ELECTRICAL RESISTANCE CHANGE OF INTERLAMINAR WOVEN-FABRIC CFRP IN MODE II FRACTURE

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Abstract

For some cases, woven-fabric CFRP laminates are inserted between a skin and a core of a sandwich structure. For the actual sandwich structures, it is very important to detect damage initiation at the interface between the woven-fabric CFRP and unidirectional CFRP. In the present study, the authors investigated the electrical resistance change of End-Notched Flexure specimens of a sandwich structure to apply the Electrical Resistance Change Method (ERCM) to the detection of delamination crack. Experimental researches were performed. As a result, electrical resistance change was composed of three stages and piezoresistivity was able to be explained using two mechanical models of the specimen according to the delamination crack propagation. In the stage before the crack propagation, electrical resistance increased because of fiber breakages at the crack tip and this remained as permanent change.

1. Introduction

Structural Health Monitoring (SHM) is attracting method to improve maintainability and sustainability of structures. Electrical Resistance Change Method (ERCM) is a kind of self-sensing SHM also for Carbon Fiber Reinforced Plastics (CFRP) as an electrically anisotropic material. In the ERCM, structural integrity is assessed by monitoring electrical resistance change associated with damages or deformations of CFRP using electrodes placed on the structures. Many researchers have investigated the electrical resistance change mechanisms [1, 2, 3] and the authors' group has also found the availabilities of ERCM to detect various kinds of damages [4, 5, 6] or under compression loading [7] and to apply to woven-fabric laminates [8] experimentally and analytically.

A composite sandwich structure composed of skin material and core material performs effectively and is widely adopted for aerospace structure. In order to reinforce the shear strength, woven-fabric CFRP is attached to the surfaces of the structure or inserted into interlayer between skin unidirectional CFRP and core GFRP (Glass Fiber Reinforced Plastics). When a load is applied to the sandwich beam, shear deformation generally causes a delamination between the layers because of the difference of the elastic modulus between skin and core material. For the woven-fabric CFRP sandwich structure, the interlaminar shear between woven-fabric CFRP and GFRP core causes fiber breakages resulting from the delamination crack propagation. These carbon fiber breakages may be detected using the electrical resistance change.

In the present study, End-Notched Flexure (ENF) test are performed. The specimens are made with unidirectional CFRP, woven-fabric CFRP and GFRP. During the ENF test, electrical resistance change is monitored. The mechanism of the electrical resistance change is examined and discussed.

2. ENF specimen and testing method

The stacking sequence of the ENF specimen is shown in Figure 1. The specimens are composed of three kinds of materials; 2-ply unidirectional carbon fiber prepreg, 2-ply plane weave woven-fabric carbon prepreg (0/90°) and 2 mm thick GFRP laminate for sandwich core material. The unidirectional carbon fibers are oriented in the longitudinal direction (*x*-direction). The warps and the wefts of woven-fabric carbon prepreg are oriented *x*-direction and *y*-direction, respectively. The adhered surface of the GFRP laminate was polished with rough (#60) sandpapers in advance. In addition, a folded 0.1 mm thick polyimide film that performs as an initial delamination crack was inserted between woven-fabric prepreg and GFRP laminate like the schematic diagram (Figure 1). The cure condition was 85 °C×0.32 MPa×2.0 hr for pre-cure stage, 135 °C×0.32 MPa×3.0 hr for curing.

Two types of specimens were prepared; for one of the specimens, 90°-direction carbon fibers of woven-fabric CFRP (so-called wefts) near the delamination crack tip were cut before fabrication of the specimen. When the delamination crack propagates under large shear load of actual structures, the wefts of woven-fabric CFRP slide and this sliding causes the fiber breakages. As it is difficult to load a large shear force that causes fiber breakages for a test specimen, the wefts of woven-fabric CFRP prepreg are cut before fabrication in the present study to simulate the fiber breakages of actual structures. Therefore, in the present study, the propagation of the delamination crack moves the cut wefts of the woven-fabric CFRP and the loss of electrical contacts between them is simulated as the fiber breakages in the present study.

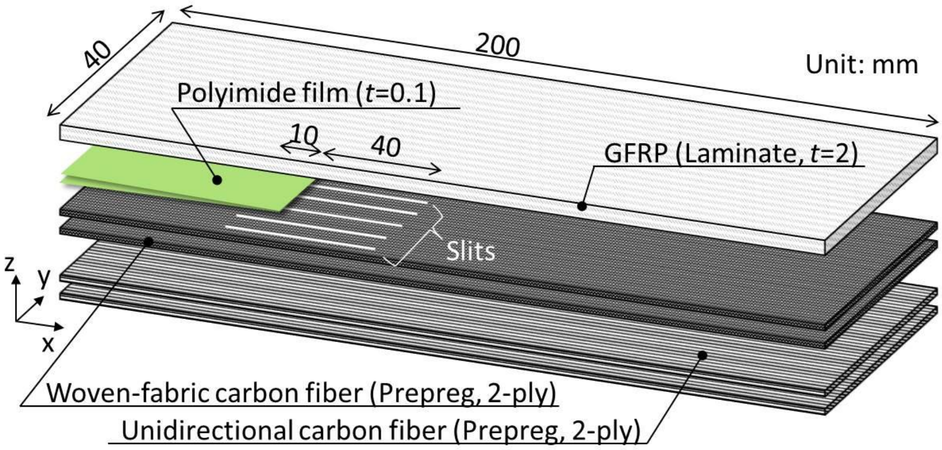


Figure 1. Stacking sequence of the specimen.

In order to measure the electrical resistance change associated with the targeted damage in the structure, authors' group has proposed and adopted copper plating electrode because of the following reasons:

1) Electrical contacts between copper electrodes and carbon fibers are very reliable because of the manufacturing by turning on electricity.
2) The quality of the electrodes is not dependent on individual technique of manufacturers.

Likewise in the present study, copper plating electrodes were placed on the specimens in accordance with the manufacturing process [9] as the configuration in Figure 2. Using the configuration of a pair of electrodes, electric current is applied between the outside ones and electrical potential between the inside small ones is measured; a four-probe method is adopted here. Four-probe method excludes the influence of contact electrical resistance between carbon fibers and plated copper electrodes by separating the electric current electrodes and the electrical potential measurement electrodes. The woven-fabric CFRP performs as a conductive path because the electrical conductivity of transverse direction of unidirectional CFRP is much higher than that of in-plane direction of woven-fabric CFRP. In addition, electric current of transverse direction can flow up to deeper part of the structure because the degree of the electrical anisotropy decreases, that is, the ratio of the electrical conductivity of unidirectional CFRP in through-thickness direction to that of transverse direction $\sigma_t/\sigma_{transverse}$ is much larger than the ratio of that of through-thickness direction to that of fiber direction σ_t/σ_{fiber}. Although each electrical potential measurement electrode is not physically enclosed with an electric current electrode, the woven-fabric CFRP can be regarded as a part of the copper electrode because of its high electrical conductivity of in-plane direction. Therefore, the electrical potential inside of each electric current electrode can be constant and this configuration enables a stable measurement of the electrical potential.

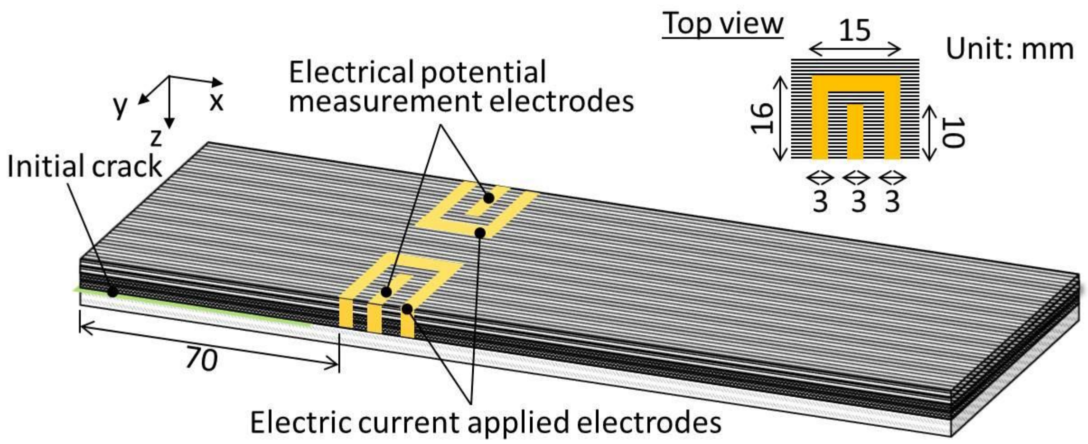


Figure 2. Configuration of the electrodes.

Three-point bending test was conducted as ENF test with a testing machine (Shimadzu, AG-I) and electrical resistance change was measured with a LCR meter (Hioki, Hytester 3522-50). The loading condition is shown in Figure 3. The procedure of ENF test follows Japan Industrial Standards (JIS) K 7078. The specimens were placed at the testing machine so that CFRP layer was below in order to prevent the compression failure of carbon fibers under a loading point. An initial delamination crack length a_0 was 30 mm and a span between supporting points 2*L* was 100 mm. Each 0.1 mm thick polyimide film was inserted between the jig and the specimen to prevent electrical contact. The loading rate was 1.5 mm/min constantly. An alternating current 30 mA of 450 Hz was applied for the measurement of electrical resistance. Since the phase angle at 450 Hz was 0 ° during the measurement, the capacitance did not exist in the impedance at this frequency. Thus, the impedance was regarded as a pure electrical resistance.

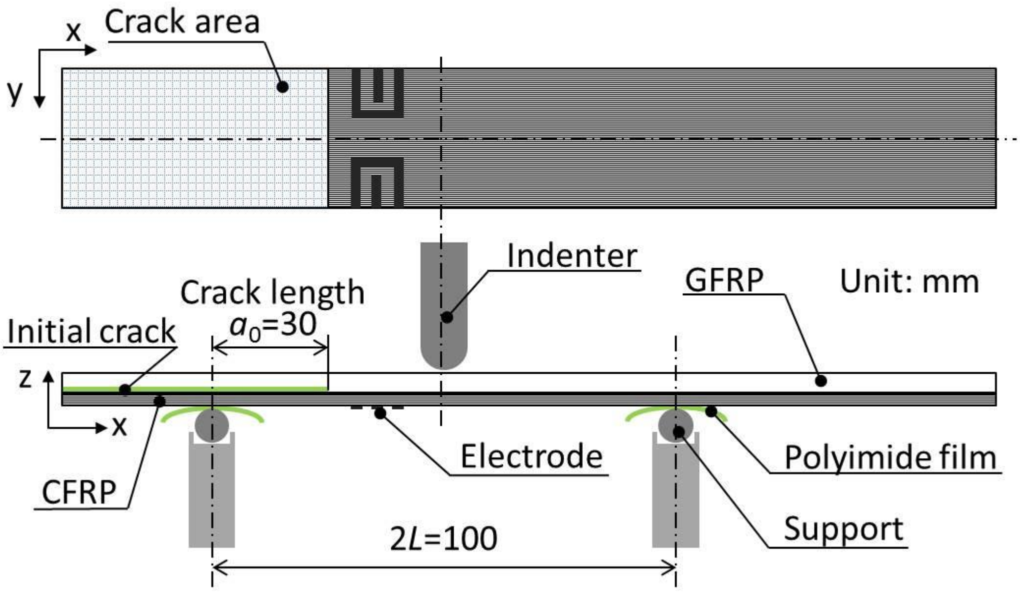


Figure 3. Three-point bending test set up.

3. Results and Discussion

3.1 Experimental results

Figures 4, 5 show the monitored electrical resistance change of the specimen; Figure 4 is for the non-cut wefts specimen and Figure 5a and 5b are for the cut wefts specimens. The horizontal axis is for the monitoring time, the left vertical axis is for the measured electrical resistance change $\Delta R/R_0$ and the right one is for the applied load. Initial electrical resistances R_0 are 76.7 mΩ, 118 mΩ and 120 mΩ, respectively. Generally, electrical resistance *R*, electrical conductivity σ, length of conducting path *L* and cross sectional area of conducting path *A* has a following relationship:

$$R = \frac{1}{\sigma}\frac{L}{A} \tag{1}$$

For the ENF specimen, assumed that *R* is initial electrical resistance R_0, *L* is specimen width and *A* is the product of specimen thickness of CFRP parts and electrode width, electrical conductivity σ can be obtained as 3.7, 4.1 and 3.9×10^4 S/m, respectively. As described in previous studies, electrical conductivity of the carbon fiber of unidirectional direction is 2.1-3.4 ×10^4 S/m at fiber volume fraction V_f= 0.43-0.58 [3]. In accordance with JIS K 7075, the fiber volume fraction of the ENF specimens was measured as V_f= 0.70 and this means that the electric current flows in the in-plane direction of woven-fabric CFRP placed under the unidirectional ply: the electric current does not flow in the transverse direction of the surface unidirectional CFRP.

In Figures 4 and 5, both electrical resistance change behaviors consist of three different stages in regardless of whether or not the wefts of woven-fabric CFRP were cut. The first and the second stages before crack propagations are shaded by blue and yellow, respectively, and the third stage means the behavior after the crack propagations. For the both specimens, the electrical resistance decreases in the first stage and increases in the second stage with increased the applied load. These can be explained as following. Figure 6 shows macroscopic load condition of ENF test. Consider that a normal load is applied at the center of the ENF specimen. In the first stage with a small deformation, the target part of the specimen can be modeled as one beam composed of CFRP part and GFRP part such as Figure 6a because the delamination crack does not propagate in the target area where the electric current flows. According to elastic modulus E_c= 136 GPa, E_g= 11.9 GPa [7], thickness of layers t_c= 0.6 mm, t_g= 2.0 mm (subscripts c and g mean CFRP and GFRP, respectively), width of specimen b= 40mm, the neutral-surface of the composite beam can be obtained to be at the middle between GFRP laminate and CFRP layers. This means that the woven-fabric CFRP is subjected to tensile strain in the longitudinal direction and compressive strain by Poisson's effect in the transverse direction. As the electric current flows in transverse direction, the electrical resistance change detects the compressive strain. Thus, the electrical resistance decreases as piezoresistivity [10]. However, the second stage shaded by yellow can be seen in the nonlinearly increased applied load area. This cannot be explained by piezoresistivity because electrical resistance increases from negative to positive in this stage as shown in Figure 5a and 5b. This is caused by fiber damages near the crack tip. The electrical resistance increase of the fiber breakages at the crack tip is permanent change and it is not relieved by the strain unloading.

In the third phase, the applied load decreases suddenly after the delamination crack propagation. For the wefts cut specimen as shown in Figure 5a, electrical resistance keenly increases because of the simulated fiber breakages. For the non-wefts cut specimen as shown in Figure 4 and wefts cut specimen as shown in Figure 5b, the electrical resistance decreases. In this stage, the same modeling of the specimen as the first stage is not applicable. The stress/strain condition is discussed using shear deformable bi-layer model [11, 12] composed of upper GFRP part and lower CFRP part as shown in Figure 6b. As show in Figure 6b, the carbon fibers at the interface to the GFRP are under the compressive strain in the longitudinal direction after the delamination crack growth. This means that the area is subjected to tensile strain in the transverse direction because of the Poisson's effect. After the delamination crack propagation, therefore, the electrical resistance starts decreasing from the increased electrical resistance caused by the fiber breakages and the increase is permanent change.

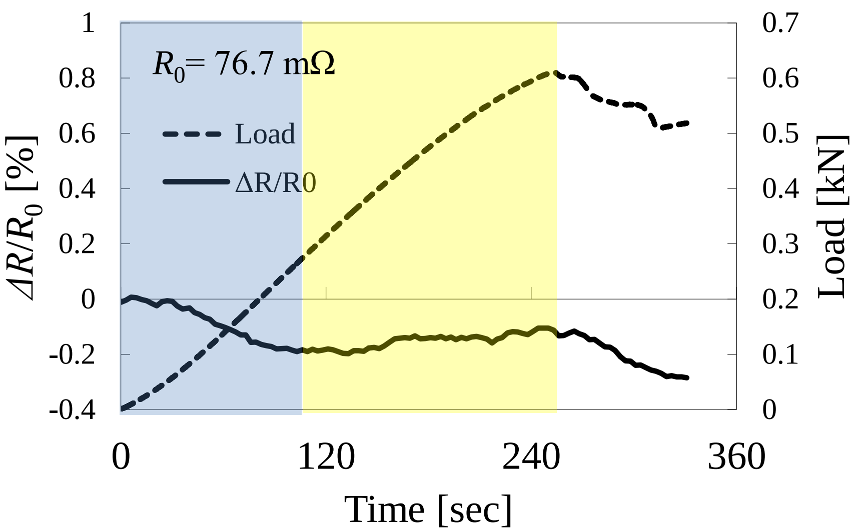
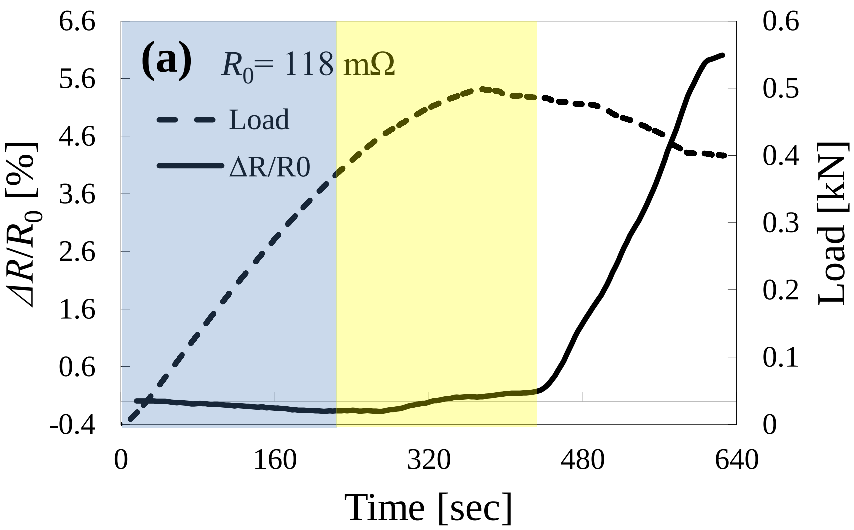


Figure 4. Electrical resistance change of the non-wefts cut specimen.



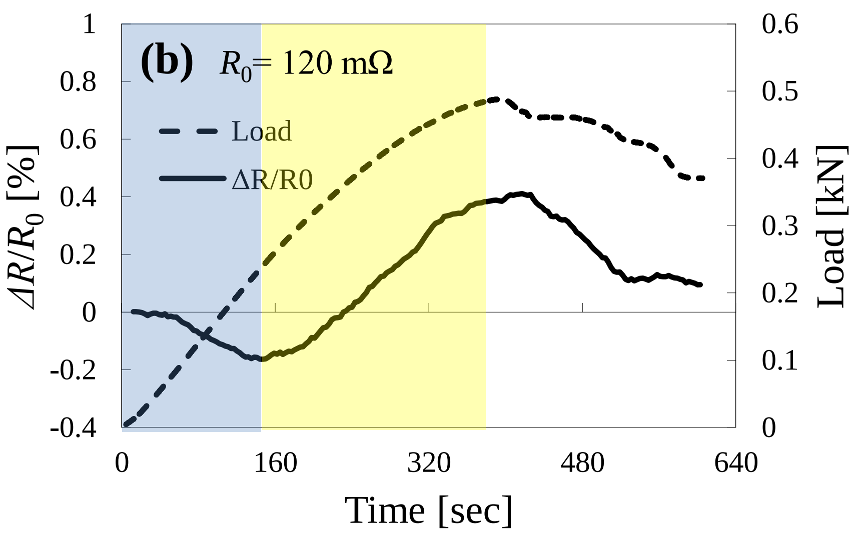


Figure 5. Electrical resistance change of the weft cut specimen.

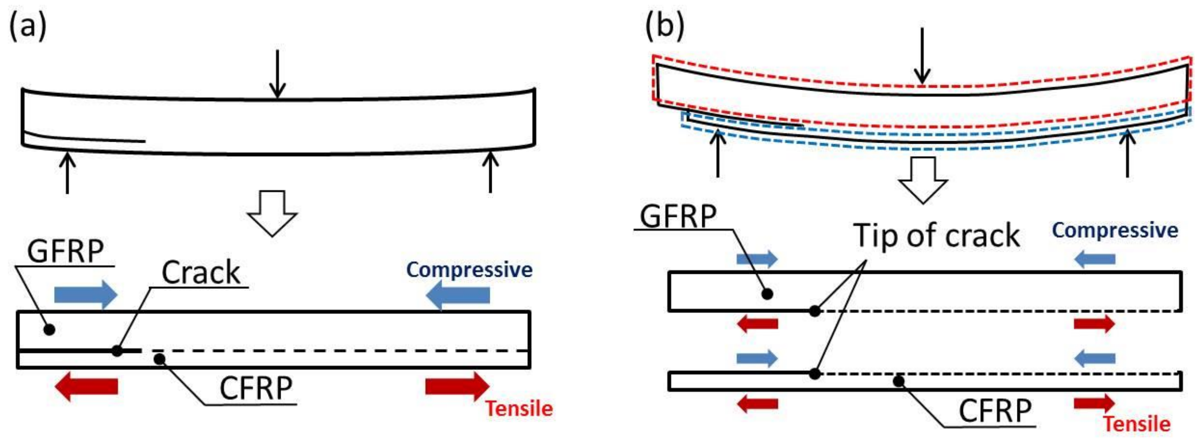


Figure 6. Macroscopic stress/strain condition of ENF test; model (a) and (b) are applied to stage 1 and 3 of electrical resistance change by piezoresistivity, before the appearance of fiber damages near the crack tip and after the propagation of the delamination crack, respectively.

4. Conclusion

1) In regardless of whether or not the wefts of woven-fabric CFRP are cut, the electrical resistance decreases due to piezoresistivity with increased the applied load until the appearance of fiber damages near the crack tip. In the first stage with small deformation, the target part of the ENF specimens can be modeled as one composite beam.

2) In the second stage, electrical resistance increases because of fiber breakages at the crack tip with increased the nonlinearly applied load. This is permanent change and it is not relieved by the strain unloading.

3) After the propagation of the delamination crack, shear deformable bi-layer model composed of upper GFRP part and lower CFRP part is applicable. In this model, the target part is under the compressive strain in the longitudinal direction and under the tensile strain because of Poisson’s effect in transverse direction. Therefore, electrical resistance decreases as piezoresistivity. Electrical resistance increase by fiber breakages remains as permanent change.

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