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Detection of Matrix Cracking of CFRP Using Electrical Resistance Changes

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Abstract. Effect of thickness of 90°-plies on a method for detection of matrix cracking of CFRP laminates is investigated here. Three types of cross-ply CFRP laminates are adopted here: $[0/90/0]_T$, $[0/90]_S$ and $[0/90_2]_T$. Tensile cyclical loading tests are performed with increasing the maximum load applied cyclic loading. Electrical resistance changes are measured using silver paste electrodes by means of a four-probe method. As a result, it was revealed that residual electrical resistance under complete unloaded condition was not applicable for an indicator of creation of matrix cracking in the thick cross-ply laminates. For the thick cross-ply laminates, tensile residual stress in the middle 90°-plies is smaller than that of the thin laminates. This small tensile residual stress causes crack closure when the specimen is completely unloaded. When the cross-ply laminates are reloaded, the electrical resistance increased rapidly with the small increase of load due to the opening of matrix cracks. From this result, we proposed a new method for detections of matrix cracking using the rapid increase of electrical resistance in small reloading.

Introduction

CFRP structures are widely adopted in aerospace structural components. For a cryogenic tank of a next generation reusable launching vehicle, a laminated composite tank is one of the key technologies for reduction of the weight [1]. For the fuel tank made from laminated CFRP, matrix cracking is a significant problem that may cause leak of fuel. Detections of matrix cracking, therefore, are indispensable for the CFRP fuel tank.

Change of electrical property of the CFRP structure has been studied as a sensing system for a smart structure or a nondestructive testing method [2-8]. Using the electrical resistance changes, applied strain has been monitored and damages such as fiber breakages have been detected in the CFRP laminated structures. Our research group has proposed a delamination monitoring method [9-13] and a strain monitoring method with reliable probes [13, 14] for the CFRP laminates. Authors have also published a paper for detecting matrix cracking by means of electrical resistance changes in our previous study using thin cross-ply CFRP laminates [15]. Matrix cracks in a thin CFRP cross-ply laminate were detected by means of the increase of residual electrical resistance under the complete unloaded condition.

For the thin laminate, tensile residual stress exists in the middle 90°-ply. Since the relief of the tensile residual stress in the 90°-ply causes the full opening of the matrix crack. This fully opened matrix crack causes residual electrical resistance even at the unloaded condition. The residual stress, however, is reduced for thick laminates [16], and this method may not be applicable to thick cross-ply laminates. The effect of the 90°-ply thickness of cross-ply laminates, therefore, is investigated in the present study.

Three types of CFRP cross-ply laminates are adopted here. Electrical resistance changes and matrix crack densities are measured while loading-unloading cyclic tests are performed with increasing the maximum tensile load. The effect of 90°-ply thickness is investigated and an alternative method for thick laminates is proposed here.

Principle of electrical resistance change method

Carbon fiber has a high electrical conductivity and the epoxy resin matrix is insulator. Unidirectional carbon/epoxy composites have high electrical conductivity in fiber direction. Although the electrical conductivities in transverse direction and in thickness direction are zero for regular-spacing ideal CFRP, an actual CFRP has electrical conductivity in transverse direction and in thickness direction due to the network structure that consists of contacts among adjoining carbon fibers. The fraction of electrical conductivity in transverse direction to that in fiber direction is approximately 10^{-3}, and the fraction of electrical conductivity in thickness direction to that in fiber direction is approximately 10^{-4} [10]. Matrix crack causes breakage of the network structure. This breakage of the network structure causes increase of electrical resistance in transverse direction. Our research group has proposed a method for detecting matrix cracking using this effect in our previous study [15]. Cross-ply laminates that has 0°-plies in its surface and 90°-plies in the middle are used in the previous study. The matrix cracks in the 90°-ply are detected by means of the increase of residual electrical resistance under the complete unloaded condition.

Experimental procedure

Material used here is carbon/epoxy prepreg PYROFIL TR30S/#380 produced from Mitsubishi Rayon Co. Ltd. This material had a single ply thickness of 0.22 mm and fiber volume fraction of the laminates of 55 %. The prepreg is stacked to make three types of laminates of $[0/90/0]_T$, $[0/90]_S$ and $[0/90_2]_T$. The CFRP laminates were cured with a hot-press at 130 °C x 90 min. Specimens of 210 mm x 15 mm were cut with a long side parallel to fiber direction of 0°-plies from each laminate.

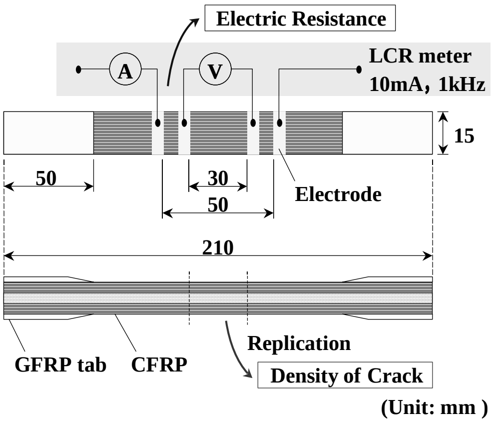


Fig.1 Configuration of test set-up

To measure the electrical resistance change during loading, a four-probe method is adopted here: a couple of outer two probes used for applying an alternate current of 10 mA of 1 kHz frequency and a couple of inner two probes is used for measuring electrical potential change as shown in Fig.1. A LCR meter(3522-50 LCR HiTESTER produced by Hioki E.E.) was used for electrical current source. The alternate current of 1kHz was tp prevent electrical noise for this system. Before the experimens, the phase angle of the measured impedance was confirmed to be zero. This means the measured impedance equal only to its real component: the electrical resistance. Electrodes of each specimen were produced using silver paste after complete polishing of the specimen surface with sandpaper to remove the surface resin. This polish of the surface is indispensable for reliable measurements [14].

To perform tensile tests, GFRP tabs are bonded to both ends of each specimen. Loading-unloading cyclic tests are performed with increasing the maximum load at each cycle. The density of matrix cracking is measured by a replica method when the tensile load came to the maximum level of each cycle. The configuration of test set-up is shown in Fig.1.

Results and discussion

Measured result of matrix crack density is shown in Fig.2. The abscissa is the applied maximum strain of each cycle and the ordinate is the measured matrix crack density. In this figure, matrix cracking initiated over 3000μ and saturated at approximately 5000μ in all specimens. Higher matrix crack density is observed in the thin specimen compared with the thick specimens shown in Fig.2. The difference of the matrix crack density is due to the difference of the residual stress in 90º-plies [16].

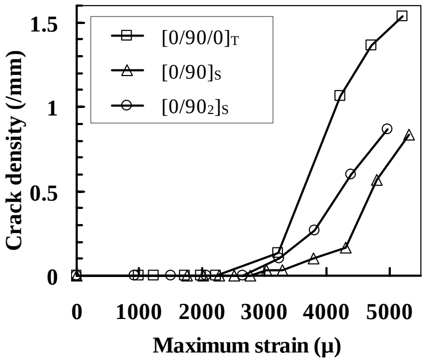
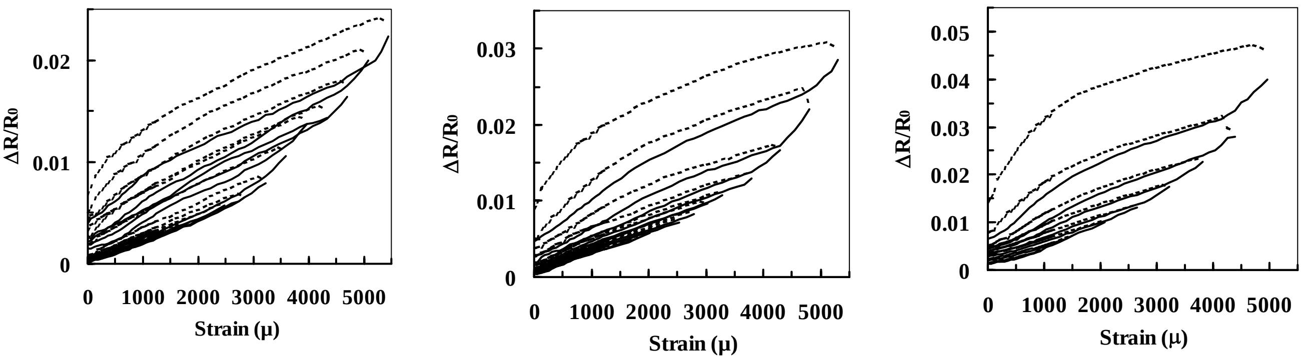


Fig.2 Measured matrix crack density of three types of the specimen thickness

Measured result of fraction of the electrical resistance change is shown in Fig.3. The abscissa is the applied strain and the ordinate is fractional change of electrical resistance to initial electrical resistance as follows;

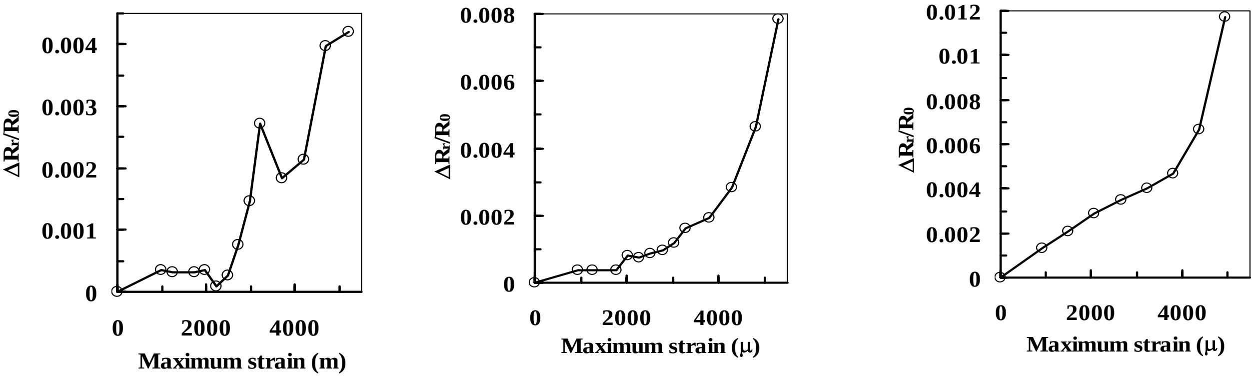


(a) $[0/90/0]_T$ ($R_0 = 224.26\mathrm{m}\Omega$) (b) $[0/90]_S$ ($R_0 = 412.45\mathrm{m}\Omega$) (c) $[0/90_2]_T$ ($R_0 = 443.75\mathrm{m}\Omega$)

Fig.3 Measured fraction of electrical resistance change of three types of specimens

$$\Delta R / R_0 = \frac{R - R_0}{R_0} \tag{1}$$

In all types of specimsn, the fraction of the electrical resistance increased with the increase of applied tensile strain. In smaller deformation ragion under 3000μ strain, changes of the electrical resistance are almost reversible. Over 3000μ, however, rapid increases of electrical resistance were observed. At the reloading stage, the rapid increase of the electrical resistance is obtained when the applied strain increases to the maximum strain of previous cycle. The initial of the rapid increase is almost equal to the strain level of matrix crack creation (3000μ).



(a) $[0/90/0]_T$ (b) $[0/90]_S$ (c) $[0/90_2]_T$

Fig.4 Measured residual electrical resistance of three types

Fig. 4 shows the measured result of residual electrical resistance under complete unloaded condition. The abscissa is the applied maximum strain of previuous cycle and the ordinate is fractional change of residual electrical resistance to initial electrical resistance. For the thin laminate of type (a), rapid increase of residual electrical resistance is recognized over 3000μ as shown in Fig.4. For the type (b) laminate of $[0/90]_S$, the increase of the fraction of the residual electrical resistance at 3000μ is not so rapid copared with the results of type (a). For the thick laminate of type (c), the fraction of the residual electrical resistance gradually increases with the increase of applied strain although the rapid increase is observed over 4000μ.

The thiner 90°-ply lamiante has higher tensile residual stress [16]. The high tensile residual stress is relieaved when the matrix crack created. That makes the matrix crack fully open under the completely unloaded condition. On the other hand, the thick 90°-ply lamiante has small tensile residual stress, and that causes crack closure at the unloaded condition. Moreover, as shown in Fig.2, the smaller number of matrix cracks exist in the thick laminate. This makes smaller electrical resistance change as the same as the crack closure effect. These two effects bring the smaller change in the fraction of the residual electrical resistance for the thick lamiante in Fig.4.

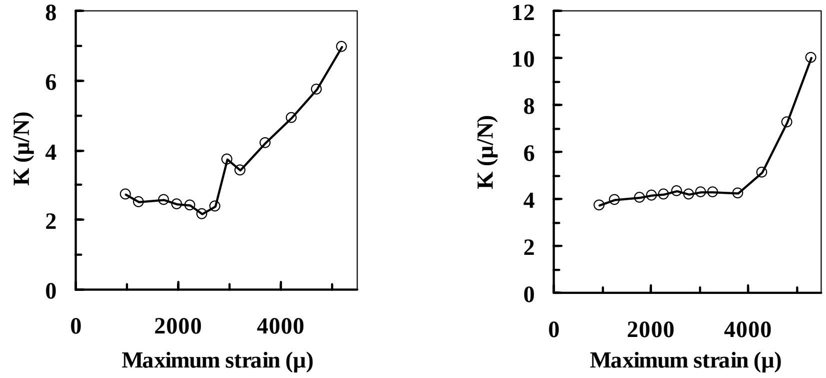
The thick 90°-ply laminate has a thick 90°-ply in the middle of the laminate. In the 90°-ply, fiber-matrix debondings are created even at the small loading [17]. For the thick 90°-ply lamiante, more debondings are created than those of the thin 90°-ply lamiante in the thick 90°-ply. These debondings may cause the increase of the fraction of the resiudal electrical resistance at the small loading for the thicker 90°-ply laimiantes as shown in Fig.4. This also brings difficulty of the usage of the fraction of the residual electrical resistance as an indicator of matrix cracking. A new indicator is required for the thick 90°-ply lamiantes.

When the cross-ply laminate is reloaded, it was observed that the electrical resistance increases rapidly even at small reloading after generation of matrix cracking. The slope of the fraction of the electrical resistance at reloading is, therefore, investigated as an indicator here. To evaluate the slope quantitatively, the slope at small reloading is defined from the load at ε_1=400μ to the load at ε_2=800μ as follows;

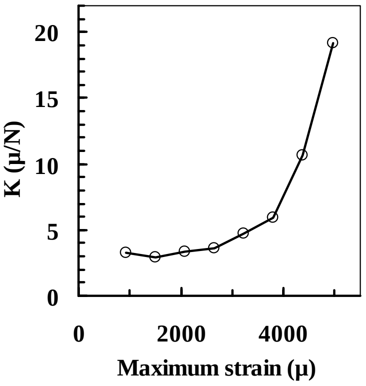
$$K = \frac{\Delta R/R_0}{\Delta\varepsilon} = \frac{(R_2 - R_1)/R_0}{\varepsilon_2 - \varepsilon_1} \qquad (2)$$

Fig.5 shows the measured reloading-slope *K* of the three types of the specimens. The abscissa is the applied maximum strain and the ordinate is the reloading-slope defined by the Eq.(2). The reloading-slope is almost constant at lower tensile load (3000μ strain). The reloading-slope vaule increases after the generation of matrix cracking (over 3000μ strain) not only for the thin laminate but also for the thick laminate. Moreover, the change of the reloading-slope is sharper than that of the fraction of the residual electrical resistance. This means the reloading-slope is a better indicator even for the thin laminates.

An actual fuel composite tank has a pressure meter. The pressure meter tells the applied strain of the tank wall. Imprementation of probes to the tank enables the measurements of the electrical resistance change. Form the measured pressure and the electrical resistance change, the reloading-slope is easily obtained. For the cryogenic fuel tank, precooling is indespensable with liquid Nitrogen before charging liquid Hydrogen. Although the pressure of the precooling stage is small, the reloading-skope method requires only small load. This enables us usage of the relaoding slope as an indicator of the matrix cracking of the cryogenic fuel composite tank.



(a) $[0/90/0]_T$ (b) $[0/90]_S$



(c) $[0/90_2]_T$

Fig.4 Measured reloading-slope of three types of specimens

Concluding remarks

Measurement of matrix crack density and electrical resistance change of cross-ply laminates due to tensile load was performed to reveal the effect of 90º-ply thickness on the matrix crack detection of CFRP using electrical resistance changes. The increase of residual electrical resistance under complete unloaded condition was too small to be detected for the matrix cracking in thick cross-ply laminates. For the thick cross-ply laminates, tensile residual stress in the middle 90º-plies is smaller and the smaller residual stress caused crack closure under the complite unloaded condition. When the cross-ply laminates are reloaded, therefore, the electrical resistance increased rapidly even in the small increase of load due to the reopening of matrix cracks. A new indicator of reloading-slope was, therefore, proposed here. For the every types, the reloading-slope showed excellent changes after generation of matrix cracking. Since every cryogenic fuel tank has pressure meter and requires precooling with liquid Nitrogen, the matrix crack can be detected by means of the reloading-slope indicator at the precooling stage.

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