The effect of electrical anisotropy on delamination detection sensitivity of self-conductive carbon fiber composite

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ABSTRACT

The electrical resistance change with respect to delamination in self-conductive carbon fiber/epoxy (CF/EP) composite was investigated. As an example of application, the case of a Double Cantilever Beam (DCB) experiment was considered, with the aim to demonstrate the damage sensing capacity of the electrical resistance change method. Two-dimensional finite models were performed to figure out the potential distribution of a delaminated composite with different electrical anisotropy ratios. Based on the simulation results and the particularity of the CF/EP composite, a theoretical model was proposed to predict the electrical resistance change of the laminate with delamination increment, and the anisotropy effect was investigated using the model. To verify the simulation and modeling result, both CF/EP composite and conductive fillers modified CF/EP composite were prepared to examine their delamination detection sensitivity though DCB experiment, the experimental result shows the damage detection sensitivity of modified specimen shows a little increase compared with unmodified specimen, furthermore, theoretical prediction shows a satisfactory agreement with the experimental data.

1. Introduction

Carbon fiber/epoxy(CF/EP) composite has been widely used in aerospace industries, owning to their high stiffness and strength to weight ratios compared with conventional metallic materials [1]. However, the mechanical properties of composite laminates in the out-of-plane direction are less outstanding compared with that in the in-plane direction, which can result in delamination in composite laminates. As the delamination is barely detectable by visual inspection, delamination inside the structures cause low reliability. To improve low reliability, real-time delamination monitoring systems are essential for composite parts. Within this context, many techniques have been investigated to monitor delamination cracks. Worth of mention are Fiber Bragg Grating (FBG) sensors
[2,3], wave-based [4] and electrical resistance change methods [5,6]. Although Fiber Bragg Grating (FBG) sensors and wave-based methods can detect the damage and degradation of composite, they both have some limitations. The FBG method is very expensive, due to the high cost of optical fiber sensors and its sensing system. What’s more, this method may reduce strength and may increase total weight of composite. As for wave-based method, several sensors are needed which will increase the weight of the structure. Since electrical resistance change method utilizes carbon fiber/epoxy(CF/EP) composite as self-sensing material, this method does not require expensive instruments and does not cause reduction of strength. What’s more, electrical resistance change method does not increase weight.

The improvement of detection sensitivity can enhance the sensing ability of early stage damage like matrix creaking or delamination which is very helpful to improve the reliability of the composite structure. Knowledge of how the detection sensitivity of carbon fiber composite differ is also helpful to design the best material solution for a specific application. So, much research has also been focus on the various factors that affect the damage detection sensitivity of electrical-based methods. Work performed by Schulte and Prasse [5,7] shows that damage sensitivity is related to the electrical network morphology. Wang et al. [8,9] investigated the effect of electrode configuration on the damage response by experimental work. Todoroki et al. [10-12] performed finite element studies to investigate the influence of anisotropy of carbon fiber composite and the spacing between surface mounted electrodes. Hansang Kim [13] proposed that contact resistance affect the sensitivity a lot. Michele Zappalorto et al. [14] proposed a fully analytical model to assess the electrical resistance increase in a laminate due to the presence of a delamination. The model shows that the resistance change is higher for lower through-thickness electric resistivity if the electric resistivity of fiber direction is constant. Crack detection sensitivity of carbon fiber/epoxy(CF/EP) composite can be enhanced by reducing the through-thickness electric resistivity. However, this model is a little difficult to use because of its complexity, and no experimental work has been carried out to prove that reducing the electrical anisotropy can improve the damage sensitivity.

In this study, two-dimensional finite models were performed to investigate the potential distribution of a damaged laminate with different electrical anisotropy ratios. A model was proposed based on the simulation results and the particularity of the CF/EP composite to evaluate the variation of the electrical resistance of a delaminated composite, and the effect of electrical anisotropy on the damage detection sensitivity was investigated. Experimental works were then carried out to validate the accuracy of the proposed model. Graphene and carbon nanotubes are introduced into unidirectional carbon fiber/epoxy(CF/E) composite to improve the conductivity of the thickness direction and eventually reduce the electrical anisotropy due to their excellent electrical characteristics of graphene and carbon nanotubes [15-18].

2. Modeling Approach

2.1 Finite Element Study

Finite element simulations were performed using COMSOL Multiphysics software. Two-dimensional
finite models were used, since the electrode were assigned along the width direction and the current in this direction is equal to zero. The typical geometry of a DCB specimen was modeled (Fig.1), with a maximal element size of 0.2mm, which is small enough to get a convergence result. Electrodes were modeled by assigning a boundary condition to a finite length along the model boundary. One electrode was assigned with a current of 0.01A while the other electrode was constrained to have an electric potential equal to zero. Delamination was set to be electric insulation with an initial length of 55 mm.

Point A and point B was set always beneath and over the delamination front., and they varied with the growth of delamination. The potential of the point A and the potential difference between point A and point B were calculated for different delamination lengths. The electrical anisotropy ratio was defined as $\rho_T/\rho_L$, where $\rho_T$ represents the electric resistivity of the thickness direction and $\rho_L$ is the electrical resistivity of the longitude direction.

Fig. 2 shows the electric potential difference at point A changes almost linearly with delamination increment although the electrical anisotropy ratios are different, which indicates that the potential distribution from point O to point A is uniform and it’s mainly depend on the electrical resistivity of the longitude direction. For the case of $\rho_T/\rho_L$ equals to 500/5 showed in Fig. 2a, the potential difference between A and B denoted by B-A starts to increase when the delamination grows to 80 mm. When $\rho_T/\rho_L$ increases to 500/2.5, B-A starts increasing when the delamination expends to 70 mm. As for $\rho_T/\rho_L$ =500/1, B-A will increase as long as the delamination grows at the beginning. This phenomenon can be explained by the defined ‘effective length’, which is dependent on the electrical anisotropy ratio, it can be found that every anisotropy ratio has its own effective length, the larger the anisotropy ratio, the longer the effective length. If the length from delamination front to the end of the specimen (residual length denoted by non-delaminated zone) is larger than the ‘effective length’, B-A won’t change. B-A only increases when the residual length is smaller than the effective length. When $\rho_T/\rho_L$ equals to 500/5 and 500/2.5, the corresponding effective length is about 50 mm and 60 mm, respectively. In term of $\rho_T/\rho_L$ =500/2.5, the effective length is larger than 75 mm. It’s worth mention that B-A is directly related to the resistance of the non-delaminated zone as the current is constant.
Fig. 2 Plot of potential at A and potential difference between A and B vs delamination length, (a) $\frac{\rho_T}{\rho_L} = 500/5$, (b) $\frac{\rho_T}{\rho_L} = 500/2.5$, (c) $\frac{\rho_T}{\rho_L} = 500/1$
2.2 A Model to Predict the Electrical Resistance Change of a Laminate with Delamination

As shown in Fig. 3, composite laminate was divided into part 1, part 2 and part 3, in which part 1 and part 3 located at delamination zone while the zone 2 was distributed in non-delaminated zone. The potential distribution of part 1 and part 3 is approximately uniform as the current in the delaminated zones oriented along the fiber direction. Therefore, the resistance of part 1 and 3 can be treated as ohmic resistors, read as:

\[ R_1 = R_3 = \frac{2 \rho_L (a_0 + \Delta a)}{tw} \]  

(1)

where, \( \rho_L \) is the electrical resistivity of the longitude direction, \( a_0 \) is the initial length of delamination, \( \Delta a \) is the increment of delamination, \( t \) is the thickness of the sample and \( w \) is the width of the sample.

For unidirectional carbon fiber composite, the electrical anisotropy is typically larger than 1000 [14], 1000 is much larger than 500 mentioned in section 2.1, so the effective length of unidirectional carbon fiber composite is longer than the sample length, it means that the resistance of part 2 increases immediately since the delamination grows. This can also be explained in the following. The real resistance zone of part 2 can be assume to be a thin layer (showing in Fig. 3), since the current can flow through the entire longitude direction easily because of the very low resistivity of carbon fiber compared with that in the though thickness direction, and the zone over and beneath the thin layer can be treated as two electrodes. The resistance of the thin layer (the resistance of part 2) is expressed as:

\[ R_2 = \frac{\rho_T L_T}{(L - a_0 - \Delta a)w} \]  

(2)

where, \( \rho_T \) is the electrical resistivity of the thickness direction, \( L_T \) is the thickness of the thin layer and \( L \) is the length of the sample.

The initial resistance of part 2 can be expressed as:

\[ R_{20} = \frac{\rho_T L_T}{(L_R - a_0)w} \]  

(3)

Combined Eq. (2) and Eq. (3):

\[ \frac{R_2}{R_{20}} = \frac{L_R - a_0}{L_R - (a_0 + \Delta a)} \]  

(4)

So, the resistance of part 2 is:

\[ R_2 = \frac{R_{20}(L_R - a_0)}{L_R - (a_0 + \Delta a)} \]  

(5)

Eventually, the resistance of the sample with delamination reads as:

\[ R = 2R_1 + R_2 = \frac{4 \rho_L (a_0 + \Delta a)}{tw} + \frac{R_{20}(L_R - a_0)}{L_R - (a_0 + \Delta a)} \]  

(6)

From Eq. (6), we can see that the only unknown parameter is \( R_{20} \). And \( R_{20} \) can be calculated easily when we measured the initial resistance of the sample expressed by \( R_0 \), since \( R_0 \) reads as:
The model can be established easily after measured the initial resistance of the sample.

\[
R_0 = \frac{4\rho_L a_0}{t w} + R_{20}
\]  

(7)

The model can be established easily after measured the initial resistance of the sample.

The ratio of \( \frac{R_{20}}{\rho_L} \) depends on the electrical anisotropy ratio \( \frac{\rho_T}{\rho_L} \), since \( R_{20} \) is proportional to \( \rho_T \). Therefore, the value of \( \frac{R_{20}}{\rho_L} \) stands for the electrical anisotropy. Fig. 4 is a plot of normalized electrical resistance change \( \Delta R/R_0 \) vs delamination increment for different values of \( \frac{R_{20}}{\rho_L} \) based on the model, the sample dimensions are taken as \( t=3.9 \text{ mm}, w=20 \text{ mm}, L_R=85 \text{ mm}, a_0=15 \text{ mm} \). The electrical resistance changes higher for lower electrical anisotropy, showing an increase in delamination detection sensitivity. So, damage detection sensitivity can be enhanced by reduce the electrical anisotropy based on the proposed model which is in an agreement with the theoretical model proposed in [15]. However, it’s worth mention that the improvement of damage sensitivity is not obvious when the electrical anisotropy is high, since the anisotropy ratio changes from 20000 to 2000 but the electrical resistance changes only a little higher. The lower the anisotropy ratio, the more obvious the improvement of damage sensitivity is.

![Fig.3 Schematic of a simple model](image1)

Fig.3 Schematic of a simple model

![Fig.4 Predicted ΔR/R₀ vs delamination increment for different values of R₂₀/ρₗ](image2)

Fig.4 Predicted \( \Delta R/R_0 \) vs delamination increment for different values of \( \frac{R_{20}}{\rho_L} \)

3. Experimental Work

3.1 Materials Preparation
Materials used in this study were unidirectional carbon fibers (supplied by Tianniao Pty Ltd, China) for the CFRPs laminates composite, the epoxy resin supplied by AXSON Technologies Shanghai Co.Ltd, and graphene carbon nanotubes compounds as conductive fillers in epoxy resin provided by TimesNano Pty Ltd, China.

Epoxies modified with 3 wt.\% graphene carbon nanotubes were prepared by physical ultrasound method, then a stoichiometric curing agent with a ratio of 100:10 was added and stirred gently to obtain the uniform mixture as the matrix of composite laminates. The composite laminates were fabricated by 8-ply of ~750 cm² unidirectional carbon fiber fabric using a lay-up method and a 10 μm thick polyimide film was inserted between the 4th and 5th plies to serve as an initial crack. The laminates were wrapped with bleeders and release film inside a vacuum bag, first vacuumed in a chamber for 0.5 h, followed by curing in a hot press at 80 °C for 12 h. A pressure of 250 kPa was applied during curing to maintain a uniform laminate thickness and a constant fiber volume fraction (60±2%). Double cantilever beams (DCB) (125 mm length x 20 mm width) were finally cut from the square panels by a wet-jet diamond saw. Before testing, all the specimens were annealed at 100 °C for 3 h to remove any possible residual stress introduced during the fabrication process.

3.2 Conductivity Measurement

Resistivity measurements were carried out using Keithley 2700. For the longitudinal resistivity measurements, rectangular specimens (120 mm×20 mm×3.9 mm) were cut from the prepared composite panel. Square specimens (10 mm×10 mm×3.9 mm) were used to the measurement of the through thickness direction. A four-probe method was adopted to ensure that the contact resistance is not introduced in the measurement of in-plane resistivity. A current was injected through the end surface of the specimen, whereas the potential difference across pairs of different electrodes on the top surface was measured. Different from the longitudinal resistivity measurement, two-probe method was used for through-the-thickness resistivity measurement since the thickness of the specimens was too small to carry out a four-probe method. Although the two-probe method is affected by the contact resistance, in this case the effect can be ignored as the contact resistance is rather small compared with the resistance of the material through the thickness direction.

The electrical resistivity of the thickness direction ($\rho_L$) for the composite without conductive fillers was found to be 6.2911 $\Omega \cdot m$, while through-the-thickness resistivity ($\rho_T$) of the composite modified by graphene and carbon nanotubes is 0.3190 $\Omega \cdot m$. The electrical anisotropies ($\rho_T/\rho_L$) were found to be $7.2656 \times 10^4$ for pure composite and $2.459 \times 10^3$ for graphene and carbon nanotubes modified composites, showing that the introduction of graphene and carbon nanotubes could highly enhance the electrical conductivity of the thickness direction and eventually reduce the electrical anisotropy as the longitudinal resistivity doesn’t change a lot.

3.3 DCB Test
Rectangular DCB specimens were cut from the composite panels with an initial delamination length of 55 mm. The geometry of the DCB specimen is showed in Fig. 5. The measurement surfaces of the DCB specimens were polished with P600 sandpaper, and carefully cleaned with alcohol. Electrodes made of a highly conductive coating were painted on the polished surfaces. Copper wires were then attached to the silver paint surfaces. Finally, all the specimens were cured in the oven to solidify the silver paint utterly.

The tests were performed under displacement control, with a crosshead speed of 2 mm/min. The load was applied to the two beam arms through two metal hinges bonded to the specimens. A millimeter scale was drawn on the edge of the specimens over an application of white correction fluid to measure the delamination length during the test, using an optical microscope. A Keithley 2700 source meter was attached to the four electrodes to record the resistance change using 4-probe method eliminating the effect of contact resistance. Resistance values were recorded by computer and Keithley data capture software.

![Fig. 5 Geometry and electrode configurations of the DCB specimens](image)

3.4 Experimental Results and Validation of the Model

Fig. 6 is a plot of electrical resistance with delamination, the prediction shows a good satisfaction with the experimental results both for baseline specimens and modified specimens, confirming the accuracy of the simple model.

The increment of the resistance $\Delta R$, normalized by its initial value $R_0$, is plotted as a function of the delamination extension, $\Delta a = a - a_0$, showing in Fig.7. In this figure, E stands for the baseline specimens and G is the specimens with graphene and carbon nanotubes fillers. The electrical resistance changed a little greater for the specimens with the introduction of graphene and carbon nanotubes compared with the base line specimens, demonstrating that the reduction of electrical anisotropy ratio will result in the improvement of damage sensing sensitivity since the introduction of conductive fillers reduce the anisotropy ratio acutely. However, it’s worth mention that this improvement of the damage detection sensitivity is not obvious compared with the huge reduction of electrical anisotropy ratio. Although the electrical anisotropy ratio is reduced a lot with the introduction of conductive fillers, the ratio is still at a very high level, so the improvement of detection
sensitivity is not obvious.

Fig. 6 Electrical resistance vs delamination. Comparison between model predictions and the experimental results. (a) baseline specimens (b) specimens with the introduction of conductive fillers
Fig. 7 Electrical resistance change vs delamination increment. Comparison between model predictions and the experimental results

4. Conclusion

In this study, an analytical and experimental study is carried out on the electrical response of a delaminated laminate. A model is proposed based on the simulation results and the particularity of the CF/EP composite to estimate the electrical resistance increase in a laminate owning to the increment of delamination, and the effect of electrical anisotropy on the delamination sensing sensitivity is investigated using the simple model. Experimental works were carried out to validate the accuracy of the result. The following conclusions can be drawn:
1. The electrical resistance of the specimen increases with the increment of the delamination length, indicating the electrical based method is applicable to detect delamination in a composite laminate.
2. The electrical resistance change is higher for lower anisotropy ratio, showing that the delamination sensing sensitivity can be improvement by decreasing the anisotropy ratio.
3. The improvement of sensitivity is not obvious if the anisotropy ratio of the modified material is still at a low level.

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Reference


