During testing, the load and the cross-head displacement were logged automatically in the computer. At least three specimens were tested for each type of composites with identical dimensions, and the average values of the experimental results were obtained.

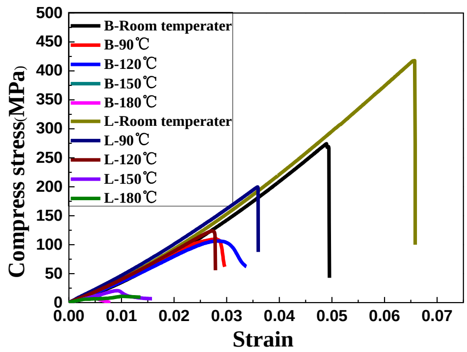

Fig. 2. The stress-strain curves for composites at 15 min of heating at different heating temperature. B: 3Dim-5Dir braided composites. L: laminated composites.

3. Results and discussion

3.1 Typical compression curves at different temperatures

The experimental compressive stress-strain curves of braided composites and laminated composites at room temperature, 90°C, 120°C, and 180°C with 15 heating times was given in Fig. 2. From Fig. 2, the cumulative process of the damage of the composites could be seen. At the room temperature, the load immediately drops after it has reached the maximal point, and no clear yield phenomenon can be observed, both of which are consistent with those from other literature [17, 20]. When the heating temperature was lower than 150°C, the relationship between stress and strain was almost a linear manner during the compressive testing process, which indicated that the combination of the resin and fiber was well in the specimen. The curve declined rapidly, and the material showed clear brittle failure feature when the compressive load reached the maximum value. The failure of the specimen was the brittle failure caused by the fiber bundle, which had been similarly reported in the other studies given at references 21 and 22.

When the heating temperature was 150°C and 180°C (from Fig. 3), the variation of the stress-strain curves for the braided composite are basically the same. However, the laminated composites are heated at 150°C and 180°C; the variation of the stress-strain curves had a large deviation. More obvious differences appeared in the initial part of the curve, and the load sharply declined at the end of the curve. This is because after the high temperature heating, when the laminated composites were subjected to compression stress, the structure became unstable. The 3Dim-5Dir braided composites were due to good integrity and structural stability; therefore, the variation of the stress-strain curves had a better consistency.

3.2 The compressive properties of composites at different temperatures

The parameters of the compression properties of 3Dim-5Dir braided composites at different temperatures are listed in Table 3. From Table 3, at constant temperature, with increasing heating time, the compression modulus of the specimen was decreased; however, the change was small. At 150°C, when the heating time was 3000 min, the compression modulus of the specimen decreased by 0.75GPa compared with that at room temperature. The compression modulus had the greatest change in this group.

Table 3. The parameters of the compression performance of the 3Dim-5Dir braided composites at different temperatures.

Composites	Heating temperature/℃	Heating time/min	Compression strength /MPa	Compression strength retention rate /%	Compression modulus / GPa
Three-dimension and five-direction braided composites	Room temperature	0	252.29	100	2.81
	90	15	123.96	49.13	2.75
		600	154.06	61.06	2.66
		1800	217.29	86.05	2.4
		3000	198.11	78.52	2.34
	120	15	106.25	42.11	2.65
		600	150.92	59.82	2.5
		1800	209.37	82.99	2.34
		3000	191.56	75.93	2.28
	150	15	18.96	7.52	2.62
		600	48.83	19.35	2.43
		1800	127.5	50.52	2.15
		3000	64.38	25.52	2.06
	180	15	8.52	3.38	2.34

The compression strength retention rate was the ratio of the compression strength at different heating temperature for different continuous heating time and compression strength at room temperature. By comparing the strength retention rate of the composites at different heating temperature for different continuous heating time, the impact of the temperature and time on the property of the material could be identified.

$$R = \frac{\sigma_{c1}}{\sigma_{c0}} \times 100\% \tag{1}$$

In which R is the strength retention rate %; σ_{c1} is the compression strength of the specimens at different heating temperatures for different continuous heating time, MPa; and σ_{c0} is the compression strength of the specimens at room temperature.

The parameters of the compression properties of 3Dim-5Dir braided composites at different temperatures were listed in Table 3. Fig. 3(a) was the line chart of compression strength retention rate for 3Dim-5Dir braided composites, which was tested at the different heating time and temperature. All the compression strength retention rate of the 3Dim-5Dir braided composite increased at the early stage and then decreased later with the increasing of the heating time. At 90℃, after heating 1800 min, the compression strength retention rate reached the maximum value of 86.05%. This is the maximum value of the compression strength retention rate of the 3Dim-5Dir braided composites in all the heated state.

The feature of 3Dim-5Dir reinforcement was that there were axis yarns along the direction of the braiding, and the braiding yarns had an angle with the axis yarns. The axis yarns and braiding yarns had different space path inside the structure of the 3Dim-5Dir reinforcement. Thus, when they subjected the loads of compression and shear, the force transfer mode had greater difference between axis yarns and braiding yarns, which made the failure form very different. When the braiding yarns are subjected to the load of compression, the force was dispersed along the fiber, which forced the fibers and the matrix to separate. The force withstood by single fiber could be gradually reduced. At room temperature, the combination between the fibers and the resin was the best, so the compression strength was the maximum. With increasing of temperature and heating time, the resin embrittled, and the binding force between resin and fibers was decreased. Therefore, the capacity of carrying the compression load of the whole specimen was reduced, which resulted in the decreased compression strength of the material. The axial yarn basically withstands longitudinal pressure directly, and the direction of which paralleled to the direction of the force. The transmission speed of the force was fast along the axial yarn. Therefore, most axial yarns were broken because of the effect of compression shear. Thus, the debonding between the axial yarn and the matrix was less. From the experimental results, it could be seen that when the temperature increased, the compression strength of 3Dim-5Dir braided composite was reduced. However, with the increase of the heating time, the compression strength retention rate of the 3Dim-5Dir braided composite increased at the early stage and then decreased later.

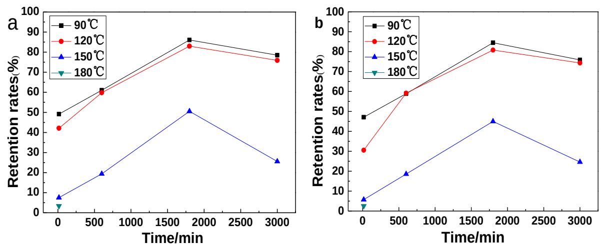

Fig. 3. The compression strength retention rate: (a) 3Dim-5Dir braid composites; and (b) laminated composites.

The parameters of the compression properties of laminated composites at different temperatures were listed in Table 4. From Table 4, it could be seen that when the temperature was constant, with the increasing of heating time, the compression modulus of the laminated composites was decreased. At 150°C, when the heating time was 15 min, the compression modulus of the specimen decreased to 1.78 GPa compared with that at room temperature, and the compression modulus had the greatest change. Through comparison between Tables 3 and 4, the reduction amount of compression modulus for the laminated composites was smaller than the braided composite. However, when the heating temperature was higher than 90℃, the reduction amount of compression modulus for the laminated composites was larger than the braided composites.

Fig. 3(b) was the line chart of compression strength retention rate for laminated composites, which was tested at the different heating time and temperature. The change trend of the compression strength retention rate for laminated composites was similar to the braided composites. At 90℃, after heating 1800 min, the maximum value of the compression strength retention rate was 84.46%. When the heating time was 600 min, at 90℃, the compression strength retention rate was increased to 58.88%; at 120℃, the compression strength retention rate was increased to 59.18%. From 90℃ to 120℃, the changes of the compression strength retention rate were only 0.3%. At 150℃, the compression strength retention rate was increased to 18.55%. From 120℃ to 150℃, the compression strength retention rate decreased by 40.63%. At 180°C, when the heating time was 15 min, the compression strength retention rate was only 2.52%. The matrix was TDE-86 epoxy resin with the glass transition temperature of 156°C,when the heating temperature close to the glass transition temperature, the resin was damaged more, and the ability of the resin for transferring load was decreased, which resulted in the greatly reduced ability of the specimen forbearing the load. Therefore, the compression strength of the specimen decreased sharply.

Table 4. The parameters of the compression performance of the laminated composites composites at different temperatures.

Composites	Heating temperature/℃	Heating time/min	Compression strength /MPa	Compression strength retention rate /%	Compression modulus / GPa
Laminated composites	Room temperature	0	417.71	100	3.75
	90	15	196.68	47.09	3.69
		600	245.94	58.88	3.70
		1800	352.81	84.46	2.81
		3000	316.87	75.86	3.37
	120	15	127.60	30.55	3.59
		600	247.19	59.18	2.97
		1800	337.50	80.80	2.76
		3000	310.52	74.34	2.81
	150	15	23.95	5.73	1.97
		600	77.50	18.55	2.75
		1800	187.97	45.00	2.63
		3000	102.81	24.61	2.34
	180	15	10.52	2.52	2.03

The compression strength retention rate of the braided composites and laminated composites was compared in Fig. 4. From Fig. 4, at constant heating temperature and heating time, the compression strength retention rate of braided composites was higher than that of laminated composites. At 120℃, when the heating time was 15 min, the differences of the compression strength retention rate between braided composites and the braided composites were the largest. The compression strength retention rate of braided composites was larger 11.56% than laminated composites; when the heating time was 600 min, the differences of the compression strength retention rate between braided composites and the braided composites was the smallest, which was only 0.3%. The influence of heating temperature and heating time on the compression strength of laminated composites was more significant than that of braided composites. Especially after 120℃, with the increasing of heating time and temperature, the compression strength of laminated composites decreased more significantly. When the resin was destroyed by the temperature, because the structure of 3Dim-5Dir reinforcement was an integrated structure, to some extent, the integrated structure could support the specimen to withstand considerable compression load and compensate the damage of the resin. Therefore, at high temperature condition, the reduction of compression strength was relatively small. However, the laminated composites were different; the changes of the resin caused the weakening of the adhesion between layers. The laminated composites were compressed, which was prone to delamination. The load bearing of the specimen decreased, which caused the compression strength to drop dramatically.

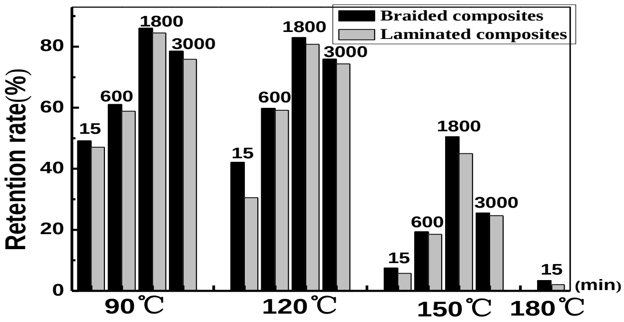

Fig. 4. Comparison of the compression strength retention rate at high temperature.

3.3 The compressive damage morphology of the composite

The morphology of compressive fractures was observed by photos and TM-1000 scanning electron microscopy. From the macroscopic and microscopic view, the type of damage and the failure mechanisms of the composites were investigated.

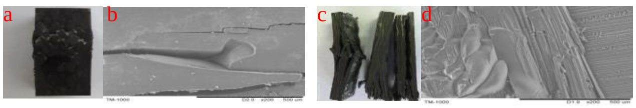

Fig. 5. The fracture photographs and the SEM photographs of compression specimen at room temperature: (a) the fracture photographs of 3Dim-5Dir braid composites, (b) the SEM photographs of 3Dim-5Dir braid composites, (c) the fracture photographs of laminated composites, and (d) the SEM photographs of laminated composites.

Fig. 5 shows the compressive fracture photographs and SEM photograph of the braided composites and laminated composites at room temperature. From Fig. 5(a) and (b), at room temperature, at the failure place of braided composites, there was much accumulation of broken resin, and at the surface of the specimen, there was no significant breakage of fibers, and the material still kept good integrity. The compressive failure of resin caused the interfacial debonding between fibers and matrix. The fiber bundles expanded outward, and the fiber bundles were loosen within each other. This showed that when the braided composites were compressed, the fiber bundles bore the main load uniformly, the deformation of the matrix was relatively large, and the shear force was applied to the fiber bundle. With the further increase of the load, the transverse crack expanded, and the brittle fracture of the resin led to the failure of the material. From Fig. 5(c) and (d), when the laminated composites were compressed at the longitudinal direction at room temperature, a significant delamination damage was observed, and the part of the fiber layer appeared as the phenomenon of crushed fibers.

Fig. 6. The fracture photographs of 3Dim-5Dir braid composites and laminated compositescompression specimen at 90℃with different heating time (a, e) 90℃, 15 min; (b, f) 90℃, 600 min (c, g) 90℃, 1800 min (d, h) 90℃, 3000 min.

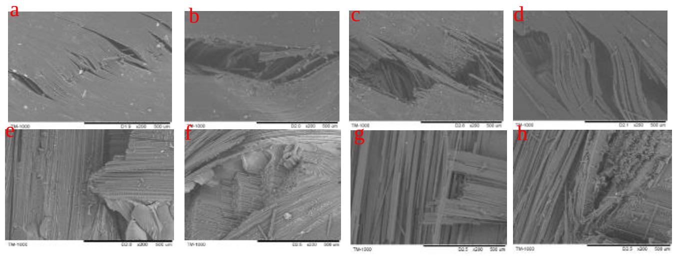

Fig. 7. The SEM photographs of 3Dim-5Dir braid composites and laminated composite fracture at 90℃ with different heating time: (a, e) 90℃, 15 min; (b, f) 90℃, 600 min; (c, g) 90℃, 1800 min;(d, h) 90℃, 3000.min.

Fig. 6 shows the fracture photographs of braid composites and laminated composite compression specimen at 90℃ with different heating time. Fig. 7 shows the SEM photograph of the composites in the longitudinal direction. From Fig. 6(a) to (d), at 90℃, at the compressed damage position of the braided composite, the accumulation of broken resin was less than that at room temperature. By SEM observation, the broken fiber bundle (Fig. 7(a) to (d)) could be observed. As can be seen from Fig. 6(e), when the heating time was 15 min, the laminated composites were compressed, causing less delamination. However, there had been obvious failure characteristics in the side of the laminated composites, which caused fiber breakage. From Fig. 6(e) to (h), with the increasing of the heating time, the fiber breakage and delamination of the laminated composites increased, and the damage becomes more serious. By SEM observation, as shown in Fig. 7(e) to (h), the broken fiber bundles were broken and delaminated along a certain direction. This showed that when the specimen was compressed, the fibers mainly bore the load; the crack between the fiber bundle led to the concentration of the stress and caused the disconnection of the fibers, which made the crack extend.

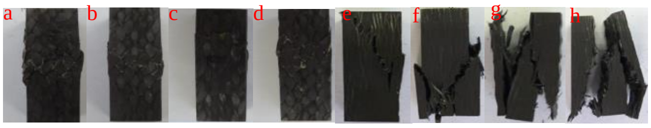

Fig. 8. The fracture photographs of 3Dim-5Dir braid composites and laminated composites compression specimen at 120℃ with different heating time: (a, e) 120℃, 15 min; (b, f) 120℃600 min; (c, g) 120℃, 1800 min, (d, h) 120℃, 3000 min.

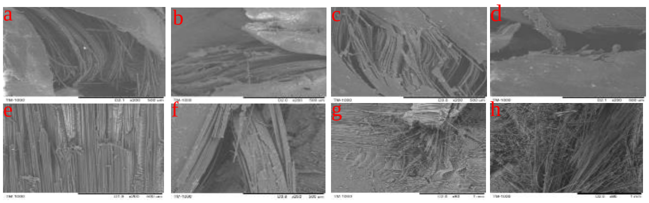

Fig. 9. The SEM photographs of 3Dim-5Dir braid composites and laminated composites fracture at 120℃ with different heating time (a, e) 120℃, 15 min; (b, f) 120℃, 600 min; (c, g) 120℃, 1800 min; (d, h) 120℃, 3000 min.

Fig. 8 showed the fracture photographs of the braided composites and laminated composites heated for 15 min, 600 min, 1800 min, and 3000 min at 120℃, respectively. Fig. 9 shows the SEM photograph of the composites in the longitudinal direction. From Fig. 8, at the damaged place of the specimen for the braided composites and laminated composites, there were more accumulation of the resin and more inflected fibers compared with that at room temperature. From Fig. 8, at the damaged place of the braided composites and laminated composites, the fractured fibers were more serious. This was because the high temperature caused the interface of the fiber bundle and the matrix to be damaged. Plastic deformation of the matrix and the damage of the interface were more obvious. There were more protrusions of the grid-like at the surface of the braided composites specimen. The fiber of the laminated composite specimen occurred delamination and fracture along the direction of 45°. With the increasing heating time, the damage at the interface of the braided composites and laminated composites looked even more serious, and the matrix between the fibers produced more obvious fragmentation. This was because when the specimen was compressed, the fiber bundle interface had a greater stress concentration, which led to the crack of the matrix, as shown in Fig. 9(a), (b), and (e). The compression load caused the squeezing between fiber bundles, which caused the shear fracture of the fiber bundles, as shown in Figure 10(c) and (f). Along the direction of the breakage, the breakage of the single fiber could be observed, which was shown in Fig. 9 (a) and (g). When the heating time was 3000 min, at the damage location of the specimen, the more accumulation of the resin appeared again, as shown in Fig. 9 (d) and (h). With long heating time at high temperature, the macromolecular chains of the resin had been changed, which caused the capacity of the bonding between the fibers and the resin to decrease and the bonding between the fibers and the matrix destroyed. Thus, the main damage of composites under longitudinal compression at 120℃ was the form of interface debonding, fiber fracture, and matrix cracking, and with the increasing heating time, the delamination of the laminated composites increased.

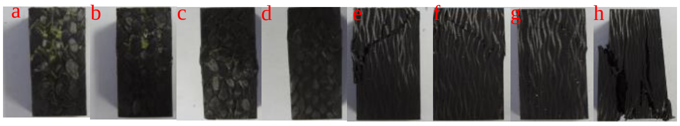

Fig. 10. The fracture photographs of 3Dim-5Dir braid composites and laminated compositescompression specimen at 150℃ with different heating time: (a, e) 150℃, 15 min; (b, f) 150℃, 600 min; (c, g) 150℃, 1800 min; (d, h) 150℃, 3000 min.

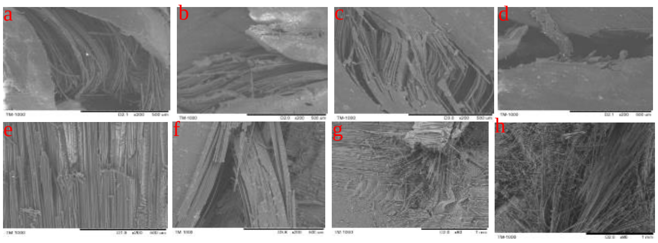

Fig. 11. The SEM photographs of 3Dim-5Dir braid composites and laminated composite fracture at 150℃ with different heating time: (a, e) 150℃, 15 min; (b, f) 150℃, 600 min; (c, g) 150℃, 1800 min; (d, h) 150℃, 3000 min.

Fig. 10 shows the fracture photographs of the braided composites and laminated composites at 120℃. Fig. 11 shows the SEM photograph of composites in the longitudinal direction. From Fig. 10 (a), when the braided composites were compressed to damage, the obvious fiber breakage could not be seen at the surface, the accumulation of resin at the surface of the specimen was enormous, and the color of the resin changed to dark yellow. In each layer of the laminated composites, the fiber bundle showed flexion, as shown in Fig. 10 (e) to (h). With the increasing of the heating time, the flexion of the fiber became more obvious. As the heating time increased, when all specimens were compressed to damage, the accumulation of resin at the surface of the specimen was decreased; the fiber breakage occurred. SEM observations showed that much matrix was compressed to crush (Fig. 11 (a), (b), (f), and (g)). When the heating time was 1800 min, many inflection and breakages can be found within fibers (Fig. 11 (c) and (g)). When the heating time was 3000 min, the matrix was also compressed to crush, and the fiber breakages were significantly increased (Fig. 11 (d) and (h)). At 150℃, as the heating time increased, when laminated composites were compressed to damage, the delamination and fiber shear fracture had increased. From Fig. 11 (e) to (h), we could clearly see the broken resin and fiber breakage.

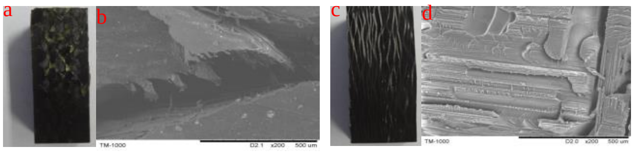

Fig. 12. The fracture photographs and the SEM photographs of compression specimen at 180℃; (a) the fracture photographs of 3Dim-5Dir braid composites; (b) the SEM photographs of 3Dim-5Dir braid composites; (c) the fracture photographs of laminated composites; and (d) the SEM photographs of laminated composites.

Fig. 12 (a) and (c) shows the fracture photographs of the specimen at 180℃ with the heating time of 15 min, and Fig. 12 (b) and (d) showed the SEM photograph. From Fig. 12 (a), when the braided composites were compressed to damage, the resin at the surface of the specimen presented peeling off of the network-like. By SEM observation, shown in Fig. 12 (b), the fibers were dislocated and torn; at the same time, the matrix was crushed to fragment. From Fig. 12 (c), when the laminated composites were compressed to damage, delamination occurred among all the layers, and all the straight and parallel fibers experienced flexion phenomenon. By SEM observation, shown in Fig. 12 (d), the matrix includes delamination of sheet. The separation between the matrix and the fiber was very serious. The reason for this phenomenon may be that the reinforcement structure of braided composites was an integrated structure; the structural integrity was strong. When it was subjected to the load, the effect of temperature on the structure of braided composites was not obvious, and the resin played a good role to transfer and disperse stress between the fiber bundles. The plurality of single-layer fabric was laid together and then cured with resin to form the laminated composites, which resulted in the fiber-reinforced needed for the resin matrix to provide binding force. After being subjected to high temperatures, the macromolecular chains of the resin had been damaged, which caused the capacity of the bonding between the fibers and the resin to decrease. In the laminated composites, the fiber between the layers could not be combined actively, which made the structure of the laminated composites to be more unstable. Therefore, after being compressed and fractured, it would cause significant delamination.

3.4 The compression damage mechanism of composites at different temperatures

Under the different experimental conditions, when the specimen of the braided composites was compressed to damage, the surface morphology of the specimen showed that all the fibers in the specimen inflected and some fibers even were broken because of the pressure. The feature of the 3Dim reinforcement was that there were axis yarns along the direction of the braiding and the braiding yarns had an angle with the axis yarns. The axis yarns and braiding yarns had different space path inside the structure of the 3Dim reinforcement, so when they subjected the effect of thecompression and shear, the force transfer mode had a greater difference between axis yarns and braiding yarns, which led to a different failure form. When the braiding yarns subjected to the effect of the compression, the force was dispersed to transfer along, which forced the fibers and the matrix to separate. The force withstood by single fiber could be gradually reduced. However, the method of load was uniform in all the experiment, and the fibers were broken by theoverload. At room temperature the combination between the fibers and the resin was the best; thus, the compression strength was the maximum. With increasing of temperature and heating time, the resin embrittled, and the binding force between resin and fibers was decreased. Therefore, the capacity of carrying the compression load of overall specimen was reduced, which resulted in the compression strength of the material decreased.

When the laminated composites were compressed in the longitudinal direction, because the fracture strain of the fiber and matrix were very different, the different deformation would cause the matrix crack. When the compression load reached a certain level, there would be delamination in the laminated composites. On the other hand, the laminated composites were subjected to compressive load, which applied axial pressure to the warp. In the carbon fiber plain weave, warp and woof were interwoven. Warp was not completely straight in the axial, which had a lot of micro-flexion. Under the effect of the compression load, the micro-flexion of the fiber in the local area would cause the shear fracture of the fiber so that made the specimen be destroyed.

The main reason of the change of the compression strength retention rate for the braided composites and laminated composites was that when the heating time increased to 600 min, the distribution of the temperature became uniform in the material, which made the structure of the material become stable. The volatilization of the water existed inside the matrix resin, and the freewater in the initial stage of the material, and the loss of the bound water in the material when the heating time increased to 600 min. These made internal structure of the material become more regular, and the bond between the molecular was more densification. The decrease of the moisture content of the specimen would make the glass transition temperature increase to a certain degree, so thecompression strength for the heating time of 600 min was larger than the heating time of 15min.

When the heating time increasedto1800 min, the resin occurred postcured, which made the mechanical properties of the matrix in the composite be improved. However, the post-cured resin made the matrix shrink, which the fiber of the laminated composite specimen occurred delamination and fracture along the direction of 45°. Formed stress between the interface of fiber and matrix. The interface bonding force was reduced by the stress. Thus, the post-cured made the performance of matrix improvement and the performance of interface decrease; the results of the competition made the compression strength be lower than the room temperature. At the same heating temperature, when the heating time was 1800 min, the compression strength retention rate was the maximum [16]. When the heating time extended to 3000 min, the specimens were exposed to high temperatures for a long time; the coefficient of linear thermal expansion (CTE) of the carbon fiber and the epoxy resin were very different. With the increase of the heating time, the degree of mismatch of the CTE of the carbon fiber and the epoxy resin would be more serious. The interface of the fiber and resin would produce stress; when serious, the interface would appear as a delamination [23]. Meanwhile, the high temperature for a long time would damage the resin, which led to the decline of the compression strength. Therefore, the compression strength of the specimen for the heating time of 3000 min was lower than that for heating time of 1800 min.

4. Conclusions

The compressive properties of 3Dim-5Dir braided composites and laminated composites at 90℃, 120℃, 150℃ for heating 15 min, 600 min, 1800 min, and 3000 min were compared and studied. The compressive properties of the specimen at 180℃ for heating of 15 min were also studied. The results are shown below:

1. When the heating temperature was constant, with the increasing of heating time, the compression strength retention rate of 3Dim-5Dir braided composites and laminated composites increased early and then decreased later.

2. The heating temperature and heating time had little effect on the compression of3Dim-5Dir braided composites and laminated composites modulus.

3. The macro- and micro-fracture morphology examinations indicated that the damage and failure patterns of the 3Dim-5Dir braided composites and laminated composites varied with the heating time and heating temperature.

4. The effects of temperature on compressive properties of the 3Dim-5Dir braided composites and laminated composites were different. This was mainly because of the different reinforcement structure. At high temperature, with the increasing of heating time, the resin was damaged, and the combination between the fibers and the resin was weakened more. The structure of the 3Dim reinforcement was an integrated structure; to some extent, the integrated structure could compensate the damage of resin at high temperature. The structural reinforcement had a significant impact on the compression properties of the composite. However, the specimen of laminated composite layering caused by the damage of the resin, which made the specimen could not share the outside o the load together, resulting in a high temperature, the compressive strength of laminated composites relatively large amplitude decreased.

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*Corresponding author: dinggang@tjpu.edu.cn
lijialu@tjpu.edu.cn