Fatigue crack growth and propagation along the adhesive interface between fiber-reinforced composites

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Abstract

There is not yet a well-developed method to conduct in situ fatigue test for interface crack of composite material. This paper presents a specified loading setup based on DCB-Uneven Bending Moments (DCB-UBM) test, which can control the mixed modes of interface crack. During the loading process, CCD camera is used to in situ monitor and record the initiation of the fatigue crack and its growth rate. In addition, digital image correlation (DIC) method is adopted to obtain the deformation near the crack tip. Finally, the experimental results and DIC analysis demonstrate some meaningful mechanism of interfacial crack propagation for composite material.

1. Introduction

Fiber-reinforced composites such as GRFP have a widely application in aircraft, wind turbine blades and construction materials due to their high strength and excellent mechanical properties [1–5]. And high-toughness adhesives are usually used to bond two composite laminates (such as the sandwich structure) in the process of the structural design. However, these aircraft structures made of the fiber-reinforced composites are usually subjected to complicated cyclic loadings during flight, such as the aerodynamic loadings, random cyclic loadings, temperature changes and rain corrosion environments [6–8]. Thus, fatigue damage and fatigue crack initiation and growth (e.g. the delamination in laminates and adhesive joints) inevitably occur in these structures and the crack propagation may lead to catastrophic accident [7,9–12]. However, the physical mechanism of the fatigue crack for composite materials (such as the crack initiation and propagation) is not yet understood fundamentally. It is therefore very important to investigate the fracture properties of composite materials under cyclic loadings.

Various test approaches for composite materials have been proposed to test the fracture toughness. For instance, Double Cantilever Beam (DCB) test method has been widely used and standardized internationally [13–15], but it is only applicable to obtain pure mode I crack fracture toughness. End Notched Flexure (ENF) test method [16–18] is the well-known method for the determination of mode II fracture toughness because of its simplicity. However, its crack propagation is unstable. Mixed Mode Bending (MMB) test [19,20] is the most widely used method for Mixed Mode fracture toughness but its instability limits its application. DCB-UBM test [21–23] achieves a range of mode mixities as well as its crack growth under both static and cyclic loadings is stable. However, there is not yet an international standard for DCB-UBM method because of its immaturity. Therefore, it is significant to develop DCB-UBM method to determine Mixed Mode fracture toughness of composite materials, as well to analyze the crack growth and propagation under cyclic loadings.

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In combination of DCB-UBM method and DIC technique, a loading setup is developed to measure Mixed Mode fracture
toughness of the adhesive interface in composite materials, which can be conducted on a standard testing machine. The
mode mixity of the interface crack can be controlled by adjusting the loading position. In addition, CCD camera is used to
in situ monitor the initiation and the propagation of the interfacial crack during the cyclic loadings. Furthermore, digital im-
age correlation (DIC) method is applied to obtain the distribution of the stresses and strains around the crack tip. Finally
crack growth rate, the singularity at the crack tip and the relation between fracture toughness and loading cycles are
analyzed.

2. Experimental methods

Based on DCB-UBM test, we propose a setup used to test the interfacial crack of composite materials especially suitable
for the sandwich-beam structure specimen, shown in Fig. 1a. The uncracked end of the specimen is fixed at the central sup-
port with two top beams. The beams of the cracked end of the specimen are jointed with the transverse arms hanging via
two springs. In this system, the loading transfer is controlled by a wire rope, which runs from a bottom beam, to a transverse
arm, then up to a top beam, to the other top beam, down on the other side and repeat the process on the back of the loading
equipment to finally form a closed circle via rollers. Therefore, the uneven pure bending moments in the cracked end of the
specimen can be created by applying loadings to the bottom beams with different distance between rollers on the transverse

\[ M_1 \] bending moment applied to bottom beam of GFRP
\[ M_2 \] bending moment applied to top beam of GFRP
\[ G_{\text{max}} \] maximum energy release rate
\[ G \] energy release rate
\[ E_1 \] plane strain modulus of GFRP
\[ E_2 \] plane strain modulus of adhesive layer
\[ E_{11} \] Young's modulus (in the \( x_1 \) direction) of GFRP
\[ E_{22} \] Young's modulus (in the \( x_2 \) direction) of GFRP
\[ E_2 \] Young's modulus of adhesive layer
\( \mu \) shear modulus
\( \mu_{12} \) shear modulus in the \( x_1 - x_2 \) plane of GFRP
\( \nu_{12} \) Poisson's ratio in the \( x_1 - x_2 \) plane of GFRP
\( \nu_2 \) Poisson's ratio of the adhesive layer
\( t \) the ratio of the plane strain modules
\( h_1 \) GFRP thickness
\( h_2 \) adhesive layer thickness
\( h_0 \) thickness parameter
\( \eta \) the ratio of thicknesses
\( P \) the applied loading
\( P_m \) the average loading
\( P_a \) the amplitude of the loading
\( l_1 \) the moment arm corresponding to \( M_1 \)
\( l_2 \) the moment arm corresponding to \( M_2 \)
\( I_1 \text{down}, I_2 \text{down}, I_1 \text{up}, I_2 \text{up} \) moments of inertia
\( \sigma_{xx} \) normal stress (in \( x_1 \) direction)
\( \tau_{xy} \) shear stress (in \( x_1 - x_2 \) plane)
\( \varepsilon_{xx} \) normal strain (in the \( x_1 \) direction)
\( \varepsilon_{yy} \) normal strain (in the \( x_2 \) direction)
\( \varepsilon_{xy} \) shear strain (in the \( x_1 - x_2 \) plane)
\( K_I \) stress intensity factor in mode I
\( K_{II} \) stress intensity factor in mode II
\( K \) interface stress intensity factor
\( K^{\infty} \) apparent stress intensity factor for homogeneous material
\( \phi \) real phase angle
\( \psi \) phase angle for homogeneous material
\( r \) the distance from the crack tip
\( \alpha, \beta \) Dundurs' parameters
\( p, e, \omega, \Omega, K, K_1 \text{ and } K_2 \) material constants
\( f \) loading frequency
arms and top beams (different moment arms), but the force of the wire rope equals everywhere in the loading process. It should be noted that the magnitude and direction of the moments can be controlled by adjusting the distance of the rollers and the way the wire goes to control the mixed mode.

Fatigue tests mentioned above are conducted by the standard materials testing machine (INSTRON 8800), shown in Fig. 1b. During the whole process of the fatigue test, the sinusoidal loading, controlled by WaveMatrix Dynamic Testing Software, is exerted on the bottom beams. The actual loading and the position of the bottom beams can also be automatically recorded and displayed by the software. Meanwhile, the CCD camera is working to in situ monitor the specimen to record the crack initiation and propagation. The region near the crack tip of the specimen is lightened by a LED light to capture pictures with appropriate brightness for 2D DIC analysis, which is an in-plane displacement measurement technique that correlates a pair of digital speckle patterns obtained at two different loading conditions and searches for the maximum correlation coefficient [24].

DIC method is taken to analyze the singularity and fatigue properties. Firstly, a set of images captured by CCD are calculated by our own DIC software with an accuracy of 200 microstrains to determine the deformation around the crack tip. Then the normal strain $\varepsilon_{xx}$ and in-plane shear strain $\varepsilon_{xy}$ around the crack tip are extracted to further analyze the property of the fracture toughness and stress intensity factor during the fatigue test. Furthermore, the in-plane normal stress and shear stress in front of the crack tip are obtained with the linear elastic assumption, in other words, the normal stress and shear stress can be expressed as $\sigma_{xx} = K(\varepsilon_{xx} + \varepsilon_{yy}) + 2\mu\varepsilon_{xy}$ and $\tau_{xy} = 2\mu\varepsilon_{xy}$, respectively. Based on linear fracture mechanics, the SIF of mode I and mode II are given by $K_I = \lim_{r \to 0} (\sigma_{xx} \sqrt{2\pi r})$ and $K_{II} = \lim_{r \to 0} (\tau_{xy} \sqrt{2\pi r})$ respectively. However, the exact value of SIF cannot be obtained at $r = 0$. Therefore, we select a set of $\sigma_{xx}$ and $\tau_{xy}$ at $r^i$ around the crack tip, and the corresponding $K_I^i$ and $K_{II}^i$ can be calculated as

$$K_I^i = \sigma_{xx}^i \sqrt{2\pi r^i}, \quad K_{II}^i = \tau_{xy}^i \sqrt{2\pi r^i}$$

(1)

Then, the SIF $K_I$ and $K_{II}$ at the crack tip ($r = 0$) can be obtained via fitting data points ($r^i, K_I^i$) and ($r^i, K_{II}^i$). The schematic diagram for proposed model of the sandwich structure, which is composed of two GFRP composite laminates and an adhesive layer, is shown in Fig. 2a. Usually, GFRP composites are anisotropic. However, in order to simplify the analysis and experiment, we still consider the GFRP as isotropic. A pre-crack lies along the interface between the top beam and the adhesive layer. The free ends of the top beam and the bottom beam are subjected to cyclic moments $M_1$ and $M_2$ dur-
ing fatigue tests, respectively. The maximum energy release rate $G_{\text{max}}$ constant test will be conducted in the fatigue test, where $G_{\text{max}}$ is the maximum energy release rate corresponding to the maximum loading per cycle during the fatigue test. The energy release rate taking account of the adhesive layer can be calculated as

$$G = \frac{1}{2E_1 I_{1d} + t_2 I_{2d,up}} + \frac{1}{2E_2 I_{2d,down}} - \frac{1}{2E_1 I_{1u} + 2t_2 I_{2u}}$$

The material and geometrical parameters are defined as following, $I_{1d} = \frac{h_0^2 - 3h_2h_0 + 3h_2^2}{3}$, $I_{1u} = \frac{h_0^2}{12}$, $I_{2d,up} = I_{1u}(4\eta^2 + 6\eta^2 + 3\eta)$, $h_0 = h_1 + \frac{t}{2}[\frac{h_1^2 + h_2^2 + 2h_1h_2}{2(h_1 + h_2)}]$, $\eta = \frac{h_1}{h_2}$ and $t = \frac{h_1}{h_2}$. Where $E_1$ and $E_2$, $h_1$ and $h_2$ are the plane strain modulus and thickness of GFRP and the adhesive layer respectively. The applied moments per unit thickness $M_1$ and $M_2$ can be obtained as $M_1 = Pl_1/2B$, $M_2 = Pl_2/2B$, $M = M_1 + M_2$. Where $P$ is the applied loading, $B$ is the thickness of the specimen, and $l_1$ and $l_2$ are the moment arms corresponding to $M_1$ and $M_2$ respectively.

### Table 1

<table>
<thead>
<tr>
<th>$E_{11}$ (MPa)</th>
<th>$E_{22}$ (MPa)</th>
<th>$\mu_{12}$ (MPa)</th>
<th>$\nu_{12}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>43,400</td>
<td>12,400</td>
<td>3830</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Fig. 3. Loading history with the maximum energy release rate 0.6 kJ/m$^2$, loading ratio 0.5 and loading frequency 0.5 Hz.

Fig. 4. Images of micro-crack propagation through the defect for No. 1 specimen. (a) A bulge defect exists before loading and there are micro-cracks around the defect. (b) A micro-crack grows when cycles are 25,640. (c) The crack grows to the middle of the defect when cycles are 40,080. (d) The crack does not continue to grow even the cycles reach 220,000.

### 3. Fatigue test

As is shown in Fig. 2b, a typical sandwich-beam structure is used in the test. The top and bottom beams are GFRP laminates, which are manufactured by vacuum resin infusion with unidirectional glass fiber E-LT 5500 and unsaturated
polyester resin R920-E. The anisotropic modulus of GFRP with a length of 300 mm, width of 30 mm and thickness of 8 mm are listed in Table 1. However, only the property along the fiber is considered for simplicity, that is, we consider the modulus of GFRP as $E_1 = 43.4$ GPa and $v_2 = 0.27$. The two composite beams are joined by adhesive layer MA560-1 with 3 mm thickness, and the modulus and Poisson's ratio of adhesive layer are $E_2 = 311$ MPa and $v_2 = 0.3$, respectively. Here, the material parameters of GFRP and adhesive layer are obtained by the standard tensile test. A pre-existing crack (main crack) of 5 mm length, 30 mm width, and 0.1 mm thickness lies along the interface between the adhesive layer and the bottom beam, which is made by a hacksaw blade. To analyze the singularity at the crack tip with DIC method, clear speckles with random black paint particles and white paint particles are sprayed on the surface of the specimen before applying loading. Adjusting test is conducted in the first step to verify that the test method can perform as intended. In the adjusting test, the valid range of the loading level, the loading frequency and the mode mixture will be checked. The results show that the maximum applied loading lower than 1004 N (the corresponding maximum energy release rate lower than 1.5 $\text{kJ/m}^2$) and the loading ratio (the ratio of the minimum applied loading to the maximum applied loading) larger than 0.5 are appropriate in this system. The loading frequency, ranging from 0.5 Hz to 0.8 Hz, works well and higher frequency leads to the hysteresis phenomenon of the applied loading because of the flexibility of the wire rope. Fig. 3 shows the loading history with the maximum energy release rate 0.6 $\text{kJ/m}^2$, loading ratio 0.5 and loading frequency 0.5 Hz. It can be seen that the loading keeps sinusoidal wave very well after a tiny fluctuation at the moment the loading is applied. Although this approach is applicable to a wide range of the loading modes, it is easier for CCD camera to capture the crack propagation in mode I dominant crack.

<table>
<thead>
<tr>
<th>Stage no.</th>
<th>$G_{\text{max}}$ (kJ/m²)</th>
<th>$P_m$ (N)</th>
<th>$P_a$ (N)</th>
<th>$f$ (Hz)</th>
<th>Total cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>555</td>
<td>185</td>
<td>0.5</td>
<td>8500</td>
</tr>
<tr>
<td>2</td>
<td>0.85</td>
<td>566</td>
<td>189</td>
<td>0.5</td>
<td>125,000</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>598</td>
<td>199</td>
<td>0.5</td>
<td>170,000</td>
</tr>
<tr>
<td>4</td>
<td>0.95</td>
<td>598</td>
<td>199</td>
<td>0.5</td>
<td>530,000</td>
</tr>
<tr>
<td>5</td>
<td>1.0–1.4</td>
<td>753</td>
<td>251</td>
<td>0.5</td>
<td>580,165</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>753</td>
<td>251</td>
<td>0.5</td>
<td>610,165</td>
</tr>
</tbody>
</table>
than mode II dominant crack since the phenomenon of interfacial delamination is more obvious than that of interfacial slippage. Therefore, the direction of moments loaded at the end of top and bottom beams is chosen to be opposite. In our test, the moment arms $l_1$ and $l_2$ are 0.138 m and 0.058 m respectively. Then, $G_{\text{max}}$ constant tests for specimen No. 1 and No. 2 are conducted. During the test, the crack propagation and the deformation near the crack tip are recorded in a certain frequency by a CCD camera.

4. Experimental results

$G_{\text{max}}$ constant test for specimen No. 1 is conducted with the maximum energy release rate 0.8 kJ/m$^2$, loading ratio 0.5 and loading frequency 0.5 Hz. Fig. 4a shows the main crack of No. 1 specimen close a defect, while the inset figure enlarges the
micro-cracks in front of the main crack tip meeting the defect. Before loading, the defect resulted from the process of the fabrication, which looks like a bulge, locates in front of the main crack tip. There are two micro-cracks (one on the left and the other one on the right) at the edge of the defect. Under the cyclic loading, the main crack does not grow, but the left micro-crack moves forward turning left nearly 45° and the right micro-crack grows along the edge of the defect in a clockwise direction. That is, both of two micro-cracks grow towards to the direction of the main crack tip, showing tendency to merge into the main crack, shown in Fig. 4b when loading cycles is 25,640. Then, both micro-cracks continue to grow with the crack tip of the left micro-crack reaching the middle of the defect when loading cycles is 40,080, shown in Fig. 4c. However, with the increase of loading cycles, the propagation of micro-cracks nearly stops and has not obvious propagation even loading cycles increase to 220,000, as shown in Fig. 4d. The process of the micro-cracks growth shows an interesting phenomenon that the micro-cracks tend to merge into the main crack.

The test process for specimen No. 2 is shown in Table 2, where f is the loading frequency. In the test, the maximum value of the applied loading increases from 633 N to 1004 N and the corresponding maximum energy release rate ranges from 0.8 kJ/m² to 1.5 kJ/m². \( P_m \) and \( P_a \) are the corresponding average loading and amplitude of the loading exerted on the bottom beam respectively when the loading ratio is 0.5. In the table, total cycle denotes the accumulated cycles.

Fig. 5 shows the crack propagation of specimen No. 2 under the cyclic loading. A set of eight-bit images with the resolution of 1024 × 768 pixels was captured in different cycles, the physical size of 1 pixel in which corresponds to 5.9 μm and the speckles are clear at this magnification level. These digital images then are used for DIC analysis. Before loading, there is a

![Figure 8](image_url)

**Fig. 8.** The strains in front of the crack tip under different loading cycles. (a) Normal strain. (b) Shear strain.

![Figure 9](image_url)

**Fig. 9.** SIF versus loading cycles. (a) SIF in mode I. (b) SIF in mode II.

<table>
<thead>
<tr>
<th></th>
<th>( K_I ) (MPa ( \sqrt{m} ))</th>
<th>( K_{II} ) (MPa ( \sqrt{m} ))</th>
<th>( \tan(\phi) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical results</td>
<td>0.526</td>
<td>0.069</td>
<td>0.131</td>
</tr>
<tr>
<td>FEM results</td>
<td>0.480</td>
<td>0.050</td>
<td>0.103</td>
</tr>
<tr>
<td>Experimental results</td>
<td>0.322</td>
<td>0.0140</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Table 3

Comparison of the stress intensity factor by theoretical, FEM and experimental methods.
main crack of 5 mm length, 30 mm width, and 0.1 mm thickness, where the crack tip is situated at (581,390) pixel, shown in Fig. 5a. Under the cyclic pure moment, the initiation of the micro-crack occurs at the tip of the main crack and it grows along the interface between composite layer and adhesive layer. As is shown in Fig. 5b, the extension of the micro-crack is 0.78 mm when the cycles are 170,000. However, the propagation of the main crack along the interface stops and a new crack (the first new crack) with the 0.429 mm length inside the adhesive layer (on the left of the main crack) initiates when cycles reach 300,000, shown in Fig. 5c. With the increase of the loading cycles, both of two crack tips of the first new crack continue to grow parallel to the interface. The total crack length reaches 0.807 mm when cycles increase to 530,000, shown in Fig. 5d. However, the crack propagation rate decreases with the increase of cycles, so we increase the applied loading from 818 N to 968 N to save the time and cost. Under the elevated loading, the crack growth rate increases obviously and the first new crack length reaches 1.91 mm when total cycles are up to 568,465, shown in Fig. 5e. Then, with the applied loading of 1004 N, the other new crack inside the adhesive layer with the 0.93 mm length appears, connecting the main crack and the first new crack when total cycles are 610,465, shown in Fig. 5f. At that time, the main crack and two new cracks merge into a long crack. It can be seen from Fig. 5 that the pre-crack between composite layer and adhesive layer may not always grow along the interface and new fatigue cracks will initiate around it. But the pre-crack and new cracks will connect together finally with the increase of the loading cycles and change the original propagation direction of the pre-crack.

Fig. 6 shows the crack extension of the No. 2 specimen versus the loading cycles under the constant maximum loading of 797 N. It can be found that the crack growth rate decreases with the increase of crack extension and almost reaches a constant value eventually. This phenomenon can be explained by the bridging zone near the crack tip. In the very early stage of the loading cycling, the crack tip propagates from the initial position rapidly without a bridging zone. With the increase of loading cycles, the bridging zone forms near the crack tip by ligaments in the interface. The ligaments effectively unload the crack tip stress field and reduce the crack growth rate by transmitting stress between the crack faces. Finally, the crack growth rate can get a steady-state value when the bridging zone is fully developed. It is concluded that the presence of large-scale bridging zone is beneficial under cyclic loading since it can increase the ability of load-bearing structures to prevent delamination crack propagation.

Finally, the singularity and fatigue properties of the main crack for specimen No. 2 are to be determined by DIC method. Firstly, a set of images captured by CCD are used for deformation analysis by our own DIC software. Then the displacement field and strain field can be obtained after DIC analysis. Fig. 7 shows the typical results of the normal strain $\varepsilon_{xx}$ contour in $x$ direction (Fig. 7a) and in-plane shear strain $\varepsilon_{xy}$ contour (Fig. 7b). It can be seen qualitatively that both of the normal strain and shear stress decrease with the increase of the distance from the crack tip with the location of (581,390) pixel, which demonstrates the obvious stress concentration phenomenon near the crack. It is also found that the shear strain is obviously smaller than normal strain because of the selected applied loading inducing mode I dominant crack.

Then, the variation of the normal strain and shear strain in front of the crack tip with respect to distance from the crack tip are extracted, shown in Fig. 8a and b respectively. It can be seen quantitatively that both of the normal strain and shear strain decrease with the increase of the distance from the crack tip. And the shear strain is an order magnitude smaller than the normal strain.

Finally, the SIF versus cycles are shown in Fig. 9 via quadrillion polynomial fitting. It can be seen that both of SIF in mode I and mode II increase with the increase of the loading cycles. It is easy for us to understand the tendency from 40,000 cycles to 170,000 cycles because the increasing of the applied loading leads to more obvious singularity at the crack tip. However, both of SIF $K_I$ and $K_{II}$ continue to increase from 170,000 cycles to 530,000 cycles when the applied loading keeps constant (see the loading stage in Table 2). It means that the singularity of the interfacial crack between GFRP and the adhesive material tends to grow under cyclic loading with the constant ratio, that is, the crack tip becomes sharp in this case. Therefore, the propagation of interface crack becomes easy under the cyclic loading.

5. Theoretical analysis and finite element method validation

Suo [22] theoretically analyzed the interface crack in the sandwich structure and obtained analytical results of the singularity and crack mode when the middle layer is small compared with other length scales of the structure. Here, to distinguish the SIF and the phase angle for the interface crack of the sandwich structure and the crack of homogenous material, we note the interface SIF $K$ and real phase angle $\phi$ for the interface crack of the sandwich structure and apparent SIF $K^\text{app}$ and phase angle $\psi$ for homogeneous material. The relation between the actual interface SIF, phase angle and the apparent SIF, phase angle associated with the corresponding homogeneous material without considering adhesive layer is as follows respectively [26]

$$K^\text{app} = pK^\text{app}e^{\psi}, \quad \phi = \psi + \omega(\alpha, \beta)$$

where $\omega$ is a real function of only Dundurs’ parameters $\alpha$ and $\beta$. The material constants $p$ and $\varepsilon$, and Dundurs’ parameters $\alpha$ and $\beta$ are defined as

$$p = \sqrt{\frac{1 - \alpha^2}{1 - \beta^2}}, \quad \varepsilon = \frac{1}{2\pi} \ln \frac{1 - \beta}{1 + \beta}.$$
\[ x = \frac{\Gamma (k_2 + 1) - (k_1 + 1)}{\Gamma (k_2 + 1) + (k_1 + 1)}, \quad \beta = \frac{\Gamma (k_2 - 1) - (k_1 - 1)}{\Gamma (k_2 + 1) + (k_1 + 1)} \]  

(4)

where \( \Gamma = \mu_1 / \mu_2, \kappa = 3 - 4v \) for plane strain problem, and \( \mu \) and \( v \) are the shear modulus and Poisson ratio respectively.

The apparent SIF \( K^\infty \) and phase angle \( \psi \) for homogeneous material are given by [16]

\[ K^\infty = |K^\infty| (\cos \psi + i \sin \psi), \psi = \tan^{-1}\left( \frac{\sqrt{3} M_1 + M_2}{2 M_2 - M_1} \right) \]  

(5)

where \( |K^\infty| = \sqrt{E_1 G} \).

Therefore, the actual interface SIF and the phase angle can be obtained by substituting Eq. (5) into Eq. (3) under the static loading. It is found that the real phase angle in Eq. (5) is controllable via changing the magnitude and direction of the moments in the developed DCB-UBM system. Theoretically, any phase angle for homogeneous material can be obtained under different moments via adjusting the distance of the rollers and the way the wire goes. However, the real phase angle for interfacial crack is much more limited in bonded joints.

The analytical results of SIF under the static loading can be obtained from Eq. (3). With the applied average loading \( P_m = 598 \) N, the SIF and phase angle are \( K_1 = 0.526 \) MPa \( \sqrt{m} \), \( K_\Pi = 0.069 \) MPa \( \sqrt{m} \) and \( \tan(\phi) = 0.131 \).

In order to validate the analytical results, FEM (Finite Element Method) analysis is conducted by utilizing Abaqus 6.9 commercial software. As shown in Fig. 2a, a sandwich structure of real size is created. At the same time, a contour integral pre-crack with the propagation direction along the interface is defined. The 4-node bilinear plane strain quadrilateral element is adopted and the elements are refined around the crack tip to reduce the inaccuracy due to the stress concentration near the crack tip. One end of the sandwich structure is fixed and the top and bottom beams in the other end are subject to two moments. With applied average loading \( P_m = 598 \) N in the experiment, the corresponding moments on the top and bottom beams per unit thickness are \( M_1 = 1375.4 \) N and \( M_2 = 578.0 \) N. Then, the corresponding SIF and phase angle can be obtained as \( K_1 = 0.480 \) MPa \( \sqrt{m} \), \( K_\Pi = 0.050 \) MPa \( \sqrt{m} \) and \( \tan(\phi) = 0.103 \).

The Comparison of the stress intensity factor by theoretical, FEM and experimental methods is shown in Table 3. It can be found that relative errors of the analytical results and FEM results for SIF in mode I and mode II are 8.75% and 27.5%, which agree relatively well with each other. However, the SIF of experimental results are lower than the analytical results and FEM results. In fact, the assumption of perfectly bonded interface and the isotropic assumption of composite materials will enhance the singularity at the crack tip. The introduction of cohesive constitutive of interface may improve the consistency. Anyway, the DIC results give a good tendency of the singularity at the crack tip under the cyclic loadings.

### 6. Concluding remarks

A loading system based on DCB-UBM method is taken to measure the fatigue properties and fracture toughness of the interface crack for composite materials, in which the mixed mode of interface crack can be controlled. The loading system can be conducted on standard material machine as well as CCD camera is used to in situ monitor the fatigue crack growth and propagation. With the combination of the DCB-UBM test system and CCD camera, the initiation of the fatigue crack of the composites and its growth rate can be recorded clearly during loading cycles with CCD camera. It is found that the crack growth rate decreases with the increase of crack extension and almost reaches a constant value eventually due to the presence of large-scale bridging zone. In addition, DIC method is used to analyze the deformation near the crack tip. Under constant values of the applied moments, the DIC results indicate that the crack tip stress intensity factor increases with the increase of loading cycles, that is, the singularity of the interfacial crack between GFRP and adhesive material still tends to grow under cyclic loadings. In conclusion, it is easier for the crack in composites to propagate under the cyclic loading than the static loading.

### Acknowledgments

We gratefully acknowledge the support from National Natural Science Foundation of China (Grant Nos. 90816007, 91116006 and 10902059), Tsinghua University Initiative Scientific Research Program (No. 2011Z02173) and Foundation for the Author of National Excellent Doctoral Dissertation of China (FANEDD) (No. 2007B30).

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