Fatigue behavior of carbon fiber reinforced composite with different stacking sequence

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Abstract. Carbon fibre reinforced composites (CFRC) were widely used in aerospace, civil aviation and construction industry. But fatigue behaviour and damage evolution of CFRC are difficulties to understand for their special structure characters. For this object, CFRC with T700 and EH104 resin were fabricated by different stacking sequence, then the CFRC samples were tested in axial tension and cycle loading with frequency of 10 Hz. Results shown that damage localization were entirely different. The $(0/90)_{12}$ sample was more sensitivity for stress concentration, comparing with $(\pm45)_{12}$ sample. And transverse cracking was formation in 0^{o} layer, then evaluated to delamination with increasing cycles for $(0/90)_{12}$ sample. But delamination propagation with transverse cracks during increasing cycles for $(\pm45)_{12}$ sample. Fatigue behaviour and damage evolution of CFRC indicated that, the critical properties of interfacial strength between fibre and resin, and different layers, were determinant fact for CFRC.

1. Introduction

Benefit by high specific stiffness, strength and weight, carbon fibre reinforced composites were widely used in many territories, such aerospace, civil aviation and construction industry [1]. To utilize the full potential of composite materials, their behaviour under various conditions has to be determined. However deficiencies of knowledge accumulation in failure analysis and damage judgment, it is difficult to give accurate evaluation of realistic accidents, and provide prevent methods. Mechanical distribution of stresses occurs during different types of loading, such as tension, compression, impact and fatigue. An issue of major concern in failure analysis of composites is associated with the occurrence of delaminations or interlaminar cracks with different loading models [2].

The fatigue models of CFRC have been classified into three categories [3]: first one was fatigue life models, based on S-N curves and Goodman-type diagrams, without consider the degradation of strength. Second was residual stiffness/strength based phenomenological models. Finally progressive damage models using more damage variables such as transverse matrix cracks or delamination size, measure the manifestations of damage [4].

The purpose of this study was to examine the relation of loading direction and stacking sequence. To realize the object, all the samples were fabricated with same carbon fibre type and resin, with same process of treatment, curing temperature and holding time, and only the stacking sequence was changed. The data generated in this investigation could be used as a guideline for the design of components from these materials under the influence of loading direction and stacking sequence.

2. Experiment

The carbon fibre and resin used in this study were list in table 1, the carbon fibre was high strength fibre T700, and resin was EH104. The stacking sequence of HKC05 samples was 0/90°, and 12 layers were made to investigate the evolution of transverse matrix cracks. The stacking sequence of HKC06 samples was ±45°, and 12 layers were stacking together.

Table 1 Carbon fibre and resin in composites

Samples	Carbon fibre	Resin	Layer sequence
HKC05	HF40	EH104	[0,90]12s
HKC06	HF40	EH104	[45,-45]12s

Fatigue test was adopted using MTS 810 with hydraulic servo system，bracing sheets were used to maintain the holding situation. The tests were performed in sinusoidal load at a frequency of 10 Hz for tension-tension fatigue test at room temperature. The load ratio of minimum stress to maximum stress was 0.1. The dimensions of fatigue specimen were shown in fig 1. After the test, he specimens were split completely and scanning electron microscopic (SEM) fracture surface observations were carried out.

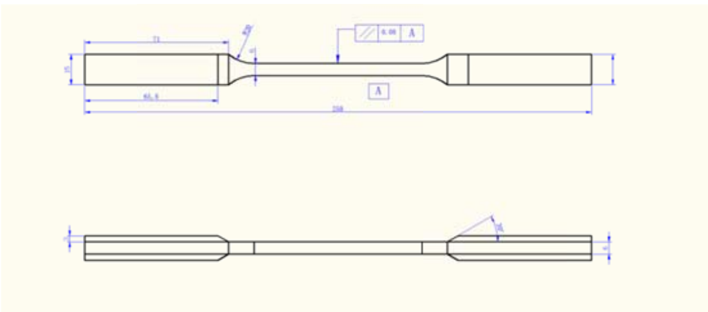

Fig 1 Dimension of fatigue specimen

3. Result and Discussion

3.1.Tension strength and S-N curve

Degradation fatigue test method was used to investigation the fatigue behaviour of CFRC materials. Before fatigue tests, quasi-static tensile was tested, and the average ultimate tensile strength of the HKC05 is about 1087 MPa, while it is about 310 MPa for HKC06 specimen, decrease by 71%.

Maximum stress vs fatigue life curves of HKC05 and HKC06 specimens were shown in fig 2, and the experiment data was fit with Basquin fatigue equation, using least square method. The abscissa axis in fig. 2 denotes number of cycle N in logarithmic scale and ordinate axis denotes maximum stress amplitude. The fitted equations were following:

HKC05

$$\delta=1087.2\times(2N)^{-0.014} \quad (1)$$

HKC06

$$\delta=310.3\times(2N)^{-0.0409} \quad (2)$$

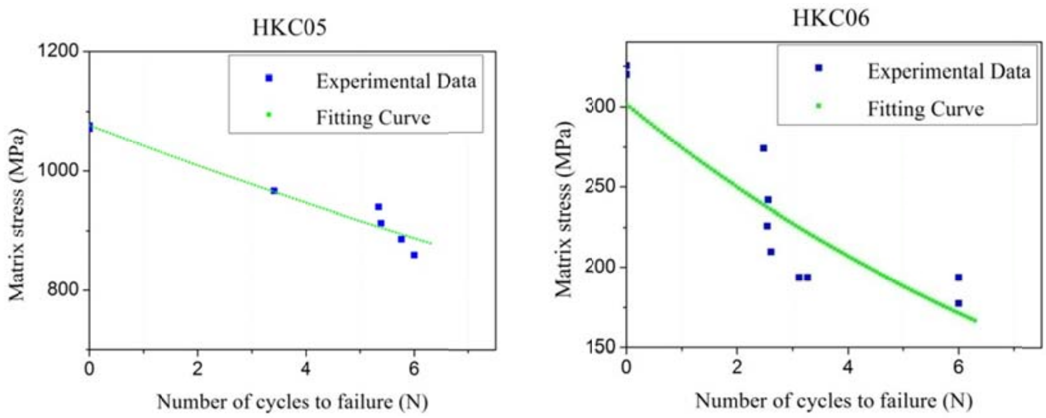

Figure 2: Maximum stress vs fatigue life of HKC05 and HKC06 specimens

While, the Basquin coefficient of HKC05 was 1087 MPa, That about three times over HKC06, and Basquin exponent was -0.014, which was -0.041 for HKC06. Experiment data of above samples indicated that, the direction of carbon fibre in 0o layers of HKC05 was major bearing direction, which was main bearing layer. But the distribution and redistribution of 0o layers and 90o layers were more ambiguous and vague.

3.2. Fracture analysis of HKC05

Tension broken model of HKC05 was shown in fig 3. firstly, the fracture located at the connected position of arc segment and parallel section, where the stress concentration factor is bigger than other place.

Secondly, observation from the side, fracture surface is flat, and scale of high -low for fracture surface was not as significant as fatigue fracture surface. Finally, in the direction of tension of 0^{o} layer, fibre broken was major failure model. But for 90^{o} layer where direction of fibre is normal to loading direction, major failure model was interfacial deboning between fibre and resin matrix.

Fractures of HKC05 broken by fatigue model were shown in fig 4. Firstly, the fracture located at the connected position of arc segment and parallel section too. But the scale of high-low was increasing with the decreasing of maximum loading and prolonging life. Then, transverse matrix cracks and delamination in 90^{0} layer were found in fatigue fracture, and the density of matrix cracks decreasing with distance from fracture surface. For the unbroken sample of HKC05 in fig 4c, even no fibre broken was found, but high density of transverse matrix cracks were found in 90^{o} layer.

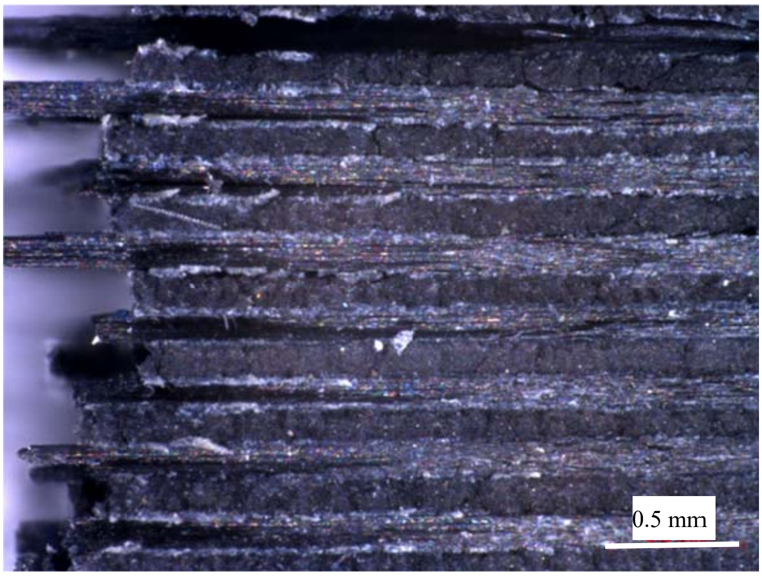

Figure 3: Side morphology of fracture broken by tension of HKC05

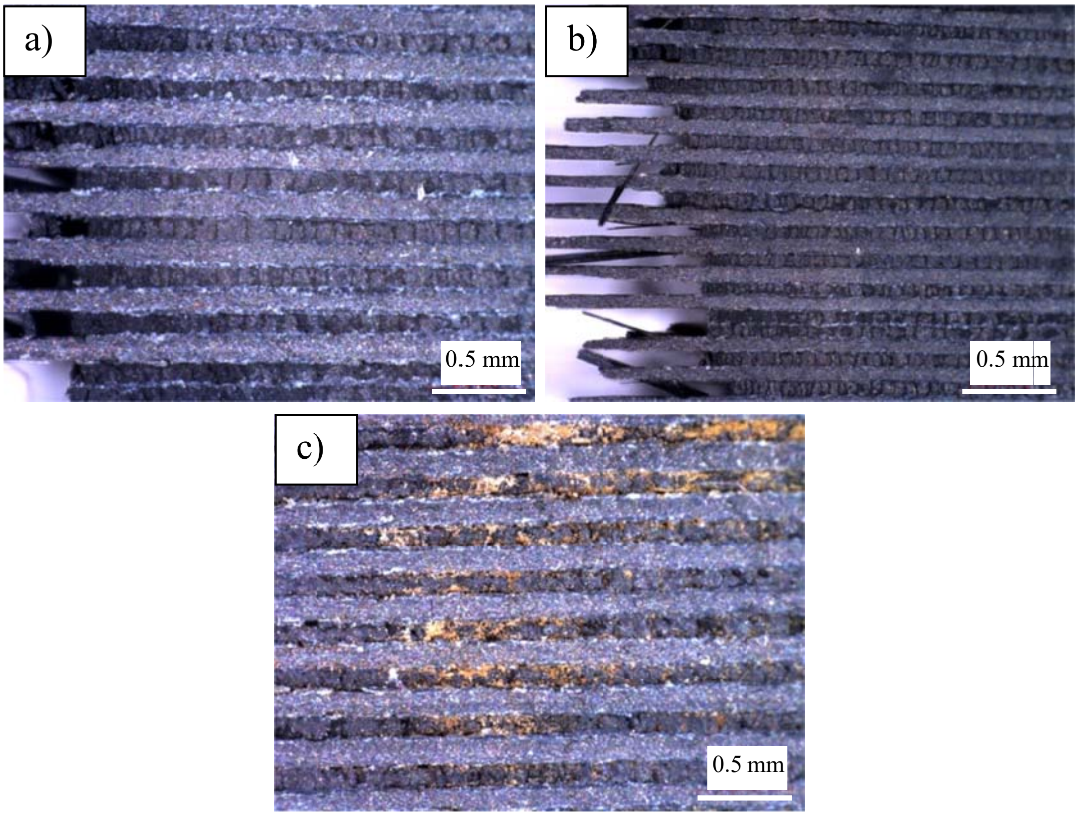

Figure 4: Side morphology of fracture broken by tension fatigue of HKC06 a) Maximum stress 966 MPa, 2545 cycles; b) Maximum stress 912 MPa, 24390 cycles; c) Maximum stress 858 MPa, never broken

3.3. Fracture analysis of HKC06

Fracture of HKC06 broken by tension stress was shown in fig 5. Obvious different from 0/90° stacking sequence of HKC05, fracture located at the middle of parallel section. Which indicated that, the ±45° stacking sequence of HKC06 was not stress concentration sensitivity. Many transverse matrix cracks were found both in +45° layers and -45° layers. Fracture surface area almost including all the parallel section. Finally, almost no fiber broken was found in fig 5.

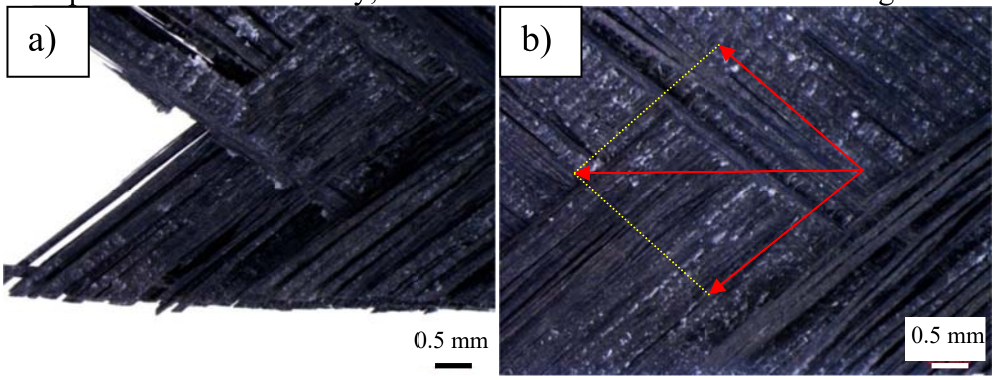

Figure 5: Side morphology of fracture broken by tension of HKC06

Fractures of HKC06 broken by tension fatigue were shown in fig 6. Different from HKC05, all the fractures of HKC06 located at middle position of parallel segment, and main cracks all propagated alone centre line of specimen, as shown in fig 6a and 6b. Even for unbroken specimen, a large number of transverse matrix cracks list alone the centre line and all the side of specimen. With the increasing distance from centre line, the crack width of transverse cracks decreased. That indicated that the main crack alone centre line formatted by saturation of transverse matrix cracks.

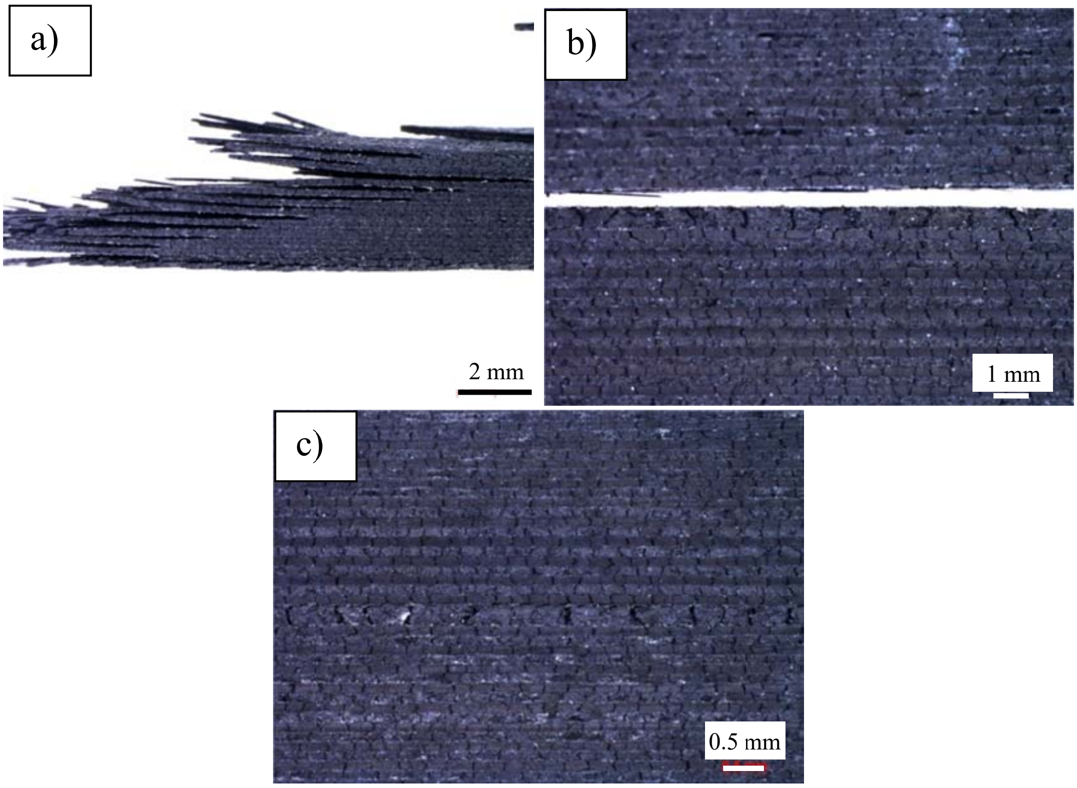

Figure 6: Fatigue fracture of HKC06 a) Maximum stress 274 MPa, 301 cycles; b) Maximum stress 193 MPa, 1856 cycles; c) Maximum stress 193 MPa, never broken

Macroscopic structure on the fracture surface of sample in fig 6a was shown in fig 7. The Fracture direction was alone 45° to tension direction. Expect some reverse of fibre, no broken fibre was found in the fracture surface. Resin broken cracks alone fibre direction as marked as yellow dotted line, and propagated at direction normal to fibre direction, as red arrow in fig 7.

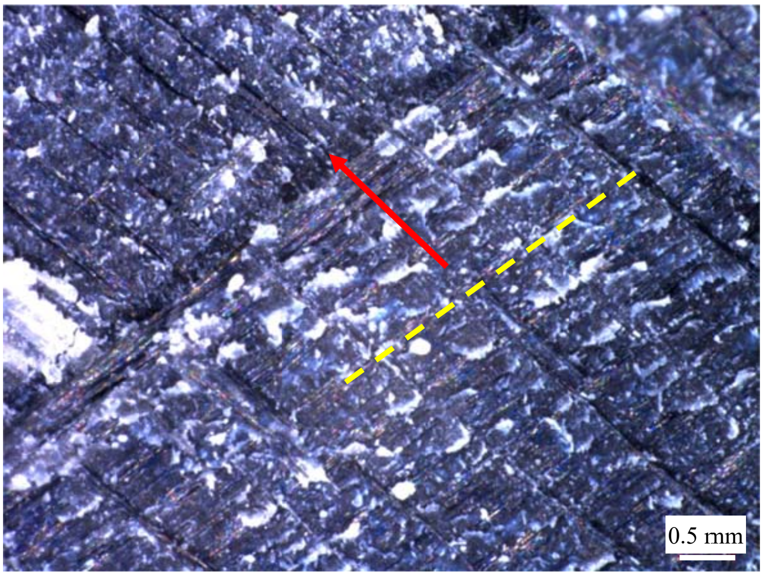

Figure 7: Fatigue surface of sample in fig 6a

As shown above, level and evolution mode of strain location was also the major failure process of fatigue for carbon fibre reinforced composites. But the realization was significant different from metal materials[5]. Weak spot and vulnerable position were also the potential initiation of cracks. For metal, the potential position always near surface, with plane stress problem and stress concentration. But it was different for carbon fibre reinforced composites, with a large number of interface, including fibre and resin matrix, different stacking layers, et al. So even one crack was initiation on individual position, stress would redistribution in matrix and fibres, and no major crack propagated alone the fracture surface. Many weak position would initiate cracks, and would hold by interface. With the density of cracks increasing, the capability of resistance deformation would dropped dramatically. For application of CFRC, improving the strength of interface is one critical problem.

4. Conclusions

The above result indicated that, failure model of CFRC relevance to stress direction and stacking sequence, with same carbon fibre and resin, and fabricated process. The bearing ability was related to the proportion of 0° layer, but 45° layer improved the resistance for stress concentration. some conclusions could get from the results:

1. With same condition, including fibre and resin, fabrication, mechanical situation, strength of HKC06(±45° layers) is lower than HKC05(0/90° layers). the tensile strength decrease 71%, from 1087 MPa to 310 MPa. The fatigue strength decrease 81 %, from 887.2 MPa to 171.4 MPa.
2. HKC05 samples more sensitive to stress concentration. at the same mechanical loading situation, all the HKC05 samples broken in stress concentration sensitive zone. while, all the HKC06 samples broken in middle of parallel segment.
3. The damage accumulated process of HKC05 was following: first transverse matrix cracks initiation and hold by interface of different layers, and closed cracks were formatted. With

increasing of loading cycles, more closed cracks formatted. The density of transverse matrix cracks improve continually, ultimately, delamination crack initiation from interface of different layers.

4. The damage accumulated process of HKC06 was following: under uniform tensile force, the stress component act on fibre direction and normal stress component act on resin matrix. But the carrying loading capacity of resin is weak, and first cracking during cycle loading and tension loading. The stress redistribution in composites, and new cracks initiation on interface or resin, finally, fatigue break is occurrence.

Acknowledgements

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