SMART NDT USING ELECTRICAL RESISTANCE METHOD FOR DELAMINATION MONITORING IN CFRP

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SUMMARY: The electrical resistance method is one of Non-Destructive-Testing method for damage monitoring in CFRP which uses resistivity of carbon fibers which are already embedded in the structure. This means, it is one of the ideal method of intelligent materials because reinforced materials on structure level themselves can be a sensor. It is, however, still on fundamental research. The relation between resistance and fiber breakage has been widely concerned, but not so mach with delamination, moreover no one on fatigue test among author's knowledge. To consider the relation between resistance and delamination, mode I tensile and fatigue tests with original electrode were carried out. Then, the factors which can effect to the value of resistance and micro mechanism were discussed in this paper.

KEYWORDS: Electrical Resistance Method, Intelligent Materials, NDT, Delamination, Fatigue, Mode I, Crack Propagation.

INTRODUCTION

To use composite materials, it has been expected to detect and identify delamination at the same time by easy and trustable way. Today, it exists lots of methods of NDT to detect delamination like by optical fibers, ultrasonic, radiography, infrared thermography Eddy current [1] and so on. But because this material is anisotropic, this object is quite difficult. Therefore, unfortunately, by which ever the method, there are always some problems and no one could have satisfied this goal yet. Then, as a new method, electrical resistance method came appear as an interactive techniques and is drawing the attention nowadays as the method which detects and identifies delamination in CFRP at the real time.
CFRP are materials that carbon fibers are embedded in polymeric matrix. Since matrix has much smaller conductivity, carbon fibers are the main part of conductivity of CFRP. If breakage of fibers happens, the electrical resistance would increase since the number of fibers which have conductivity decreases. Therefore, delamination of CFRP might be detected and identified only by measuring electrical resistance of materials. The method so-called electrical resistance method is based on this simple conception. Yet, it has not been well researched and is waiting future works to solve the problems that it has.

For example of its problems, it is said that there are three ways of conductivity; direction of fiber by fibers, that of traverse by contact among the fibers, and that of thickness by contact

among the plies. So that, even if there is fiber breakage, the current would pass by another direction.

To say the results first, by study until now, it became clear that the change of resistance wouldn't correspond exactly to mechanical properties of specimens. But, of course, there exist certain relations.

EXPERIMENTS

Specimen, Test Devices and Loading Tests

Unidirectional Double Cantilever Beam (DCB) specimens of T800/Epoxy, that configuration of 150, 25, 3 mm of length, width, and thickness, respectably, were used. Artificial defects were induced by inserting Teflon film of 60 mm length, which has no conductivity, between the middle thickness plies. These specimens were connected by Al block-type jigs to a loading machine INSTRON 1122, which has capacity of 500N, or MAYES, capacity of 500N. Then, Mode I tensile and fatigue tests were carried out with various conditions. Direct current of 0.1A was installed through an active arm of Wheatstone bridge. To correct electrical values, Corvergie Multimeter type 400 was used. Since, the areas of the interfaces of the middle thickness plies which attach each other are more important for resistance value, even crack length is normally obtained as a parameter on Mode I fatigue test [2], increase of crack propagation was compared with resistance in this report. When 2 pairs of electrode were used, two circuits were changed by switch.

Electrode

After so many trials of electrode, the best electrode was determined as follows (see Fig. 1); Polish and wipe the surface. Glue copper plate of 3*30 mm to the center of rubber of 25*25 mm. Put silver past on copper plate. Put adhesion on only rubber part, and glue to the surface. Sold copper plate and lead wire which is fixed on that rubber.

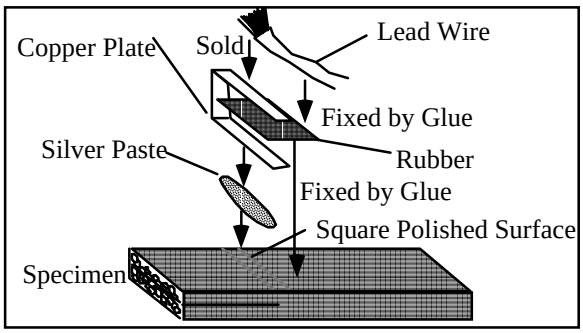

Fig. 1. Authors' Electrode

This method is convenient to obtain constant resistance with minimum noise, and is tough to swing of fatigue test. The results on this paper, however, were mixed with the ones with other electrodes. The pair of this type of electrode was located at the initial crack tip on the opposite side of specimen. When two pairs were used, the other pair was located at the end of specimen.

Bundle Test

To know some factors which can effect resistance, carbon fiber bundle itself was drawn out. These bundles, covered by Epoxy or non covered, were directly attached to the machine INSTRON.

PRINCIPAL RESULTS

Tensile Test

Fig. 2 shows the typical relation between resistance change and load on tensile test. It can be seen that resistance increases by time, or in other terms, by the Crack-Opening-Displacement (COD). In expanded figure, lots of not step-wise but small mounts of resistance value can be observed. Fig. 3 shows the relation between resistance change and crack propagation. Fig. 4 shows the result with lower speed where decrease of resistance value in the beginning are clearly to be seen, instead, Fig.2 had only a few seconds. After crack starts, even thought, resistance started increasing and it showed the same curve.

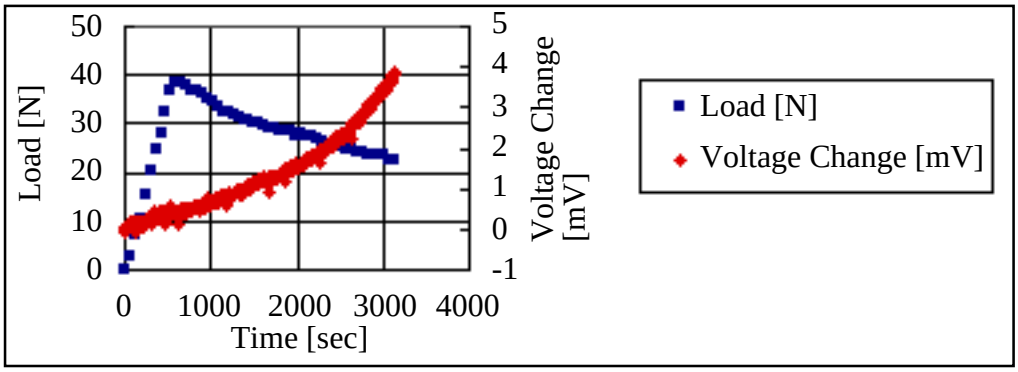

Fig. 2. Load and Resistance against Time on Tensile Test

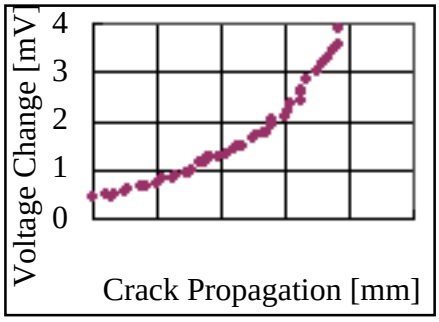

Fig. 3. Resistance against Crack Propagation on Tensile Test

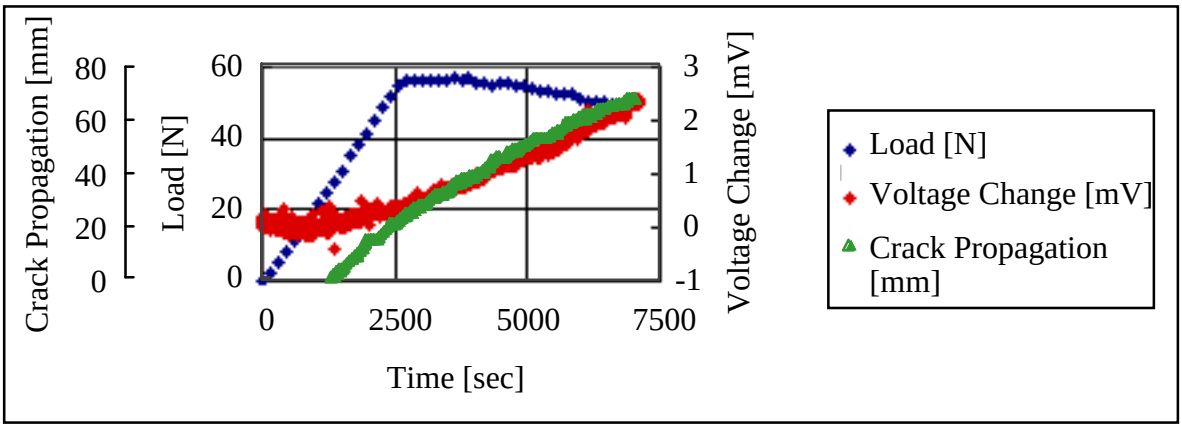

Fig. 4. Load and Resistance against Time on Tensile Test with Slow Speed

Fatigue Test

Fig. 5 shows typical relation between resistance change and number of cycle on fatigue test. At these keen mounts of resistance change till 1100 cycles, up and down, some sounds of breakage were confirmed, even crack propagation did not occur visually. Interesting is that resistance value jumped up and down, but it went back to former value at 800 cycles. With higher frequency, more prominent points were observed. But since narrow range of frequency was installed in all of experiments, from 0.1 Hz to 5 Hz, frequency effect did not observed.

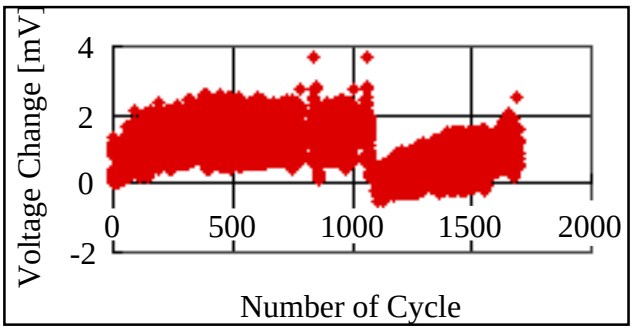

Fig. 5. Absolute Resistance Value against Small Number of Cycle on Fatigue Test

Since authors had always analyzed until 1000 cycles of this figure, another type of results in which all of resistance values decrease from the beginning was doubt long time [3], but it became clear that resistance decreases always below the first value when crack had not progress. So that, Fig. 5 is the result with absolute resistance value, with that misunderstanding caused by Wheatstone bridge circuit. At around 1200 cycles, the resistance showed big steps entirely, even here neither crack did not progress visually.

To see this result more clearly, result from another specimen with more number of cycle would be given as Fig. 6. This shows some increases of resistance value entirely at exactly when crack progressed, means around 2500, 11000, and 23000 cycles. Moreover, it can be seen that decrease of resistance happened not only in the beginning of loading test, but even after these entirely increases of resistance possibly caused by crack progress.

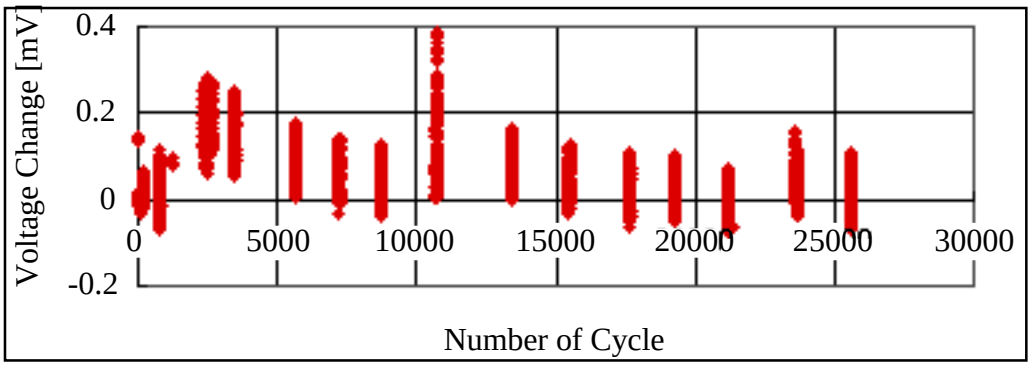

Fig. 6. Clear Increase of Entirely Resistance against Number of Cycle on Fatigue Test

If resistance always decreases in this way, even it converges, it seems impossible to get reasonable relation between resistance and crack progress. Even existences of crack progress are possible to be seen in this way, continued observation does not seem interesting in industrial level.

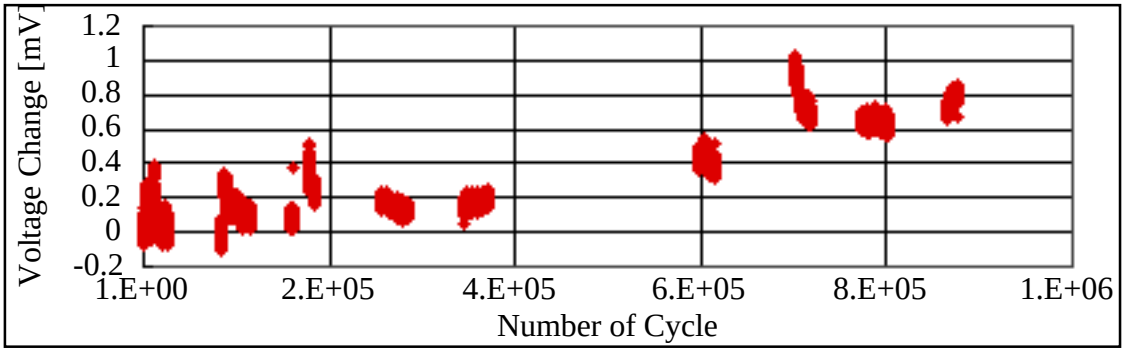

Fig. 7. Resistance against enough Large Number of Cycle on Fatigue Test

Fig. 7 answers with continued much more numbers of cycle of the same specimen to Fig. 6. Since two pairs of electrode were used this time (this result is from one of them), the effect by switching is unfortunately included in this figure. It can be seen here, however, that increase of resistance following to more crack progress up to 5 mm became much higher enough to ignore that keen mounts and decrease.

Bundle Test

Fig. 8 is the typical result of load and resistance against time on tensile test of bundle. Bundle itself which is not covered breaks as sparkling. Clear relation between loading and resistance is observed in this figure, but this should be related not to delamination but to fiber breakage.

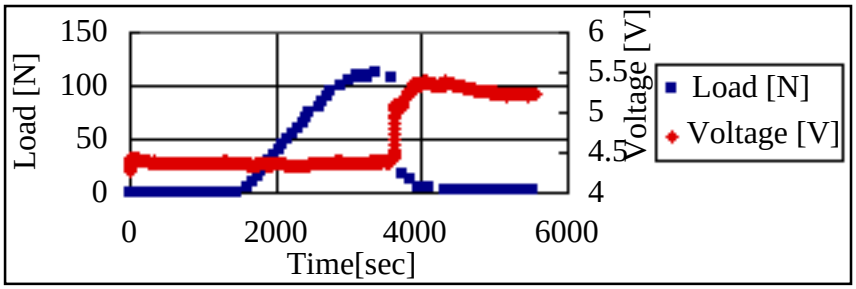

Fig. 8. Load and Resistance against Time on Tensile Test of Bundle

Two Pairs of Electrode

Since there remain some problems to put some pairs of electrode, there were not enough data to determine the result from two pairs of electrode which located at different place. It was, however, easily observed that resistance values from father electrode to crack tip showed less effect by crack progress.

DISCUSSION

On tensile test, clear relation between resistance and crack propagation was obtained. Also on fatigue test, unfortunately it is not so clear but resistance showed some relation with mechanical properties. But what are these mechanical properties? What can effect to the value of resistance? Two points should be discussed here. First one is that big question; why that resistance would decrease? By progress of crack, it is natural to imagine that there should be some increases of resistance. Decrease of resistance must mean increase of current. For this phenomenon, temperature effect, stiffness effect, and fiber bridging effect would be discussed. The second point is that if resistance change appear differently between tensile and fatigue test? After these considerations of factors, one of the fracture model based on results would be suggested at the end.

Temperature

It was described that there is no temperature effect to the specimen caused by current below 1A on CFRP [4]. But also there is another report describing that temperature of specimen keeps increasing for first 5 minutes after installation of current, then, becomes constant after all [5]. With this amount of current here, 0.1 A, it is assumed that there were no effect of temperature, but all the loading tests had done more than 10 minutes after current was installed to make sure. In fact, resistance did not change after then for 6 hours without loading.

But even after that installation of current, temperature effect might happen by loading especially on fatigue test. To know this fact, loading was stopped. After tensile test, when it was stopped, resistance stayed on the same value. After fatigue test with small load for 6 hours, not to have crack progress, resistance value moved to its one side of entirely movement, but did not move more than that. If there exists this effect, decrease of resistance

should not have convergence. So that it is concluded that there were no temperature effect even on fatigue test.

Stiffness and also another kind of Resistance; from Results of Bundle Test

When load is applied on specimen, it is assumed that fibers obtain tension since its stiffness changes. Bundle results showed quite direct relation between bundle breakage and resistance, At the beginning, however, resistance movement was surely observed, even load was still zero since bundle was slackened. From this result, this effect seems confirmed, but not sure in which meaning yet.

Also from these results of bundle, resistance movement after breakage was observed. This recalls the other type of resistance caused by friction of fibers.

Fiber Bridging

Many fiber bridges were obviously observed especially on fatigue test. The fracture surfaces showed that there were fibers which must had been bridges even on tensile test. It is easy to be assumed that these bridges could effect to resistance. To consider this fact, thin paper was installed between two middle plies on fatigue test, described as an arrow on Fig.9. It can be assumed that there was crack progress around 800 cycles. Paper was installed just before 2000 cycles. Since paper has enough thickness and crack tip must not form straight line but curve, this is not scientific experiment. It can be seen, even thought, that resistance arrived to the value level before decrease started. This says that decrease of resistance relates to fiber bridge mainly. In the beginning of loading, it is also surmised that fiber arrangement by loading happened, but no explanation for this.

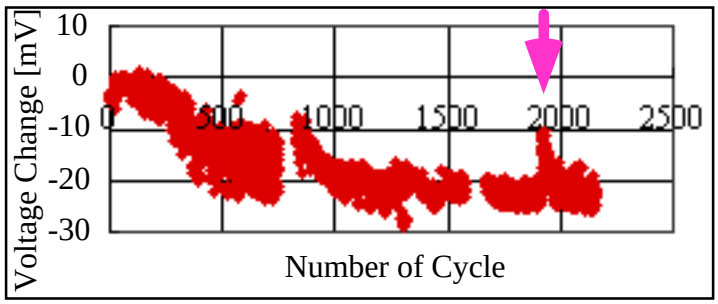

Fig. 9. Insertion of Paper on Fatigue Test

Fracture Surface by SEM

On the fracture surface observed by SEM after tensile test, there were many fibers cut in the surface, and that resin surface was flat enough. Instead, after fatigue test, surface was quite rough. Not only long edges which should had been fiber bridging, but there were many fibers observed of which short edges came out from the surface.

Crack Progress, COD, Maximum Displacement, and Maximum Load

Fig. 10 shows the comparison of crack progress, COD, maximum displacement to resistance value on fatigue test where maximum load was changed to higher at around 2000 cycles. Fig. 11 shows relation between resistance and these factors where crack progress has good correspondence. With big attention, it can be observed that change of resistance was bigger when maximum loading was higher from where crack progress the same 2 mm at around 400 cycles and at around 2200 cycles.

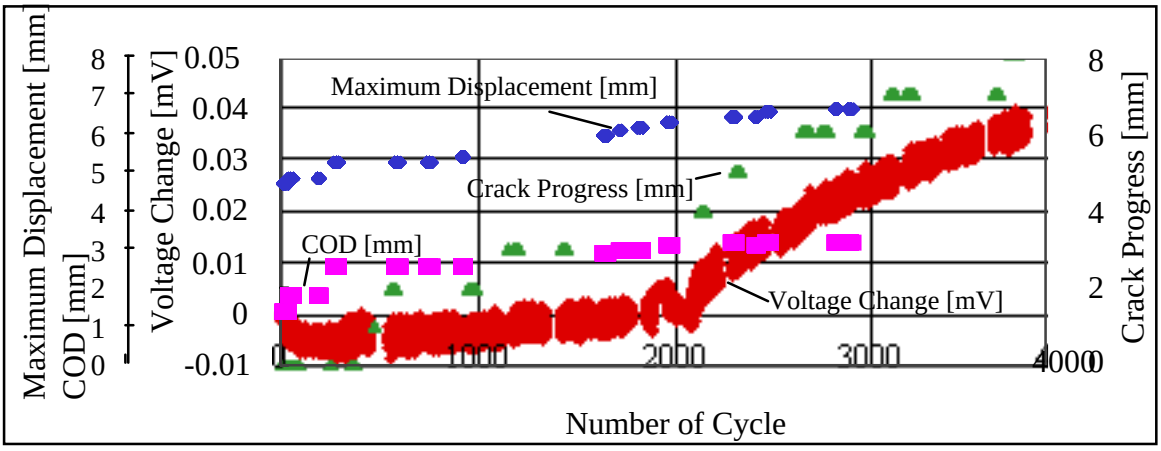

Fig. 10. Resistance and Some Factors on Fatigue Test with Change of Maximum Load

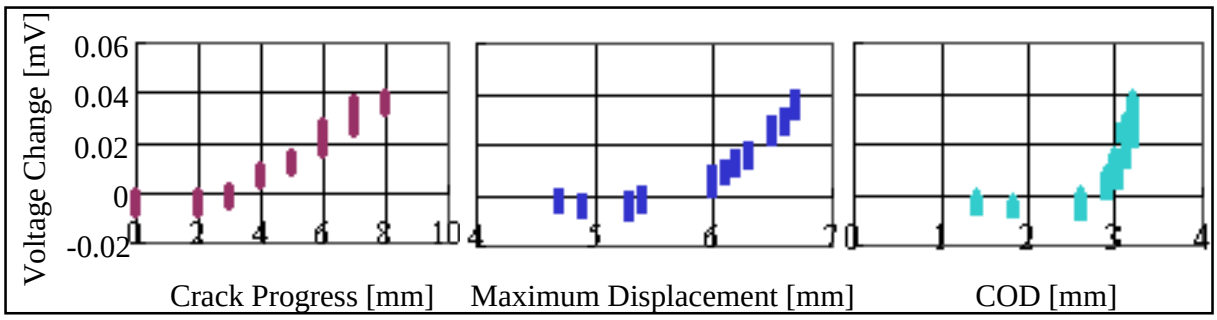

Fig. 11. Comparison of Factors against Resistance on Fatigue Test

Fracture Model

From these results above, one fracture model had been made as shown in Fig.12. On tensile test, from the fact that resistance did not move whenever load was stopped, and from the fracture surface, it is assumed that crack progressed as straight as (a) and (b) in the resin. Some time, it cuts the fibers which lie on both of middle plies, then it cuts these fibers, shown as (b), resistance shows mounts.

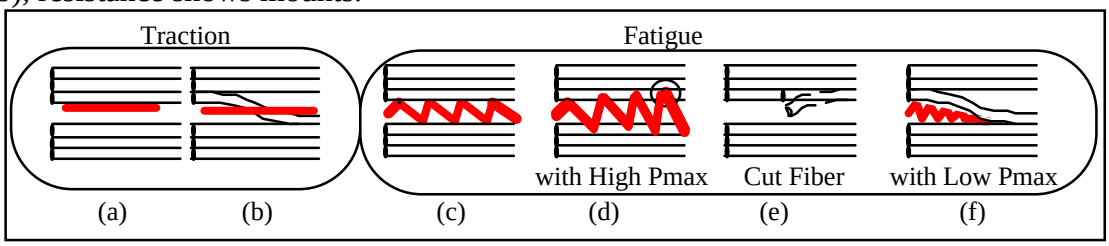

Fig. 12. Fracture Model

Instead, on fatigue test, crack progresses as tooth of saw as shown in from (c) to (f). When this tooth becomes bigger with higher maximum load, it cuts the fibers which lie even parallel to the others as shown in (d). When DCB opens, this edge goes out as shown in (e), but when the surface becomes quite flat again, as when DCB closes or as when crack tip goes deeper, this cut edge can go back to its former place. This is from the fact that the resistance goes to its former value. Moreover, when maximum load is quite small, it is possible to be assumed that not only that crack can not cut fibers parallel to the others but also it does not cut fibers which lie on two plies, and follow to interface as shown in (f). Yet, this is based on the idea only on two-dimension. Three-dimension has to be considered for fiber bridging and its effect to inter layer.

CONCLUSION

Not only contact problem and so on remain but also this method has not yet showed clear relation even here. But in any case, certain relation between resistance and delamination even on fatigue test was observed. Also, even continued observation is not interesting on industrial level, this method provides interesting result to know the mechanism of fracture. In other words, it can be said that this method is applicable to monitoring delamination, and moreover, it seems also able to use for explaining mechanism of fracture of CFRP. As a result, this electrical resistance method has high possibility to use as NDT, and this means study of this method is able to contribute to fundamental research of Smart Structure because reinforced materials themselves on structure level can be a sensor.

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