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Matrix crack detection of CFRP using electrical resistance change with integrated surface probes

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Abstract

For the cryogenic tanks of next generation reusable launching vehicles, the laminated composite tank is one of the key technologies. For composite fuel tanks made from laminated carbon fibre reinforced polymers (CFRP), matrix cracking is a significant problem that may cause fuel leakage. In the present paper, an electrical resistance change method with integrated probes on a single side of the surface of a CFRP composite structure is adopted to detect the matrix cracking of the laminated composites. For a fuel tank structure made of a CFRP laminate, we cannot mount electrical probes on the end of structure or on the inside of the tank structure. We have to mount all probes only on the outside surface. The present method used finite element analyses (FEA) to search for the best placement of probes for matrix crack detection using a rectangular plate. To simulate the tank structure, all probes are placed on a single surface of the CFRP plate specimen. The present study adopted a four-probe method for measuring the electrical resistance change. The FEA revealed that the electrical resistance increases linearly with increase in the number of matrix cracks inside of the probes. By means of thin CFRP cross-ply laminate, the method was experimentally confirmed to be useful for detecting matrix crack density between the probes. Residual electrical resistance at the completely unloaded condition increased with increase in matrix crack density. Measurements of the residual electrical resistance enabled us to detect the matrix crack density without loading.

Keywords: A. Carbon fibres; A. Polymer-matrix composites; B. Matrix cracking; C. Finite element analysis; B. Electrical properties; B. Electrical resistance

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1. Introduction

Carbon fibre reinforced polymer (CFRP) laminated structures are very effective for weight saving in aerospace structural components. The cryogenic tank of next generation reusable launching vehicles adopts laminated composite tanks [1]. For a fuel tank comprising a laminated CFRP, matrix cracking of the CFRP laminates causes fuel leakage, and detection of matrix cracking, therefore, is a demanded target.

Change of electrical resistance of the CFRP structure has been applied to the detection of damage to the CFRP structure like fibre breakages, fibre–matrix debonding, matrix cracks and delamination [2–11]. Applied strain and fibre breakages of the CFRP structures are monitored using the electrical resistance changes: electric current is applied to the end of the rectangular specimens [2,4,6]. The research group of Chung [3,5] uses circumferential lead wires with silver paste as probes for the unidirectional CFRP laminated specimen to apply the electric current.

The authors' research group has proposed a delamination monitoring method [12–16] and a strain monitoring method with reliable probes [17,18] for the CFRP laminates. For this research, multiple probes for applying electric current and to measure electric voltage change are integrated on the single specimen surface using co-cured copper foil or silver paste. Since the integrated surface probes method requires installing electrodes on only a single side of the target CFRP structures, the method does not cause troublesome wire placement on inside surfaces of the

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composite tank structures. This enables us to install the electrical resistance change measurements on a CFRP composite tank without design changes to the target composite fuel tank.

The previous method for monitoring the delamination location and size employs a two-probe method with narrow spacing probes on a single side surface. These probes produce electric current in the thickness direction, and this enables delamination monitoring without electrical resistance change due to matrix cracking [19]. To detect matrix cracking, modification to the spacing of probes and the applicability of the integrated surface probe must be investigated. In the present study, therefore, a cross-ply CFRP laminate was adopted as a target specimen, and FEM analyses were performed to confirm the applicability of the electrical resistance change method with the integral surface probes. Experimental investigations were also conducted to confirm the applicability of the method at room temperature using tensile tests of cross-ply CFRP laminates.

2. Principle of the electrical resistance change method

In CFRP laminates, carbon fibres have high electrical conductivity; the epoxy matrix is its insulator. The actual carbon fibres in a unidirectional ply are not straight. The curved carbon fibres contact one another, comprising a carbon–fibre network within a ply. The contact-network brings non-zero electric conductivity even in the transverse direction. In the same way, the fibre-network produces non-zero electrical conductivity in the thickness direction in a ply. Electric conductivity in the transverse direction is much lower than that in the fibre direction. Abry et al. [7] and the authors' group [14] found experimentally that the fraction of electrical conductivity in the transverse direction (σ_{90}) to the fibre direction (σ_0) is very small, and that the fraction of the electrical conductivity in the thickness direction (σ_t) to the fibre direction is smaller than that of the transverse direction. The results indicate that CFRP laminates have significantly strong orthotropic electrical conductivity.

Although the fibre-network structure in the thickness direction is almost identical to the structure of the transverse direction in a ply, through-the-thickness conductivity σ_t of a laminate is smaller than the transverse conductivity of a single-ply (σ_{90}) for normal laminates. That is because a thin electrically insulating resin-rich layer exists there. For actual CFRP composites, however, prepreg plies are curved like the fibres in a ply. The ply curvature induces fibre contact through the plies and causes non-zero electrical conductivity in the thickness direction, even for thick laminated CFRP laminates. Contact among plies causes non-zero electrical conductivity in the thickness direction. Thus, the σ_{90} is usually larger than the σ_t. When a crack grows in the matrix of the CFRP laminate, the crack breaks the fibre-contact-network in a ply. Breakage of the contact network causes increased electrical resistance of CFRP composites.

Fig. 1 shows a schematic representation of the delamination-monitoring system proposed by the authors [12–16]. Multiple probes of equally narrow spacing are integrated on a single surface of the specimen as shown in Fig. 1. All these probes are placed on a single side of the specimen. Usually, it is impossible to place electrodes and lead wires outside aircraft structures. Location of electrodes on a single side surface is a model of placing electrodes inside a thin shell aircraft structure. The authors have performed several finite element analyses (FEA) and concluded that the electric current should be applied in the fibre direction of the surface ply to monitor delamination cracks [14]. The electrical resistance change of each segment between the electrodes is measured with a conventional electrical resistance bridge circuit. The electrical resistance changes among all segments are measured for various delamination sizes and locations. Using the measured values, the relationship between the electrical resistance changes and

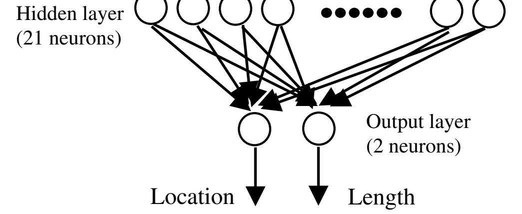

Fig. 1. Schematic representation of delamination identification method using electrical resistance change method with an artificial neural network.

delaminations (location and length of delaminations) are obtained using a tool of inverse problems such as artificial neural networks or response surfaces [12–16].

In this delamination-monitoring system, the electric current is applied in the fibre direction of the surface ply, and the spacing between probes is from 25 to 35 mm. In this system, half of the applied electric current flows in the surface layer in the fibre direction, and the remaining half of the electric current tends to flow in the bottom surface layer in the fibre direction. This causes flow of the electric current in the thickness direction, and this causes a large electrical resistance change when a delamination crack is created. The electrical resistance change is not affected by the existence of matrix cracking for delamination monitoring [19].

3. FEA to configure monitoring system

3.1. Analytical method

In this study, FEA were performed with commercially available FEM code ANSYS. Since a tension type specimen is used for experiments, a two-dimensional type specimen model was adopted for FEA as shown in Fig. 2. The stacking sequence of the specimen laminate was $[0/90/0]_T$. The length of the specimen was 210 mm and its thickness was 0.75 mm: each ply had a thickness of 0.25. Four 3-mm-wide probes made of copper electrodes were mounted on the single specimen surface. The outer two probes were used to apply the electric current, and the inner two probes were used for measuring the electric voltage.

Four-node rectangular elements were used for FEA: the length of an element was 0.25 mm and its approximate height was 0.0625 mm. An automatic mesh division system installed in ANSYS was used in this study.

A direct current of $I = 10$ mA was applied at one outer electrode and the electrical voltage of the other outer electrode was set to 0 V, and the inner pair of electrodes were used to measure electrical voltage V. Electrical resistance change R is here defined as $R = V/I$.

Orthotropic electrical conductivities used in these FEA were derived from the experimental results of reference [14]. In this study, the case of the fibre volume fraction $V_f = 0.62$ was employed for the FEA. The electrical conductivity of the fibre direction (σ_0) was 5500 S/m, the electrical conductivity of the transverse direction (σ_{90}) was 204 S/m, and the electrical conductivity of the thickness direction (σ_t) was 20.4 S/m.

A matrix crack was made in the middle 90° ply between the surface 0° plies as shown in Fig. 2. All FEM nodes of the candidates of the matrix cracks were doubly defined to represent matrix cracking. When a matrix crack was made, the doubly defined nodes on the target position were separated from each other to represent insulation of the electric current. For a matrix crack induced in the finite element (FE) model, the present study subsumes that the crack mouth is fully opened after matrix cracking. Since the tensile residual stress due to curing of epoxy exists in the 90° ply, a matrix crack caused opening of the crack mouth due to the relief of the tensile residual stress. The FE model represents this crack opening.

3.2. Results of FEA

Fig. 3 shows the results of the FEA of the electrical resistance variation plotted against the location of a single matrix crack in the middle 90°-ply. The ordinate is the calculated electrical resistance change normalized by the initial electrical resistance, and the abscissa is the location of a single matrix crack in the middle 90°-ply. Since the origin of the coordinates is defined to be in the middle of the specimen as shown in Fig. 2, a location smaller than 15 mm means that the matrix crack is located inside the pair of inner probes. The symmetric specimen enabled us to omit the calculations of matrix cracking on the left side. An almost identical electrical resistance change was observed when the matrix crack was located inside the pair of the probes (when the location is smaller than 15 mm). Only when the matrix crack was located outside the inner couple of the probes (the location exceeds 15 mm), the electrical resistance change decreased. This means that the electrical resistance change indicates matrix cracking inside the pair of the inner probes.

Fig. 4 shows the results of the electrical resistance change with increase of matrix crack density. The ordinate

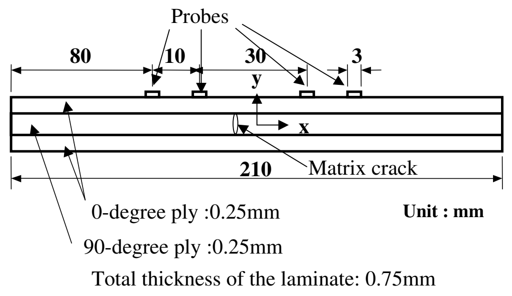

Fig. 2. Configuration of FE model for matrix crack detection using an electrical resistance change method with four-probe method.

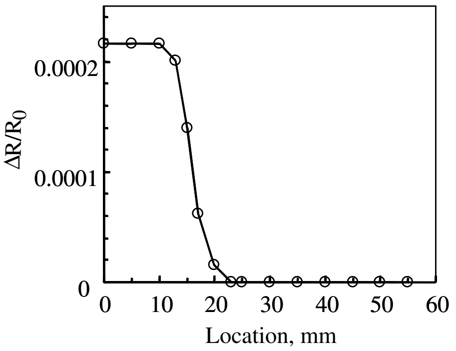

Fig. 3. Electrical resistance change due to the generation of a single matrix crack in the middle 90°-ply obtained by means of FEA.

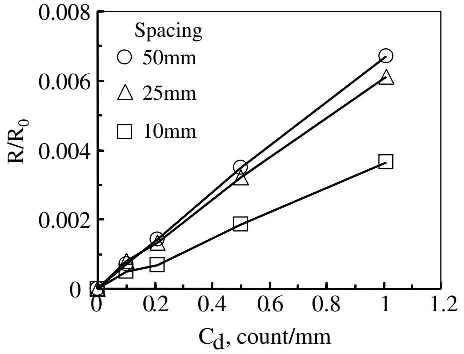

Fig. 4. Electrical resistance change for three kinds of spacing between probes with increase of matrix crack density obtained by means of FEA.

is the calculated electrical resistance change normalized by the initial electrical resistance, and the abscissa is the matrix crack density inside the pair of inner probes for three types of spacing of the probes. The spacing shown in Fig. 4 is the one between the outer probes. The spacing of the specimen in Fig. 2 was 50 mm. For a spacing of 25 mm, the spacing between the inner couple of probes was 5 mm and the spacing between the outer probe and the inner probe was 10 mm. For a spacing of 10 mm, the spacing between adjacent probes was 1/3 mm.

In all cases, the electrical resistance change increased almost linearly with increase of the matrix crack density. Although the shorter spacing of the probes caused a smaller electrical resistance change, the shorter spacing of the probes enabled the location of the high matrix crack density at the target segment between the probes to be monitored. On the other hand, the shorter spacing required many probes to be placed on the structural surface, and that was a tiresome problem. In this paper, to know the matrix crack density of a wider range area, a spacing of 50 mm was adopted.

In our previous study on delamination monitoring with the electrical resistance change method [19], a single matrix crack observed with a delamination crack had little effect on the estimation of delamination. To confirm the effect of a single matrix crack on the electrical resistance change, FEA were performed. Fig. 5 shows the results of the FEA of electrical resistance changes of the specimens with a delamination crack of 30 mm. The open rectangular symbols show the electrical resistance change caused by a straight delamination crack located between the surface 0°-ply and the middle 90°-ply. The ordinate is the calculated electrical resistance change, and the abscissa is the location of the delamination crack of 30 mm length. Since the spacing of the outer probes was 50 mm and the spacing of the inner probes was 30 mm, the delamination crack located further out than 40 mm means the delamination was located completely outside the outer probes. When a delamination was located at 0 mm, the delamination did not overlap even the inner probes. Fig. 5 shows that delamination cracks that do not overlap the probes, have negligible electrical resistance change.

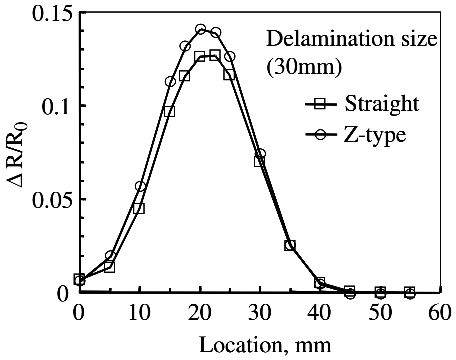

Fig. 5. Electrical resistance change of two kinds of delamination crack configurations obtained by means of FEA: straight delamination crack and Z-type delamination crack.

The open circle symbols in Fig. 5 show the electrical resistance changes of a delamination crack that consisted of a delamination crack and a matrix crack. The configuration of the delamination is like the letter of Z: half of the delamination crack was located between the upper 0° ply (the 0°-ply where probes were mounted); the middle 90°-ply and rest of the half delamination crack was located between the lower 0°-ply and the middle 90°-ply. The matrix crack in the 90°-ply jointed the two half-size delamination cracks. As shown in Fig. 5, the electrical resistance changes of the Z-type delamination crack show little difference compared with the results of the straight delamination crack. This is why the matrix crack has negligible effect on the identification of the delamination crack location in my previous paper. A small difference, however, exists between the results of the straight delamination crack and the results of Z-type delamination cracks. Since the electrical resistance change due to a delamination crack causes significantly larger electrical resistance change compared with the electrical resistance change of a matrix crack, the effect of matrix crack can be neglected for identification of a delamination crack. This means that the detection of matrix cracking is only possible for a composite structure without a delamination crack.

On the basis of these results, we can conclude that the detection of the matrix crack density is possible even when we mounted all probes on the same side of the specimen surface (the outer surface of a tank). This enables the application of the electrical resistance change method to matrix crack detection of a composite tank structure.

4. Experimental feasibility study

4.1. Specimen and test method

The material used here was a prepreg sheet of Q-1111/2500 (carbon/epoxy, Tohotenux). The prepreg was stacked to make two kinds of laminates, a single-ply unidirectional CFRP of $[0]_T$ and cross-ply CFRP laminate of $[0/90/0]_T$. The laminates were cured in a two-step curing process of 90 × 40 and 130 °C × 50 min at 0.5 MPa using a hot press machine. From the laminates, rectangular specimens of 15×210 mm were fabricated. Tabs made of GFRP were attached on both sides of the ends of the specimen to protect the specimen surfaces from damage due to chucking.

To measure the electrical resistance change during loading, a four-probe method was adopted in the present study. Electrodes for each specimen were produced using silver paste after polishing the specimen surface using sand paper to remove surface resin layer. Our previous study showed that complete removal of the surface resin is indispensable [18,20]. All of the four electrodes were mounted on a single side of the specimen to simulate the matrix crack detection of a composite tank. The specimen configuration and electrodes are shown in Fig. 6.

The electrical resistance change was measured by means of a LCR meter produced by HIOKI Co. Alternating current of 1 kHz was used for the measurements for all specimens. Since the capacitance element of the CFRP in 1 kHz is very small (a phase angle is almost zero) when it is compared with the resistance element, almost all measured impedance change was caused by the resistance change in this alternating current. Therefore, we focused on the electrical resistance change even though we used alternating current.

Using a material testing machine, displacement-control tensile tests were conducted at the loading rate of 0.1 mm/min. For every specimen, a strain gage was mounted on the middle of the specimen, and a strain–electrical resistance curve was monitored. Loading and unloading tests were performed to measure residual electrical resistance change under a completely unloaded conditions and to measure the electrical resistance change during reloading. For the cross-ply laminates, matrix crack density was measured using a replica method made from the specimen side surface.

4.2. Results of unidirectional CFRP

Fig. 7 shows the results of the electrical resistance change during tensile tests of unidirectional CFRP of $[0]_T$. The abscissa is the applied strain measured with a conventional strain gage attached on the specimen surface, and the ordinate is the measured electrical resistance change normalized with the initial resistance ($R = 472$ mΩ). In this test, the applied maximum strain was 1100μ and unloaded cyclically as shown in Fig. 7. This figure shows that the electrical resistance increases with increase of applied tensile strain, and the relationship between the electrical resistance change and applied strain is almost linear. The slope did not change in the cyclic test.

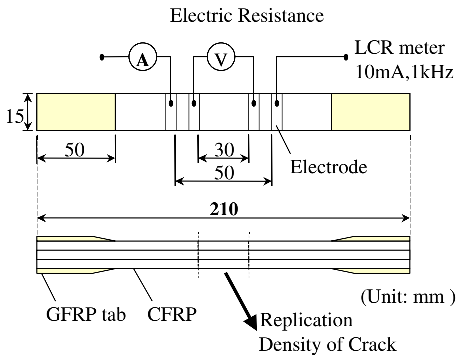

Fig. 6. Specimen configuration for matrix crack detection.

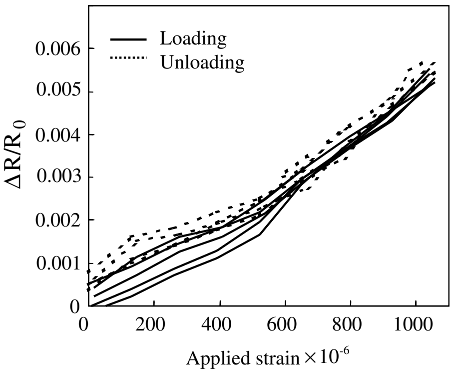

Fig. 7. Measured electrical resistance change for cyclic loading (constant maximum strain) of a single-ply unidirectional CFRP $[0]_T$. Initial electrical resistance $R = 472$ mΩ.

Schulte et al. have measured the electrical resistance change of unidirectional CFRP in the fibre direction [2]. They reported that the electrical resistance increases with increase of applied strain, the same as a strain gage in the elastic deformation region. On the other hand, Wang and Chung have reported negative piezoresistivity in unidirectional CFRP [21]: electrical resistance decreases with increase of applied tensile strain. Fig. 7 supports positive piezoresistivity: electrical resistance increases with increase of applied strain. This positive piezoresistivity is reversible and there is no residual electrical resistance change in the completely unloaded condition.

Fig. 8 shows the electrical resistance change of unidirectional CFRP of higher applied strain. The maximum applied strain is increasing at every cycle of loading up to over 5000μ. The abscissa is the applied strain and the ordinate is the measured electrical resistance change. As shown in Fig. 8, up to 4000μ, the load–unload relationship

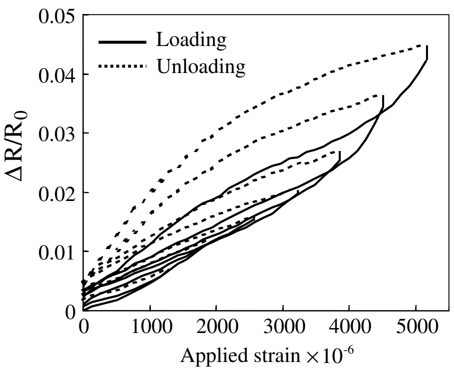

Fig. 8. Measured electrical resistance change for cyclic loading (maximum strain increased for every cycle) of a single-ply unidirectional CFRP $[0]_T$. Initial electrical resistance $R = 472$ mΩ.

is almost linear. Over the 4000μ strain, the measured electrical resistance change increases rapidly, and the load–unloading curve draws a hysteresis loop. Schulte et al. [2] suggested that the rapid increase of the electrical resistance of unidirectional CFRP is caused by breakages of weaker carbon fibres inside the specimen. This means that the electrical resistance increase under 4000μ strain is caused only by the piezoresistivity of CFRP when the CFRP has no matrix cracking.

4.3. Results for cross-ply laminates

Fig. 9 shows the electrical resistance change for cyclic loading of a cross-ply laminate. The maximum strain of cyclic loading here was 1000μ strain. The abscissa is the measured applied strain and the ordinate is the measured electrical resistance change. As with the unidirectional CFRP shown in Fig. 7, the load–unload relationship is almost linear and there is no residual electrical resistance in the completely unloaded condition. This electrical resistance increase was caused by the piezoresistivity.

Fig. 10 shows the electrical resistance change of cross-ply CFRP of higher applied strain. The maximum applied strain increased for every cycle of loading up to over 5000μ as shown in Fig. 8. The abscissa is the applied strain and the ordinate is the measured electrical resistance change. As shown in Fig. 8, the load–unload relationship is almost linear up to 4000μ, and over 4000μ strain, the measured electrical resistance change increases rapidly due to fibre breakages. For the cross-ply, however, a rapid increase of electrical resistance change is observed at 3000μ strain, and a residual electrical resistance exists at the completely unloaded condition when the maximum strain was over 3000μ.

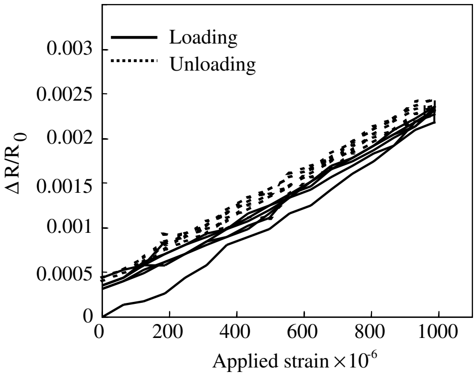

Fig. 9. Measured electrical resistance change for a cyclic load (maximum strain is kept constant) of a cross-ply CFRP $[0/90/0]_T$. Initial electrical resistance $R = 224\ \mathrm{m\Omega}$.

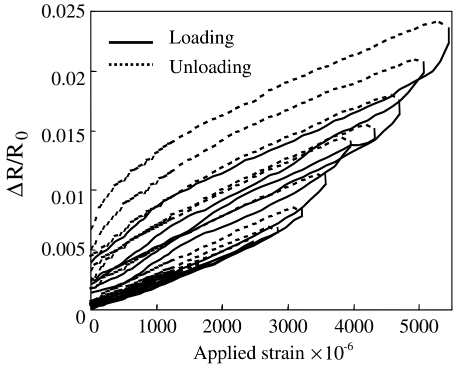

Fig. 10. Measured electrical resistance change for a cyclic load (maximum strain increased at every cycle) of a cross-ply CFRP $[0/90/0]_T$. Initial electrical resistance $R = 224\ \mathrm{m\Omega}$.

Fig. 11 shows the matrix crack density measured at the specimen side surface by means of a replica method. The abscissa is the applied strain and the ordinate is the measured matrix crack density. As shown in Fig. 11, matrix cracking was generated at an applied strain of 3000μ. The matrix crack density increased up to 5000μ.

The rapid increase of the electrical resistance of the cross-ply laminate is observed over applied strain of 3000μ in Fig. 10. Since the applied strain of 3000μ was smaller than the strain at the start of fibre breakage at 4000μ observed in Fig. 8, the rapid increase was judged to be caused by the matrix cracking. This shows that the method is applicable for matrix crack detection even under the loaded condition.

For practical tank structures, we have to know about any matrix cracking before charging the tank. As shown in Fig. 10, the residual electrical resistance at completely unloaded increases after the generation of matrix cracking over the applied strain of 3000μ. Fig. 12 shows the results of the residual electrical resistance change in the completely unloaded condition. The abscissa is the maximum applied strain before unloading and the ordinate is the residual electrical resistance change measured in the completely unloaded condition. This figure clearly shows that the residual electrical resistance rapidly increases after matrix crack generation over an applied strain of 3000μ. This result suggests that we can use the residual electrical resistance to detect matrix cracks.

In the present study, a thin cross-ply laminate was used. The thin cross-ply laminate had high residual stresses. In the 90°-ply, tensile residual stress existed The matrix crack

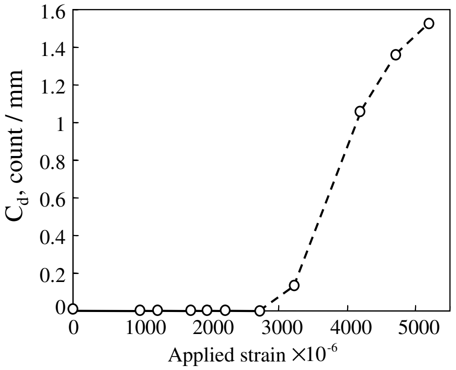

Fig. 11. Matrix crack density with an increase of applied strain measured by means of a replica method.

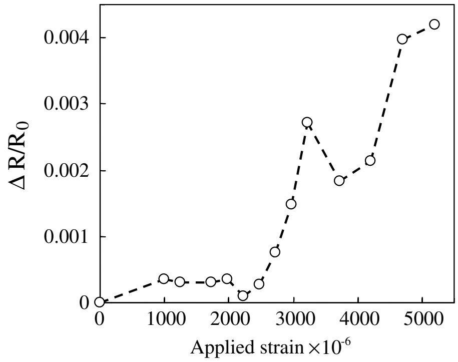

Fig. 12. Measured residual electrical resistance change of a cross-ply CFRP for the completely unloaded condition plotted against the applied maximum tensile strain.

surface remained open under the completely unloaded condition due to the relief of the high tensile residual stress. This made the residual electrical resistance change in the completely unloaded condition. Since a practical composite fuel tank aerospace structure is made of thin laminate, the residual electrical resistance change is applicable to matrix crack detection.

5. Conclusions

In the present study, we proposed a new method for matrix crack detection by means of electrical resistance change with integrated probes on a single surface of a CFRP composite structure. For a fuel tank structure made of a CFRP laminate, we cannot mount electrical probes on the end of structures or on the inside surface of the tank structures. We have to mount all probes only on the outside surface. The present method used FEM analyses to search for the best placement of probes for matrix crack detection using a rectangular plate. To simulate the tank structure, all probes were placed on the single surface of the CFRP plate specimen. The present study adopted a four-probe method to measure the electrical resistance change. The results obtained are as follows.

(1) The FEM analyses revealed that the electrical resistance linearly increased with the increase of the number of matrix cracks between the inner probes.
(2) By means of thin CFRP cross-ply laminate, the method was experimentally confirmed to be useful for detecting the matrix crack density between the probes.
(3) The residual electrical resistance at the completely unloaded condition increased with increase of matrix crack density.
(4) Measurements of the residual electrical resistance enabled us to detect the matrix crack density without loading.

References

[1] Aoki T, Ishikawa T, Kumazawa H, Morino Y. Cryogenic mechanical properties of CF/polymer composites for tanks of reusable rockets. Adv Compos Mater 2001;10(4):349–56.
[2] Schulte K, Baron Ch. Load and failure analyses of CFRP laminates by means of electrical resistivity measurements. Compos Sci Technol 1989;36(1):63–76.
[3] Chen PW, Chung DDL. Carbon fibre reinforced concrete for smart structures capable of non-destructive flaw detection. Smart Mater Struct 1993;2(1):22–30.
[4] Kaddoour AS, Al-Salehi FA, Al-Hassani STS. Electrical resistance measurement technique for detecting failure in CFRP materials at high strain rate. Compos Sci Technol 1994;51(3):377–85.
[5] Wang X, Chung DDL. Sensing delamination in a carbon fibre polymer-matrix composite during fatigue by electrical resistance measurement. Polym Compos 1997;18(6):692–700.
[6] Irving PE, Thiagarajan C. Fatigue damage characterization in carbon fibre composite materials using an electric potential technique. Smart Mater Struct 1998;7(4):456–66.
[7] Abry JC, Bochard S, Chateauminois A, Salvia M, Giraud G. In situ detection of damage in CFRP laminates by electric resistance measurements. Compos Sci Technol 1999;59(6):925–35.
[8] Seo DC, Lee JJ. Damage detection of CFRP laminates using electrical resistance measurement and neural network. Compos Struct 1999;47(1–4):525–30.
[9] Weber I, Schwartz P. Monitoring bending fatigue in carbon–fibre/epoxy composite strands: a comparison between mechanical and resistance techniques. Compos Sci Technol 2001;61(6):849–53.
[10] Park JB, Okabe T, Takeda N, Curtin WA. Electromechanical modeling of unidirectional CFRP composites under tensile loading condition. Compos Part A 2002;33(2):267–75.
[11] Ogi K, Takao Y. Characterization of piezoresistance behavior in a CFRP unidirectional laminate. Compos Sci Technol 2005;65(2):231–9.
[12] Todoroki A, Matsuura K, Kobayashi H. Application of electric potential method to smart composite structures for detecting delamination. JSME Int J A 1995;38(4):524–30.
[13] Todoroki A. Effect of number of electrodes and diagnostic tool for delamination monitoring of graphite/epoxy laminates using electric resistance change. Compos Sci Technol 2001;61(13):1871–80.
[14] Todoroki A, Tanaka M, Shimamura Y. Measurement of orthotropic electric conductance of CFRP laminates and analysis of the effect on delamination monitoring with electric resistance change method. Compos Sci Technol 2002;62(5):619–28.
[15] Todoroki A, Tanaka Y, Shimamura Y. Delamination monitoring of graphite/epoxy laminated composite plate of electric resistance change method. Compos Sci Technol 2002;62(9):1151–60.
[16] Todoroki A, Tanaka Y, Shimamura Y. Identifying delamination in cross-ply and quasi-isotropic beams of CFRP by a standardized electrical resistance method. Polym Polym Compos 2004;12(1):75–85.
[17] Todoroki A. Electric resistance change method for cure /strain/ damage monitoring of CFRP laminates. Key Eng Mat 2004;270–273:1812–20.
[18] Todoroki A, Yoshida J. Electrical resistance change of unidirectional CFRP due to applied load. JSME Int J A 2004;47(3):357–64.
[19] Todoroki A, Tanaka M, Shimamura Y, Kobayashi H. Effects of delamination shape with a matrix crack on monitoring by electrical resistance method. Adv Compos Mater 2004;13(2):107–21.
[20] Todoroki A, Yoshida J. Apparent negative piezoresistivity of single-ply CFRP due to poor electrical contact of four-probe method. Key Eng Mater 2005;297–300:610–5.
[21] Wang S, Chung DDL. Piezoresistivity in continuous carbon fibre polymer-matrix composite. Polym Compos 2000;21(1):13–9.