Elevated temperature fatigue and failure mechanism of 2.5D T300/QY8911-IV woven composites

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Abstract

Static tensile and tension-tension fatigue tests were conducted on 2.5D woven composites at room and elevated temperatures. Macro-Fracture morphology and SEM micrographs were examined to understand the corresponding failure mechanism. The results show that the stress-strain curves and the fractured morphology are significantly different in the room and elevated temperature environments. Furthermore, the static tensile properties decrease sharply with increasing the temperature due to the weakness of fiber/matrix interfacial adhesion. The fatigue life and damage progression at elevated temperature are also substantially different compared with those at room temperature. Meanwhile, a damage mechanism, called rotation deformation mechanism, was proposed to explain the elevated fatigue behavior.

Keywords: 2.5D woven composites, Elevated temperature, Stress-strain behavior, Fatigue behavior, Scanning electron microscopy, Damage progression

Introduction

Textile composite materials are widely used in advanced aerospace industry, owing to their good comprehensive mechanical performance. However, numbers of structural components exposed to long-term temperatures in 100-200℃, such as aero-engine casing, require that polymer matrix composite materials have an advantage of elevated temperature resistance performance. A new generation of high glass-transition temperature (T_g) polymers such as QY8911-IV[1] has enabled this progressive development, which can be easily used to manufacture the composites by resin transfer modeling (RTM). Additionally, compared to the relatively complex 3D braided or woven structure, a new class of 2.5D angle-interlock woven composites has been proposed. Therefore, it is of great importance to understand the mechanical behavior, especially the fatigue behavior of the materials at various temperatures.

Unfortunately, due to the high-cost and difficult-to-test at elevated temperatures, the related researches related to the static behavior and fatigue life at elevated temperature are relatively backward and most of investigations were focus on FRP[2-4] or the mechanical properties of 2.5D woven composites at room temperature (RT)[1]. Selezneva et al.[5] investigated the failure mechanism in off-axis 2D woven laminates at elevated temperature by experiment, and found that the woven yarns began to straighten out and rotated towards the loading direction just prior to failure. Vieille and Taleb[6] studied the influence of temperature and matrix ductility on the behavior of 2D woven composites with notch and unnotched, and the results revealed that the highly ductile behavior of thermoplastic laminates was quite effective to accommodate the overstresses near the hole at temperatures higher than their T_g. Several static and fatigue tests were conducted by Montesano et al.[7,8] to investigate the fatigue behavior of a triaxially braided composites at elevated temperatures, and the corresponding stiffness degradation model was proposed based on the measurements of actual observed damage mechanisms.

This study aims to investigate the static tension and fatigue behaviors of 2.5D angle-interlock woven carbon fiber/ QY8911-IV composites at room and elevated temperatures by experiments. In the first part, the corresponding elevated experiments are conducted. After that, scanning electron microscopy (SEM) is employed to study the failure mechanism subjected to the static or fatigue loading at different temperatures. Finally, some useful conclusions are presented.

According to this basic research, the database related to the elevated temperature performances and fatigue behavior of 2.5D woven composites can be established at room and elevated temperatures.

Materials and experimental procedure

2.5D woven fabric was prepared using T300 carbon fiber yarns that consist of 3K filaments per bundle, and the matrix is QY8911-IV with a glass transition temperature 256℃.

The flat composite panels with six plies of weft yarns were manufactured by the resin transfer molding (RTM) process. The static and fatigue test specimens with a fiber volume fraction of 42.94% were obtained (see Fig. 1). In addition, the microstructure is actually a spatial net-shape fabric, which is formed by interlacing binding threads in the thickness direction to join adjacent layers of warp and weft together, and cured with matrix under certain conditions. The architecture of 2.5D woven composites studied in this paper is also shown in Fig. 1.

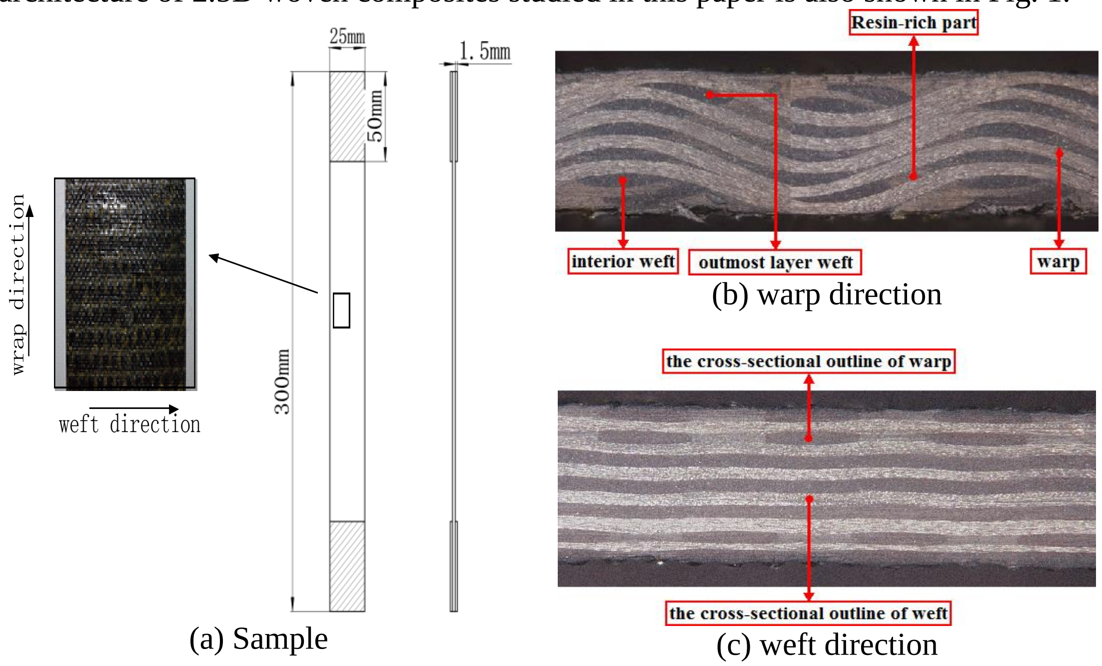


Figure 1. Static tensile/ fatigue samples and the corresponding internal microstructure

As there are no standards of static tensile and tension-tension fatigue tests for the 2.5D woven composites at elevated temperature, the corresponding test procedures were followed by ASTM D 3039[9] and ASTM D 3479[10], respectively. All of the tests were conducted by an MTS 810 hydraulic servo dynamic material test machine (see Fig.2a) with a 25.4mm MTS-634-25 extensometer (see Fig.2b) used to monitor the strain continuously during the static and fatigue tests. Moreover, an MTS809 furnace with an integrated temperature controller was used, which can ensure the temperature in the chamber is consistent throughout the duration of all tests within 2℃.

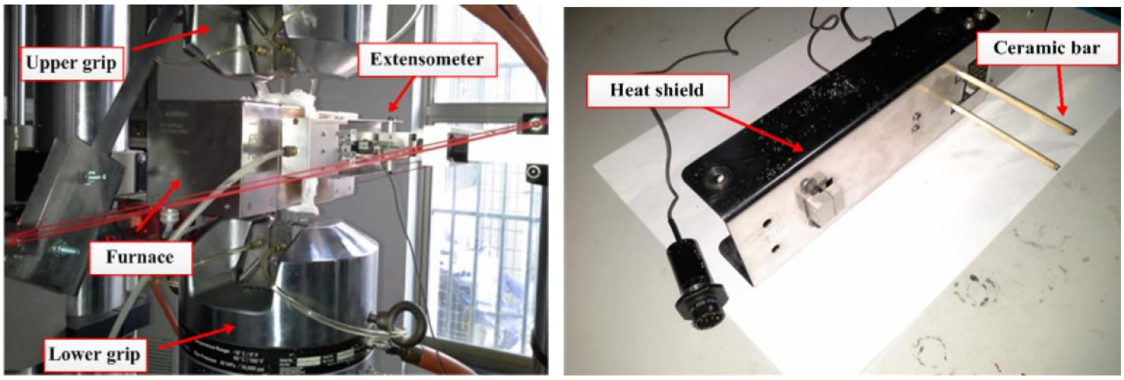


Figure 1. Photograph of MTS-810 test machine (a) and 634-25 extensometer (b)

Results

3.1 Typical stress-strain behavior at different temperatures

Fig. 3(a) shows the typical stress vs. strain curves of 2.5D woven composites tested at 20℃ and 180℃. At room temperature (20℃), the materials behave almost in a linear manner up to approximately 1%, after which an obvious nonlinear behavior can be observed up to the failure. At 180℃, the slope of the curves reduces significantly due to the resin matrix softening, interfacial debonding or sliding, resulting in a nonlinear response up to ultimate fracture.

Fig. 3(b) summarizes the modulus and UTS of the composites at 20℃ and 180℃. Comparing the properties at RT with that at 180℃, the average moduli are 48.39GPa and 40.78GPa, respectively, and the modulus at 180℃ decreases by 15.73%. Meanwhile, the average tensile strengths are 515.09MPa and 431.89MPa, respectively, and the property at 180℃ decreases by 16.15%. The results indicate that the mechanical properties are very sensitive to temperature (180℃).

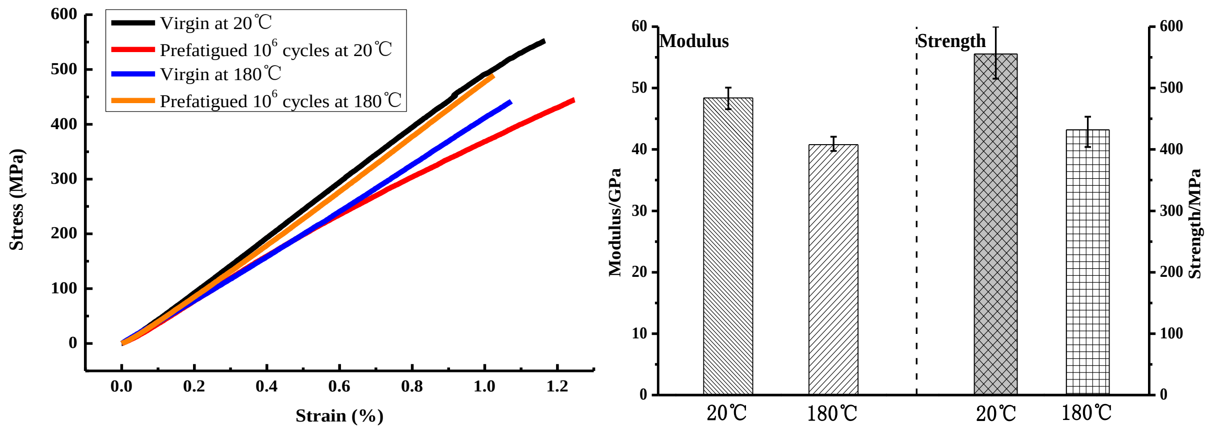


Figure 3.(a) Representative tensile stress-strain curves of 2.5D woven composites for the virgin and fatigued specimens at 20℃ and 180℃;(b) Tensile properties of 2.5D woven composites at RT and 180℃

3.2 S-N curves at various temperatures

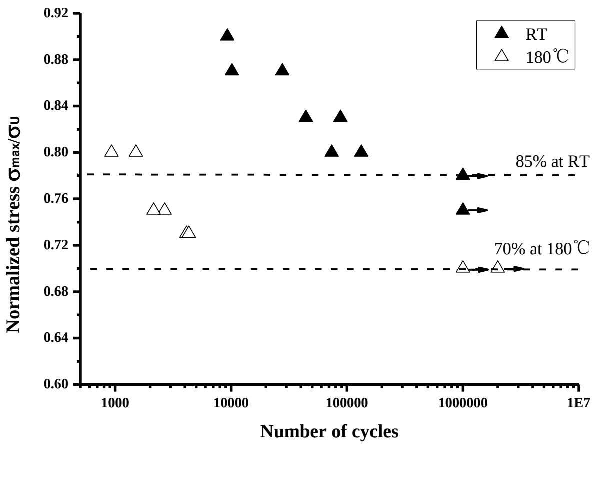
Fig. 4(a) shows the normalized stress-fatigue life curves of 2.5D woven composites at RT and 180℃ and the corresponding values are listed in Table 1 and 2. There are significant differences in fatigue behavior between RT and 180℃. The elevated temperature causes a reduction in the fatigue life, and the fatigue strength for the specimens tested at RT is about 1.2 times of that at 180℃. Additionally, it seems that there is a threshold for the elevated S-N curves. The elevated specimens subjected to the maximum fatigue loading in the range of 73%-80% have a quite short fatigue life (less than 1×10^4 cycles). Nevertheless, when the stress levels are lower than 70%, the fatigue life reaches the predefined infinite life. This phenomenon was also observed by Zhu[11], who studies the fatigue behavior of 3D braided composites at RT.

Table 1. Fatigue life (cycles) test result of 2.5D woven composites at room temperature

Stress level	No.	Peak load/N	Valley load/N	Fatigue life	Average life
$90\%\sigma_u$	1	23.13	2.32	9303	9303
$87\%\sigma_u$	2	22.31	2.23	27658	18909
	3	21.83	2.18	10159	
$83\%\sigma_u$	4	21.33	2.13	44149	44149
$80\%\sigma_u$	5	21.21	2.12	73918	103545
	6	21.36	2.14	133171	
$78\%\sigma_u$	7	20.25	2.033	10^{6*}	10^{6*}
$75\%\sigma_u$	8	20.33	2.04	10^{6*}	10^{6*}

Table 2 Fatigue life (cycles) test result of 2.5D woven composites at 180℃

Stress level	No.	Peak load/N	Valley load/N	Fatigue life	Average life
$80\%\sigma_u$	1	18.06	1.81	1511	1221
	2	18.60	1.86	931	
$75\%\sigma_u$	3	16.81	1.68	2672	2411
	4	17.34	1.73	2150	
$73\%\sigma_u$	5	16.13	1.61	4125	4221
	6	16.44	1.64	4317	
$70\%\sigma_u$	7	15.65	1.57	10^{6*}	10^{6*}
	8	15.31	1.53	10^{6*}	10^{6*}
	9	15.70	1.58	10^{6*}	10^{6*}



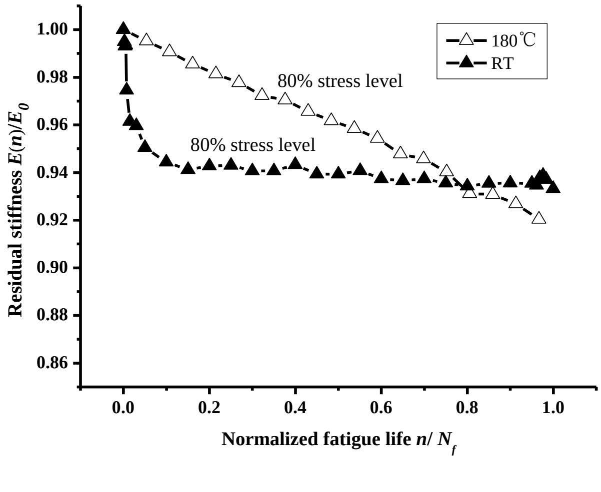


Figure 4(a). S-N curves of 2.5D woven composites at RT and 180℃;(b) Normalized stiffness for maximum applied stress of 80% UTS at RT and 180℃

Additionally, from the view of residual strength (Fig .3(b)), it can be found that the residual strength at elevated temperature is higher than the virgin strength at the corresponding temperature, which can result in an infinite life is reached.

3.3 Stiffness degradation behavior at various temperatures

Fig. 4(b) shows the normalized dynamic stiffness vs. cycle curves for test specimens cycled with maximum applied stress level of 80% at RT and 180℃. The stiffness degradation behavior for the specimens tested at RT can be characterized by a rapid stiffness degradation trend during the first stage of cycling, followed by a gradual stiffness degradation trend during the subsequent stage and a rapid stiffness drop occurs prior to final fracture. The stiffness degradation feature obtained at RT is similar with that for laminated composites tested at RT[12]. Whereas, the notably difference in stiffness degradation behavior is relative to the elevated temperature specimens compared to the room temperature specimens. Compared with the room temperature stiffness behavior, a more gradual stiffness degradation characteristic is observed at elevated temperature environment (Fig. 4(b)). This may result from the duration of matrix affected by elevated temperature.

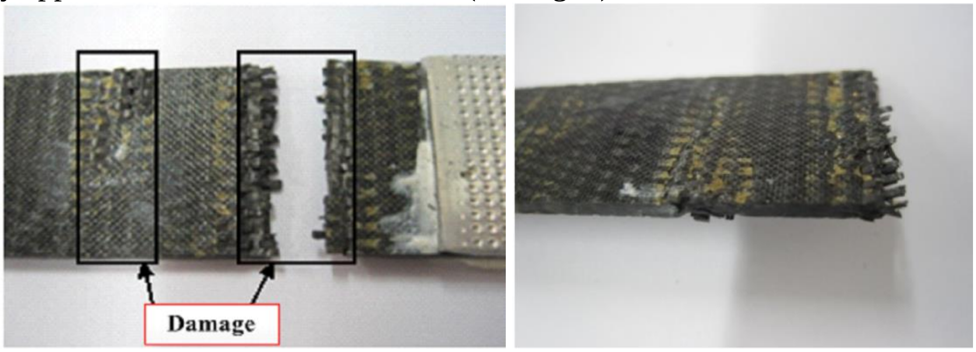
3.4 Residual strength behavior

In order to investigate on the abnormal fatigue behavior tested at 180℃ mentioned above, residual strength tests were performed subjected to 80% stress level at RT and 180℃. After reaching a certain cycle number (1×10^6 cycles), fatigue tests were terminated, and then the as-fatigue strength (defined residual strength) was measured. The corresponding results have been plotted in Fig. 3(a). It can be seen that the tensile stress vs. strain behaviors at RT or 180℃ after the cyclic loading are clearly different from those for the virgin specimens at the corresponding temperatures. The room temperature strength and modulus are both lower than the corresponding fatigued composites, however, the elevated strength and modulus are higher than the fatigued composites conducted at the same temperature, which suggests that although the elevated temperature specimen has been experienced 1,000,000 cycles, the elevated mechanical properties can be strengthened instead. The increase in strength is in agreement with those observed on other composites[13, 14].

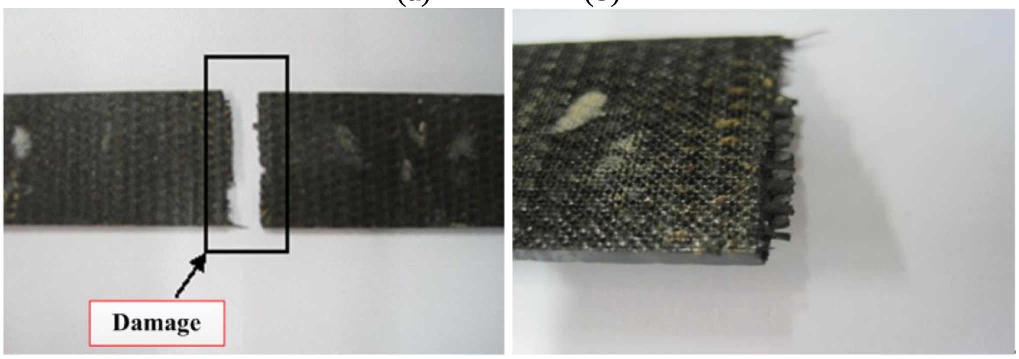
3.5 Fractured surface morphology

Fig. 5 and Fig. 6 display the morphology of fractures observed from the macroscopic and microscopic views for the static tensile samples. From Fig. 5, there is no obvious necking phenomena observed at the fractured surface at RT and 180℃, indicating a brittle-natured fracture. The fracture mainly occurs in the warp bundles at the crossover points of warp and weft bundles. Although larger damage regions and more delamination cracks are observed at RT (see Fig. 5a, b), there is relatively less fiber pull-out for the specimen tested at RT (see Fig. 6).

Fig. 7 and Fig. 8 show the magnified SEM photomicrographs of the fractured surface of the 2.5D woven composites tested at RT and 180℃. From Fig. 7, for the room temperature failure fractures, the failure behaves as interfacial debonding between fibers and matrix and the localized fibers bundles loosen within each other observed near the fractured surface. Whereas, for the elevated temperature failure fractures, the material maintains good integrity and less interfacial debonding damage. Similar fractured morphology with the static tests at 180℃, it is noticeable that the presence of fiber pull-out for the specimens conducted at 180℃ is revealed by the brushy appearance of the fracture surface (see Fig. 8).

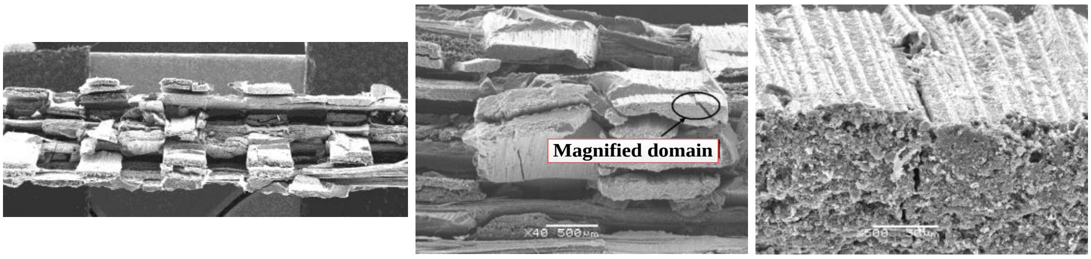


(a) (b)

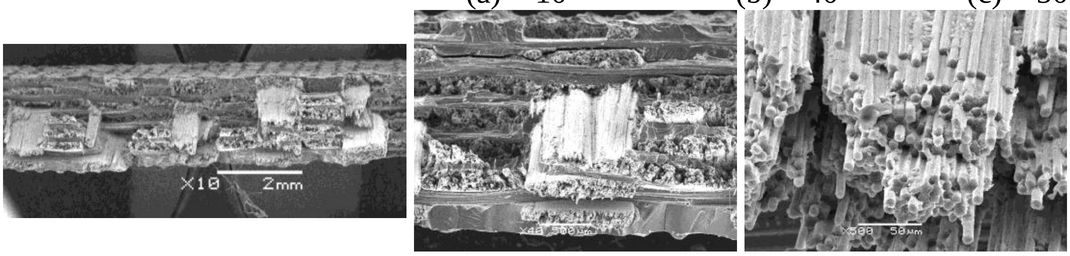


(c) (d)

Figure 5. The fracture photographs of static tension samples at (a)-(b) room temperature and (c)-(d) 180℃

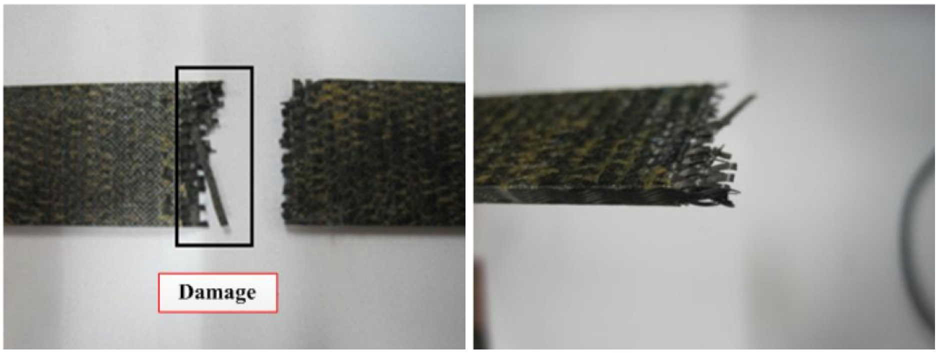


(a) ×10 (b) ×40 (c) ×500

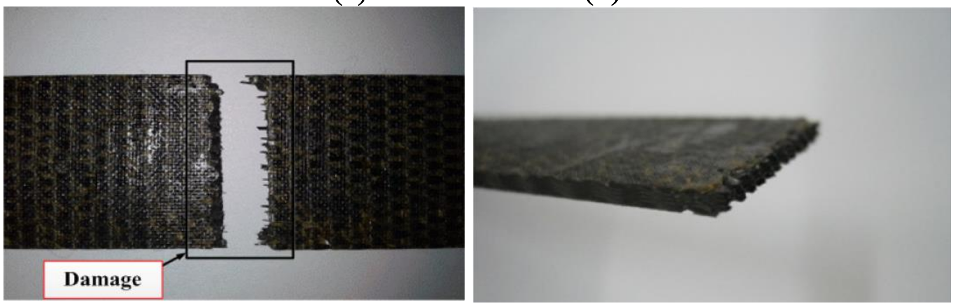


(d) ×10 (e) ×40 (f) ×500

Figure 6. SEM photomicrographs of fracture surface taken from specimens subjected to static loadings, (a)-(c), RT, and (d)-(f), 180℃

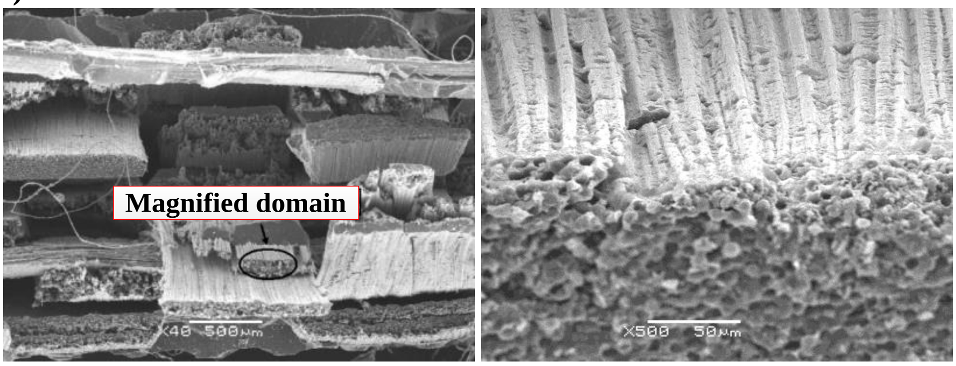


(a) (b)

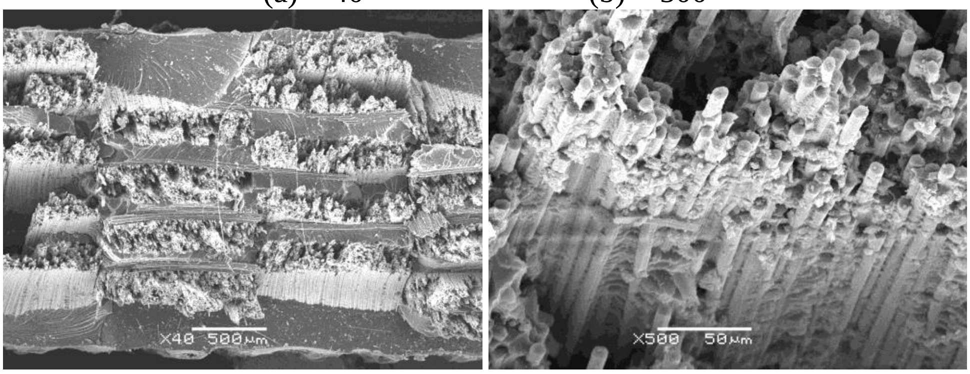


(c) (d)

Figure 7. Fracture surfaces of the fatigue composites subjected to 80% UTS. (a), (b) RT, and (c), (d) 180℃



(a) ×40 (b) ×500



(c) ×40 (d) ×500

Figure 8. SEM photomicrographs of the fatigue composites subjected to 80% UTS. (a), (b) RT, and (c), (d) 180℃

Conclusions

An investigation on the static and fatigue mechanical behavior of 2.5D woven composites at room and elevated temperatures was accomplished. The influence of temperature on the stress vs. strain curves, tensile modulus, strength, fatigue behaviors, stiffness degradation behaviors and residual strength at RT and 180℃ were analyzed and discussed in detail. The damage mechanisms were revealed by observing the fractured morphology and measuring the residual tensile properties. Several useful conclusions were made as following:

(1) The results show the room temperature stress-strain curve has an initial linear behavior, followed by a non-linear feature, while the curves at 180℃ show an obvious non-linear feature. But both of the curves exhibit a brittle fracture feature.

(2) The fatigue life and fatigue strength at 180℃ decrease significantly compared with those at RT subjected to the same stress level. However, the residual strength at 180℃ can be strengthened by fatigue.

(3) The fracture morphology examinations indicate the damage and failure patterns of composites vary with the environmental temperatures. When the temperature is 180℃, there are little indication of large-scale debonding, but the presence of fiber pull-out is revealed by the brushy the bare fibers under the fatigue loading.

References

[1] Shimokawa, T., Kakuta, Y., Aiyama, T. (2008) Static and fatigue strengths of a G40-800/5260 carbon fiber/bismaleimide composite material at room temperature and 150,℃, *J Compos Mater* **6**, 55-79.

[2] Berthe, J., Brieu, M., Deletombe, E., Portemont (2014) Temperature effects on the time dependent viscoelastic behaviour of carbon/epoxy composite materials: Application to T700GC/M21, *Mater Design* **62**, 241-246.

[3] Ludovico, M. D., Piscitelli, F., Prota, A., Lavorgna, M., Mensitieri, G., Manfredi, G. (2012) Improved mechanical properties of CFRP laminates at elevated temperatures and freeze–thaw cycling, *Constr Build Mater* **31**, 273-283.

[4] Bai, Y,, Keller, T., Vallée, T. (2008) Modeling of stiffness of FRP composites under elevated and high temperatures, *Compos Sci Technol* **68**, 3099-106.

[5] Selezneva, M., Montesano, J., Fawaz, Z. (2011) Behdinan K, Poon C. Microscale experimental investigation of failure mechanisms in off-axis woven laminates at elevated temperatures, *Composites Part A: Applied Science and Manufacturing* **42**, 1756-1763.

[6] Vieille, B., Taleb, L. (2011) About the influence of temperature and matrix ductility on the behavior of carbon woven-ply PPS or epoxy laminates: Notched and unnotched laminates, *Compos Sci Technol* **71**, 998-1007.

[7] Montesano, J., Fawaz, Z., Behdinan, K., Poon, C. (2013) Fatigue damage characterization and modeling of a triaxially braided polymer matrix composite at elevated temperatures, *Compos Struct* **101**, 129-37.

[8] Montesano, J., Fawaz, Z., Poon, C. (2014) Behdinan K. A microscopic investigation of failure mechanisms in a triaxially braided polyimide composite at room and elevated temperatures, *Mater Design* **53**,1026-36.

[9] ASTM D3039 (2008) Standard test method for tensile properties of polymer matrix composite materials, *ASTM International*

[10] ASTM D 3479 (2007) Standard test method for tension-tension fatigue of polymer matrix composite materials, *ASTM International*

[11] Zhu, Y, L. (2012) Research on prediction of damage failure and fatigue life for C/C composites. *Nanjing: Nanjing University of Aeronautics and Astronautics*.

[12] Cheng, Y. Z., Xuan, W. W., Yong, S. L., Bo, W., Dong, H. (2013) Tensile fatigue of 2.5D-C/SiC composites at room temperature and 900 C, *Materials and Design* **49**, 814-819.

[13] S.F. Shuler, J.W. Holmes, X. Wu, D. Roach (1993) Influence of Loading Frequency on the Room‐Temperature Fatigue of a Carbon‐Fiber/SiC‐Matrix Composite, *J Am Ceram Soc* **76,** 2327-2336.

[14] Liu, Z., Zhang, H., Lu, Z., Li, D. (2007) Investigation on the thermal conductivity of 3-dimensional and 4-directional braided composites, *Chinese Journal of Aeronautics* **20,** 327-331.