와전류 탐상기법을 이용한 무릎보조기용 섬유강화 폴리머의 이방특성 분석

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Analysis of Anisotropic Characteristic in Fiber Reinforced Polymer for the Knee Brace Using the Eddy Current Inspection

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Key Words: Eddy Current Inspection(와전류탐상), Fiber Reinforced Polymer(섬유강화폴리머), Isotropic Characteristic(이방특성), Prepreg(프리프레그), Defect Depth(결함깊이)

Abstract

The development of new material systems like Carbon Fiber Reinforced Polymer (CFRP) places ever higher demands on the techniques for non-destructive material characterisation. Image-producing eddy current methods also need to satisfy these demands. Eddy-current imaging of FRP is based on the anisotropic electrical properties of the material investigated. Significant differences in conductivity between carbon fibres, polymer matrix and integrated functional components can be found. The availability of high-resolution sensors enables access to the local distribution of the electromagnetic properties. The static and dynamic procedures for isolating influential characteristics, already in use in eddy-current technology, can now be supplemented by topographical images. The precondition for a successful implementation of the eddy-current procedure is a deeper understanding of the image-generating process which allows correct interpretation of the images obtained.

1. Introduction

Fiber Reinforced Polymer (FRP) such as the carbon/epoxy laminates (i.e., CFRP) has the better fatigue strength and mechanical properties rather than those of the conventional metallic materials. In spite of these advantages, it is weak against the high temperature, the impact and the corrosion since it was fabricated by the lamination of the prepreg made from the uni-axial carbon fiber. When the high radial and fatigue loading was applied, the fatigue mechanism of CFRP was apparently different from that of the general metals. The typical fatigue fractures of CFRP are the micro crack, the craze and the delamination. When the linkage of the micro-crack and the growth of delamination are parallel to the fiber direction, the abrupt failure happens and it is believed that the non-destructive test is one of the most important fields for the fatigue fracture analysis. The strength properties of constructions of unidirectional CFRP are very sensitive to small differences in the fiber direction angle as shown in Figure 1. From the research review of the NDT related to the CFRP, it was known that the ultrasonic C-scan inspection was the main stream for these researches.[(1~3)] The research using eddy current test (ECT) was limited for the particle reinforced metal composites.[(4)] It had been impossible to detect the eddy current since the

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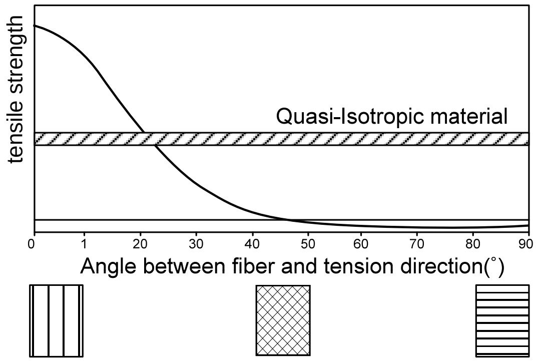


Fig. 1 Variation of tensile strength as function of carbon fiber orientation

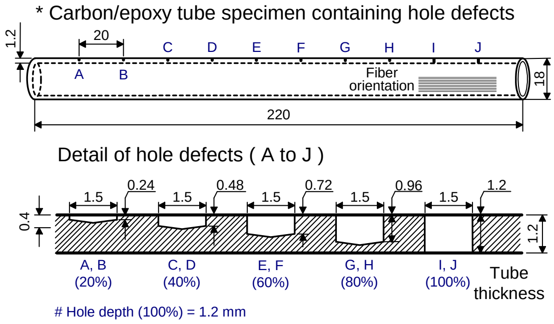


Fig. 2 Geometries of CFRP tube specimen containing circular hole defects

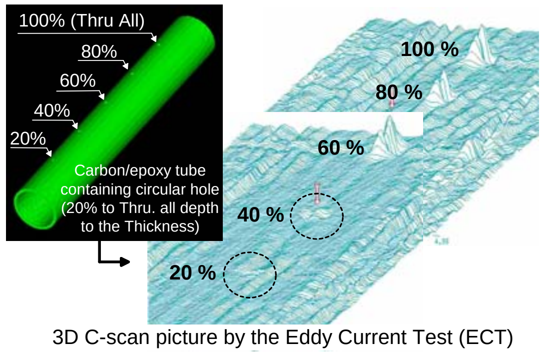


Fig. 3 Three-dimensional picture by the ECT in CFRP tube containing circular hole (20% to thru all depth to the specimen thickness)

CFRP had the low electric conductivity of resin layer. However, it has been successful for our research group to detect the flaw using the eddy current. It resulted in the qualitative evaluation of the eddy current signals according to the notch types and the variation of flaw depth and the 3-D analysis using the ultrasonic C-scan was also possible. In the case of loading to the CFRP, the researches of the failure behavior in the CFRP and of the EC variations have not been carried out. Therefore, this research focused on the comparison and the evaluation of the eddy current signals according to the change of the defect depth using the unloading and the radial-loading CFRP tube. The performed studies were as follows. i) The change of the eddy current signals under the radial loading. ii) The stress distribution according to the defect depth using finite element analysis.

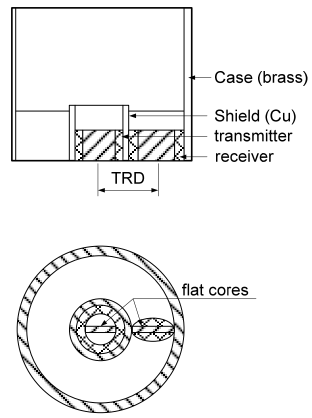
2. Fabrication of fiber reinforced polymer tube and eddy current inspection

2.1 Fabrication of CFRP tube specimen with the circular defects of different depths

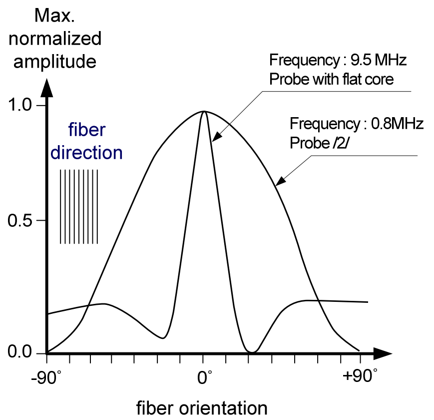
Even though the electric conductivity of the carbon fiber is good enough to detect the eddy current, the carbon/epoxy prepreg which includes over 40% resin of all, made it impossible to detect the eddy current due to the very low electric conductivity. The EC inspection of fiber reinforced polymer tube manufactured by carbon/epoxy prepreg is not possible due to the high resin contents. Therefore, to accomplish the purpose of this research which is the electric conductivity improvement of CFRP tube, the CFRP tubes are fabricated with the lamination of the Al alloy foils on the carbon/epoxy prepreg. The longitudinal direction of the specimen coincided with the direction of the fibers and it made the longitudinal mechanical properties strengthened. Therefore, our developed procedures made the electric conductivity of the specimens improved. The specimens were hardened at 130°C for 90 minutes and its pressure was 1.2MPa. The configuration of the specimens were displayed in Fig. 2 and Fig. 3. The circular flaws whose diameter were 1.5mm, were made by the micro-drill and the depths of them was machined as 20%, 40%, 60%, 80% and 100% of the specimen thickness.

2.2 Eddy current probes

The special demands on the design of eddy current probes to detect fiber orientations in CFRP with a high resolution are, high directivity; sufficient signal to noise ratio of the output signal; working frequencies of some MHz due to the low conductivity of CFRP; shielded transmitter and receiver to suppress undesired electromagnetic fields as shown in Fig. 4. The coil system is shielded. For these investigations only a transformer probe is possible. The directivity of a parametric probe design is much lower.[5]



(a) Schematic view of probe design for the different fiber orientation in carbon fiber reinforced plastic



(b) Lateral resolution with unidirectional fiber reinforced plastic in comparison with probe

Fig. 4 Schematic view of probe design and its lateral resolution with unidirectional reinforced CFRP in comparison with the probe in Ref. 6

2.2 The eddy current detection of CFRP tube

To detect the eddy current, MIZ-18 Digital Data Acquisition System and DDA-4 Digital Data Analysis System were used as shown in Fig. 5. For this research, the unloading specimen and the radial loading specimen were detected under the different conditions. If the overall micro-cracks and the delamination of the loading specimen were bigger than the circular flaw, it was very difficult to detect the signal of the flaws. Therefore, as compare with the unloading specimen, it was required for the loading specimen to set up the low probe cycle, the less sample detecting number and the high detecting frequency to induce the detection of the accurate signals. The lift-off effect caused during the signal detecting of both type specimens, was also restricted. While the detecting signal was remarkable from the plus point coil of the MRPC probe for both unloading

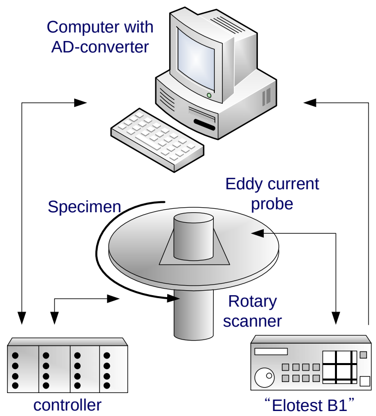


Fig. 5 Experimental setup of measurement equipment for eddy current inspection in the CFRP

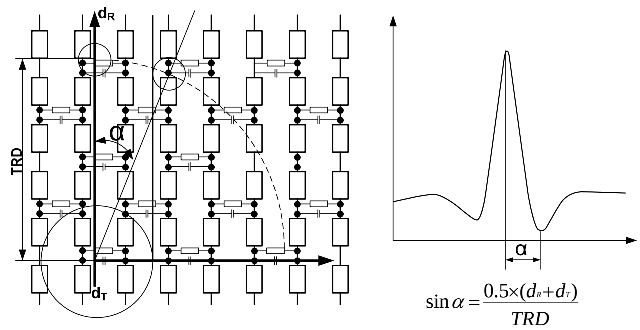


Fig. 6 Interdependence between probe design and output signal shape

and loading specimens, it was very difficult to detect the signal from the pan cake coil.

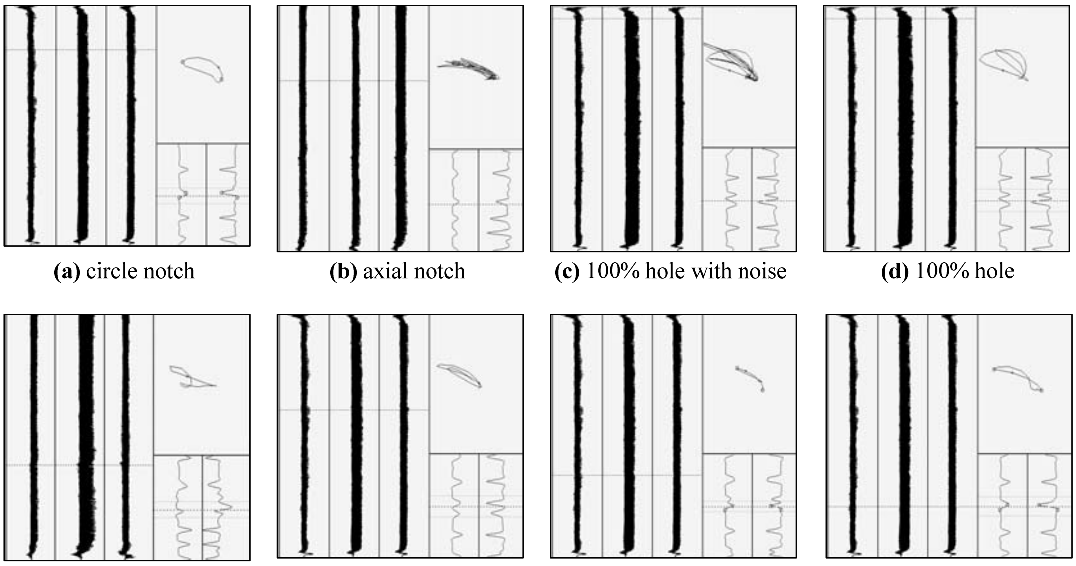
3. Experimental results and discussion

3.1 The plateau effect

In real components fibers may contact due to the displacement of resin. Even if no contact results, the capacity between two fibers dramatically increases with decreasing fiber distance. These current paths and capacitors are responsible for the increasing eddy current density. They are the cause of the mentioned plateau effect. The local minimum between the maxima corresponding with the fiber direction and the plateau effect depends on probe design and test frequency as shown in Fig. 6.

3.2 Change of the eddy current by the radial loading

The new detecting technique of the eddy current from the CFRP tube had been developed by our previous study and the following results had been obtained. 1) While the flaw detection of the low frequency band was not possible due to the weak



(a) circle notch **(b)** axial notch **(c)** 100% hole with noise **(d)** 100% hole

(e) 80% hole **(f)** 60% hole **(g)** 40% hole **(h)** 20% hole

Fig. 7 Results of the eddy current inspection in CFRP tube containing hole defects (20% to through all 100%)

signal to noise ratio (S/N ratio), the high frequency band made it possible to detect the flaw and it was known that just 300kHz was the optimized frequency to detect the flaws. 2) As the flaws were getting deeper, the phase angles were becoming lower and the eddy current amplitudes were increasing. 3) When the depth of the flaw was over 40% of the specimen thickness, the 3-D flaw analysis by ultrasonic C-scan became possible as shown in Fig. 7. 4) Due to the strong anisotrophy of CFRP and the effect of the magnetic vector potential, the circumferential flaw was shown distortedly. Based on the above results, this study compared the eddy-current signal of the unloading specimen with that of the radial loading specimen. Not only the circular flaws but also many numbers of micro-cracks, the craze and the delamination were found over the all area of the specimen under the radial loading. Therefore, it was impossible to detect the flaw signal from the strip chart. Amplifying the signals from the high frequency band such as 300~500kHz, setting the phase angle of the noise element to 180° and the eliminating the noise element, caused the satisfying results in Fig. 7. Fig. 7 showed the detection of the flaw signals except the other trivial signals and the noise using the multiple frequency method. The procedures to combine these frequencies is to make the arithmetic deduction for the coincidence of the inter-relation by the transformation of the phase angle and by the control of the amplitude after the detection of the flaw signal from the different frequencies. While the phase angle was displayed at the top of these figures, the bottom showed the amplified signals obtained during one rotation of the MRPC probe. For the circular flaw, the flaw signals were detected four times during one rotation of the probe. The circular flaw of the unloading specimen where the flaw signal can be comparatively well-detected, could be monitored by No. 3 signal. However, since the loading specimen made the flaw signal, the noise and the micro-crack signal complexly from channel No. 1 to No. 4, it was impossible to detect the flaw signals. According to the analysis results based on the unloading specimen, the flaw signal from No. 3 was able to be detected. Through Fig. 7, the detection results between the unloading and the loading specimens were compared as follows. 1) The through flaw (100%) of the loading specimen was not disturbed by the signal such as micro-cracks, delaminations etc., but it was similar to that of the unloading specimens. The reason was not that the crack and delamination could happen continuously over thickness of the specimen due to the characteristics of CFRP tube, but it was distinguished from the through flaw signals because of existence

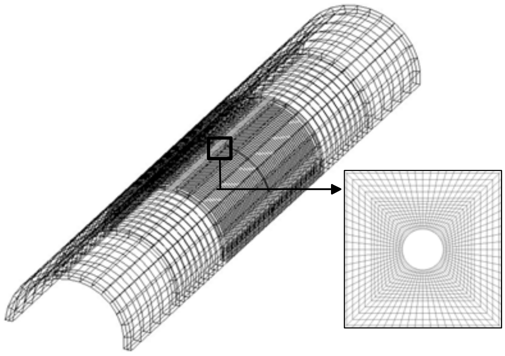


Fig. 8 Finite element model of CFRP tube containing a circular hole defect

of the discontinuity. As a consequence, both the phase angle of the unloading specimen and that of the loading one were 15 and Lissajous figure also looked after the elliptical piled shape such as the signal of the conventional circular flaw. 2) Reviewed the relation between the phase angle and the flaw depth in Fig. 7, 80% depth flaws of the unloading and the loading specimens had the similar phase angles. 3) From the part-through flaws less than 60% depth, the effects of the micro-cracks, the delaminaitons and the noise were so severe that the difference of the phase angle between the loading and the unloading specimens was getting bigger. Namely, as the flaw depth was getting lower, the difference of the phase angle was severe and the phase angle of the loading specimens was suddenly increased. Therefore, the part-through flaw less than 60% depth was affected by the micro-cracks, which made it difficult to detect the eddy current signals. For the part-through less than 20% depth, it was impossible to measure the phase angle. It was easily guessed that the micro-cracks distributed over the specimen were less than 60% of the specimen thickness. The reason was that it was possible for the flaw signals of 80% and 100% depth to be detected regardless of the effect of the micro-cracks. 4) Reviewed the relation between the amplitude of the eddy current and the flaw depth in Fig. 7, the amplitude of the eddy current was slowly increasing as the flaw depth of the unloading specimen was getting deeper. The reason was that the eddy current flowed at the surface of the specimens sufficiently and its flow was decreasing with the depth was since the eddy current was the alternating current. Since the eddy current was determined by the function of the

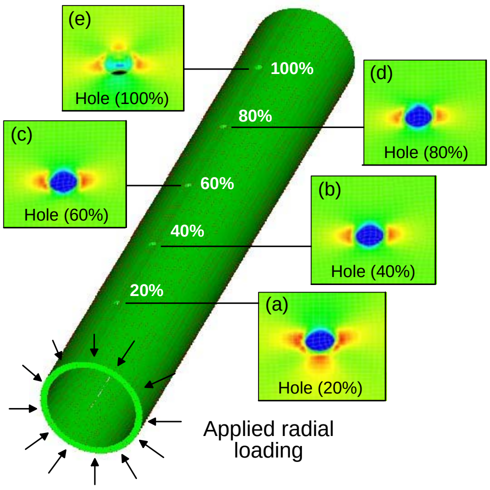


Fig. 9 Stress distribution near a hole defect (20% to 100% depth to the specimen thickness)

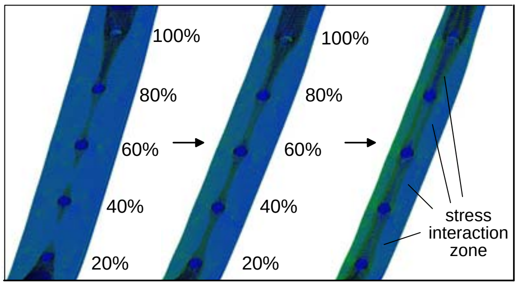


Fig. 10 The variation of deformed meshes and equivalent stress interaction between neighbor hole defects according to radial load

frequency, the electric conductivity and the permeability, the penetration depths were decreased as these parameters were increased. In other words, the penetration depth was deeper but the sensitivity of the flaw was worse as the frequency or the amplitude of the eddy current was lower. It implied that the possible high frequency and the amplitude of the eddy current should be chosen with the requirement of the penetration depth. Consequently, the amplitude of the eddy current was increased, as the flaw depth was greater. However, it was known that the relation between the amplitude of the eddy current and the flaw depth was very irregular due to the noise effect from the micro-cracks and the delamination of the loading specimens.

3.3 Stress distribution by the flaw depth using FEA

Finite element analysis was performed to compare the stress distribution of CFRP tube under radial loading with the eddy current detection of the loading specimens. For modeling of CFRP tube with the circular flaw, modelling program was used and the stress analysis was performed. Fig. 8 showed the mapped mesh of CFRP tube and Fig. 9 demonstrated the stress distribution according to the flaw depth. Fig. 10 represented the mesh deformation and the variation of the surface stress distribution by the processing of the radial loading. Reviewed the stress distribution according to the flaw depth, the edge effect by the fixing parts of 20% and 100% flaw depth specimens was observed. If it was ignored, it was found that 20~80% depth flaw showed the similar stress distribution regardless of the flaw depths except 100% flaw depth. Besides, the CFRP tube could easily transmit the stress between flaws since the fiber direction was parallel to the direction of the specimen length. To check the stress distribution of the CFRP under the radial loading shown in Fig. 10, it was known that the flaw depth could not strongly influence on the stress distribution. It implied that the micro-cracks and the delamination of the radial loading specimens were widely distributed over the entire specimen as well as the vicinity of the flaw. Since the effect of the flaw depth on the stress distribution was so feasible, it was believed that the stress distribution was not directly related to the signals of the eddy current.

4. Conclusions

To evaluate the behavior of the eddy current according to the variation of the flaw depth (20%, 40%, 60%, 80% and 100% of the specimen depth), the CFRP tubes under the unloading and the radial loading were used. The obtained conclusions are as follows.

1) Since the micro-cracks, the craze and the delamination were made over the whole unloading specimen, it was very difficult to detect the circular flaw. However, if the flaw signals of the loading specimens were amplified and the phase angle of the noise element was set to 180° with the elimination of the noise element, the eddy current signals similar to that of the unloading specimens could be obtained from the loading specimen of 80% flaw depth.

2) Regardless of the unloading and the loading specimens, the flaws of 100% and 80% flaw depths had the similar phase angles and Lissajous figures. From flaws less than 60% depth, the difference of the phase angles between the unloading and the loading specimens was getting severe. For flaws less than 60% depth, it was very difficult to detect the eddy current due to the strong effect of the micro-cracks and for flaws less than 20% depth it was impossible to do it.

3) It was guessed that the length of micro-cracks distributed at the whole specimens under the loading was less than 60% of the specimen thickness. The reason was that the flaws of 80% and 100% depth was not affected by the micro-cracks and that the flaw signal similar to that of the unloading specimen could be detected.

4) Reviewing the stress distribution of CFRP under the radial loading, it was known that the flaw depth did not have strongly influence on the stress distribution. Therefore, it was believed that the stress distribution was not directly related to the signals of the eddy current.

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