Key Engineering Materials Vols. 353-358 (2007) pp. 1298-1301
online at http://www.scientific.net
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Online available since 2007/09/10

Damage Monitoring of Thick CFRP Beam using Electrical Impedance Changes

Akira Todoroki[1, a], Masahito Ueda[2, b], and Yoshinobu Shimamura[3, c]

[1]Department of Mechanical Sciences & Engineering,
Tokyo Institute of Technology (I1-58), 2-12-1, Ookayama, Meguro, Tokyo, 152-8552,

[2]Graduate Student of Tokyo Institute of Technology

[3] Faculty of Engineering, Shizuoka University
836 ohya, shizuoka-shi, shizuoka-ken 422-8529, JAPAN

[a]atodorok@ginza.mes.titech.ac.jp, [b]mueda@ginza.mes.titech.ac.jp,
[c] tysimam@ipc.shizuoka.ac.jp

Keywords: Composites; Monitoring; Delamination; Monitor; Electric impedance; Response Surface.

Abstract. Electrical resistance change method has been applied to monitor a delamination crack of a thin CFRP laminate. For a thick CFRP laminate, multiple delamination cracks are made with many matrix cracks, and the electric current in the thick CFRP laminate may not flow in the thickness direction due to the strong orthotropic electrical conductivity. The present study employs an electric impedance change method for the identification of damage location and dimension of the damaged area; applicability of the method is investigated experimentally using thick beam-type specimens fabricated from cross-ply laminates of 36 plies. After making the damage, electrical impedance was decreased. A residual stress relief model was proposed to explain the decrease. From the measured electrical impedance changes, the relationships between the electrical impedance changes and damages are obtained by means of response surfaces. The response surfaces estimated the damage location and dimension of the damaged area exactly even for the thick CFRP laminates. The electrical impedance change method can be used as an appropriate sensor for measurement of residual stress relief due to damages of thick CFRP laminates.

Introduction

For the Carbon Fiber Reinforced Polymer composites (CFRP), detection of delaminations and matrix cracking is a difficult task for visual inspections. Difficulty of detection underlines the importance of development of smart structures for monitoring delaminations CFRP laminated composites. An electrical resistance change method is applied to detect damages of CFRP composites or strain of CFRP structures [1-12]. Authors have studied an electrical resistance change method to monitor a delamination crack in a thin CFRP laminate [8-12]. For a thick CFRP laminate, multiple delamination cracks are made with many matrix cracks caused by an impact load, and the electric current may not flow in the thickness direction due to the strong orthotropic electrical conductivity of a CFRP laminate. The electrical resistance change method, therefore, should be experimentally confirmed for the thick CFRP laminates.

This study employs an electric impedance change method for identification of damage location and dimension of the damaged area; applicability of the method is investigated experimentally using thick beam-type specimens fabricated from cross-ply laminates of 36 plies. By using an alternating current, the electrical current in the thickness direction may be increased. Several types of alternating frequencies are adopted in the present study. On the specimen surface, multiple electrodes are mounted by co-curing copper foil to measure electric impedance changes. Four-probe method is adopted to measure the electrical impedance change to prevent the effect of the damage at the electrodes during making damages. Interlamina shear tests are performed to make a practical delamination crack in a beam-type specimen. Damage identifications are performed from the experimental data in the present study.

Experimental Procedure

Specimen and test method. Material used here is prepreg Q-1111/2500 (carbon/epoxy, Tohotenux). The prepreg is stacked to make laminates of 36 plies of $[(0_2/90)_6]_s$. The laminates were cured at 130°C×90min during 2 hours. From the laminates of the thickness of 7.5mm, two types of rectangular specimens of 15mm×150mm (type A) and 20mm×227mm (type B) were fabricated. These two types of the specimens are shown in Fig.1 and 2.

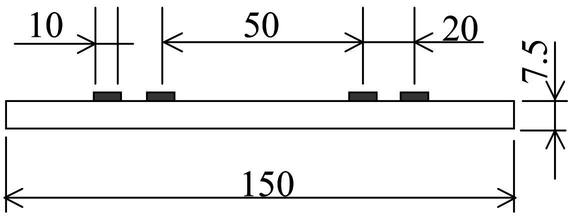


Fig.1 Specimen configuration of type A

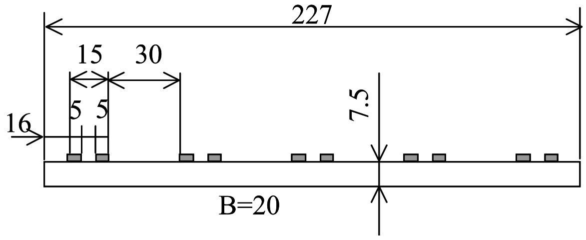


Fig.2 Specimen configuration of type B

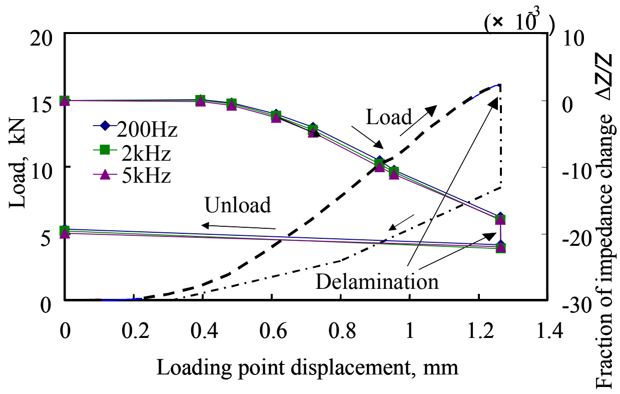
To measure the electrical resistance change during loading, a four-probe method is adopted in the present study. Thin Copper foil of 200μm thickness is co-cured. The specimen configuration and electrodes are shown in Fig. 1.

The electrical resistance change was measured by means of a LCR meter model #3522 produced by Hioki Co. Three kinds of alternating current of 200, 2k and 5k Hz were used for the measurements to investigate the effect of frequency. For the measurement of electrical impedance change, a four-probe method is adopted here to prevent electrical resistance change at the electrodes. For the type A specimen, an interlamina shear test was performed with measuring the impedance change during the loading at various alternating current frequencies. The loading span is 30mm for the type A specimen and 25mm for the type B specimen. The center load of the interlamina shear test was applied on the opposite surface of the electrodes with silicon rubber film: the electrode side surface is tensile stress side for bending stress. For the type B specimens, damage-monitoring tests were performed.

Results and Discussion

Type A test. Figure 3 shows the results of the interlamina shear test with measurement of electrical impedance change. The abscissa is the loading point displacement of a testing machine and the ordinates are the load and the electrical impedance change. The broken curve shows the load-displacement result and the solid curves show the electrical impedance measurements. The fraction of the impedance changes of three frequencies show completely identical results. This means that there is no effect of frequency change and measurements of phase angle of the alternating current were all almost zero. This implies that the impedance comes only from resistance at least less than 5kHz for CFRP laminates.

Electrical resistance decreases with the increase of loading. For the thin CFRP plates, electric current flows both on the tensile and the compression sides [9], [10], which causes no resistance change. For the thick CFRP, however, electric current flows only near the surface where electrodes mounted. Figure 4 shows the results of the FEM analysis of electric current density in the x-direction (longitudinal direction). This shows that the electric current flows only within 3mm from the surface.



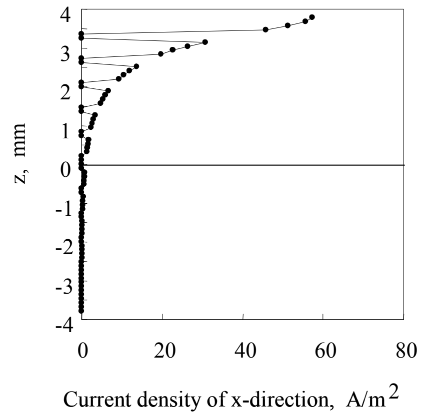


Fig.3 Electrical impedance change in interlamina shear test. Fig.4 FEM analysis of electrical current

Although the electric current flows in the tensile side, the resistance decreases with the increase of loading. This means the electrical contact at the electrodes are poor, and compression strain due to Poisson’s ration effect causes decrease of the electrical resistance [12]. After the delamination creation, electrical resistance decreases and there is a residual decrease of electrical resistance.

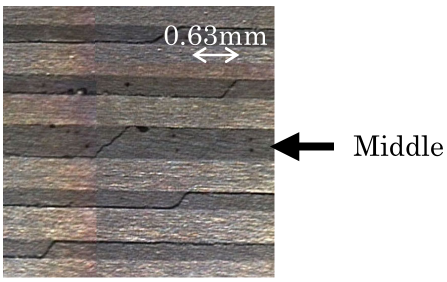


Fig.5 Specimen side view

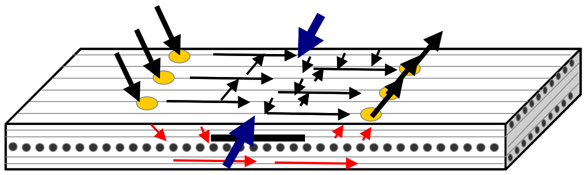


Fig.6 Electrical resistance change model

As shown in Figure 5, delamination cracks are created near the middle of the thick plate. Since the electric current did not flow near the middle of the plate, this decrease at the delamination creation is not due to the impedance of the crack. As shown in Fig. 6, poor electrical contact at electrodes generates electric current in the transverse direction in the surface. Delamination cracks bring residual stress relief in the transverse direction at the surface ply. Since the residual stress is tensile in the surface ply, the relief of the residual stress causes compression strain at the surface. This means that the method measures the residual stress relief due to the delamination creation.

Type B test. As shown in previous section, this method can be used to measure the residual stress relief of the thick CFRP. 31 tests of interlamina shear with the type B specimen were performed, and electrical resistance changes were measured with the change of delamination dimension (damaged area size observed from the specimen side) and location. Response surfaces of cubic polynomials are adopted to obtain the relationships between the measured electrical resistance changes and delamination location and dimension as the same way described in the reference [9] and [10].

Figure 7 shows the results of the estimations of delamination location. The abscissa is the measured location observed from the specimen side and the ordinate is the estimated delamination location. Plots on the diagonal line mean that the estimations are exact. As shown in Fig.7, the estimations of delamination location show excellent results. Figure 8 shows the results of estimations of delamination dimension. Since multiple delamination cracks are created, the dimension of the delamination is defined as the distance from the left end of the leftist delamination crack to the right end of the rightist delamination crack. The figure shows that the estimations are excellent. For both estimations, the adjusted coefficient of determination is over 0.95.

Since the previous section shows that we can measure the residual stress relief at the surface of thick CFRP laminate by means of electrical impedance change. The results of the estimations show that the delamination can be identified from the residual stress relief of the thick CFRP laminates.

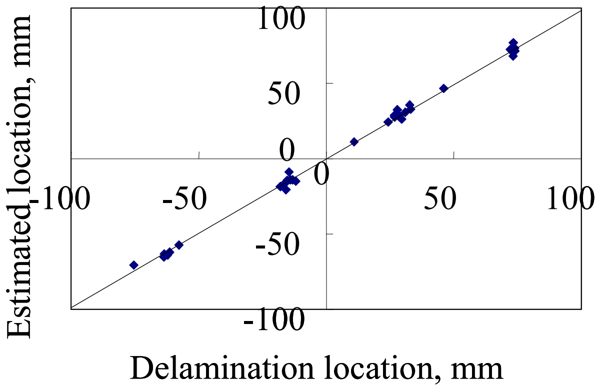


Fig. 7 Estimation of delamination location

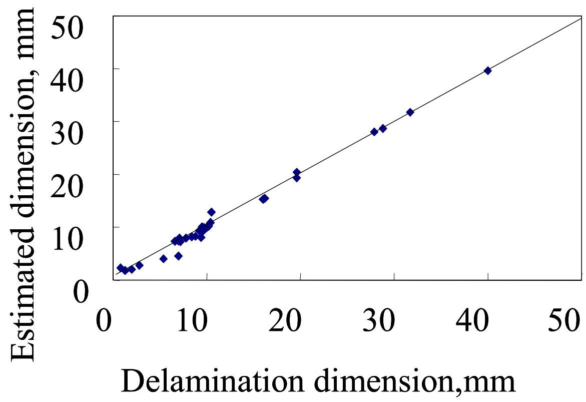


Fig.8 Estimation of delamination dimension

Conclusions

The present study performed experimental investigations about the applicability of the electrical impedance change method to monitor delaminations of thick CFRP laminates using a four-probe method. The results obtained are as follows.

(1) Poor electrical contact at the electrodes causes electrical resistance decrease during tensile test and residual resistance decrease after delamination due to the electric current flow in the transverse direction.
(2) The method measures the residual stress relief due to the delamination creation on the surface ply.
(3) From the residual stress relief, delamination location and dimension can be identified using the response surface method.

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