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Variation in Thermal Conductivity of CFRP Plates due to Impact Damage

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Abstract CFRP plates were subjected to impact loading by a drop-weight impact testing machine. Stacking sequence of the plates was [cloth/0^o/90^o/0^o/90^o/0^o/cloth]. Dimension of the plates was 60 mm in length and width and 2mm in thickness. Then thermal conductivity of the plates in the thickness direction was measured by the static comparison method. Although it is difficult to measure the absolute value of thermal conductivity in general, reproducibility of the measurement was improved and variation from the initial value was discussed in the present paper. Distribution of the thermal conductivity due to impact damage on the plane was clarified as a function of distance from the impact point. On the other hand, the CFRP plates were cut by diamond saw and cross sections of the plates were observed by an optical microscope. Then length and number of delamination and transverse cracks were measured respectively on the photomicrographs. Distribution of damage such as delamination and transverse cracks on the plane was also clarified as a function of distance from the impact point. Finally, the relationship between variation in thermal conductivity and impact damage was clarified experimentally on the basis of the experimental measurements.

Keywords CFRP, Impact damage, Thermal conductivity, Delamination, Transverse crack

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1. Introduction

Carbon fiber reinforced plastics (CFRP) have remarkable properties such as high strength-to-density ratio, tailor-made strength, etc. as well as advantages of polymers. Using the advanced properties, CFRP are utilized for many engineering structures and products of daily use. Especially, usage of CFRP for airplanes is increased recently from the viewpoint of weight reduction in order to save fuel consumption.

Considering the usage of CFRP in airplanes and automobiles, impact loading is unavoidable in their operations. For instance, bird strikes during flight, drop of tools during maintenance and collision during driving. Delamination, transverse cracks and debonding between matrix and fibers are well-known as internal damage of CFRP due to applied loading. When CFRP is fabricated by laminating prepreg sheets, impact loading causes internal damage such as delamination. Since internal damage causes reduction of mechanical properties and residual life, development of non-destructive inspections for CFRP [1–6] is important to guarantee reliability for structures.

Hammering tests among non-destructive inspections are often used practically for large-scale structures. The method of hammering tests is very simple and necessary tools are only hammers. However, the test results depend on experience of inspectors and only qualitative results are obtained. On the other hand, since X-ray inspections [3] and ultrasonic inspections [3] are precise methods, expensive equipments and special techniques are necessary and testing places are restricted. Non-destructive tests by infrared pulse thermography [4–6] are simple method, however, resolution to inspect internal damage is not so high.

Internal damage causes variation in material properties [7], so that internal damage can be inspected from the variation in material properties inversely. In practice, distribution of temperature is measured in non-destructive tests by infrared pulse thermography, and the distribution is caused by variation in thermal conductivity due to internal damage [8, 9]. In the present research, in order to improve the resolution to inspect internal damage by infrared pulse thermography, assistance by numerical simulation is considered. Namely, if distribution of temperature in CFRP plates due to internal damage can be simulated, the internal damage could be predicted from the distribution of temperature by inverse analyses. For the numerical simulation, the relationship between thermal conductivity and internal damage is necessary. Accordingly, in the present paper, in order to investigate the relationship as a first step, CFRP plates are subjected to impact loading by a drop-weight impact testing machine, and variation in thermal conductivity from the initial value and internal damage such as delamination and transverse cracks are evaluated. Then the relationship between thermal conductivity and internal damage is clarified.

2. Experimental Methods

2.1. Drop-weight impact test

CFRP plates are used as specimens. Dimension of the plates is 60 mm in length and width and 2mm in thickness, and the stacking sequence is [cloth/0^o/90^o/0^o/90^o/0^o/cloth]. The CFRP plates are fixed in a drop-weight impact testing machine (Instron, CEAST9310) by the plate with a hole 40 mm across. A hemispherical tup falls on the center of specimens inside of the hole. Diameter of the tup is 12.6 mm. Three levels of impact energy are applied to specimens, and they are 5.1, 9.9 and 21.0 J. In the tests, drop height is fixed to 0.7 m and mass of weight is changed.

2.2. Measurement of thermal conductivity

Thermal conductivity of CFRP plates in the thickness direction is measured by the static comparison method [10]. Fig. 1 shows schematic diagram of the method. Self-making apparatus is used. In the static comparison method, a specimen and a reference sample whose thermal conductivity is known are placed in series. Then heat flow is given to the reference sample and specimen in series by a heater, and the difference in temperature ΔT_1 and ΔT_2 between both ends of specimen and sample is measured by thermocouples, respectively. The thermal conductivity of the specimen λ is evaluated relatively from the thermal conductivity of the reference sample λ_{ref} by using the ratio of the difference in temperature ΔT_1 and ΔT_2 and dimensions of specimen and sample [10].

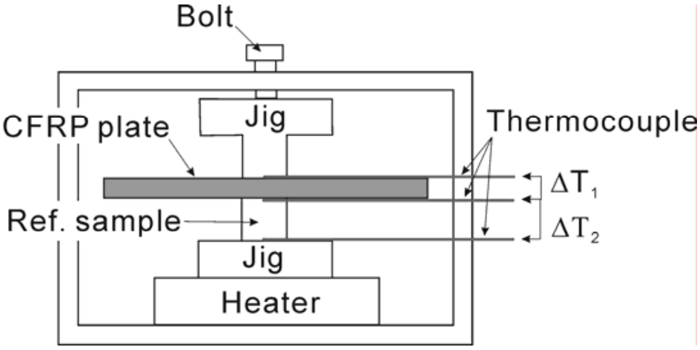


Figure 1. Schematic diagram of the static comparison method to measure thermal conductivity in the thickness direction of CFRP plates.

In order to improve reproducibility of measurement, the measurement is carried out in a vacuum vessel. The reference sample is selected so that thermal conductivity of the sample λ_{ref} is close to that of specimens. In the present paper, type 304 stainless steel (SUS304) is used as the reference sample. The measurement is carried out in two cases. Namely, heat flow is given to specimen through reference sample, and heat flow is given to reference sample through specimen. The order of sequence for specimen and reference sample is changed. In the calculation of thermal conductivity λ, difference in temperature is necessary. However, if gradient of the relationship between difference in temperature and input electric power of heater is used instead of the difference in temperature, the reproducibility of measurement is improved [10].

Although it is difficult to measure the absolute value of thermal conductivity in general, reproducibility of the measurement could be improved. Since objectives of the present research are non-destructive inspection based on variation in material properties, the reproducibility is important because variation in material properties from their initial values is measured and discussed.

Fig. 2 shows positions of measuring thermal conductivity in specimens. Impact loading is applied to the center of specimens and the loading point is numbered 1. Thermal conductivity is measured at nine points (No. 1 through 9) as shown in the figure.

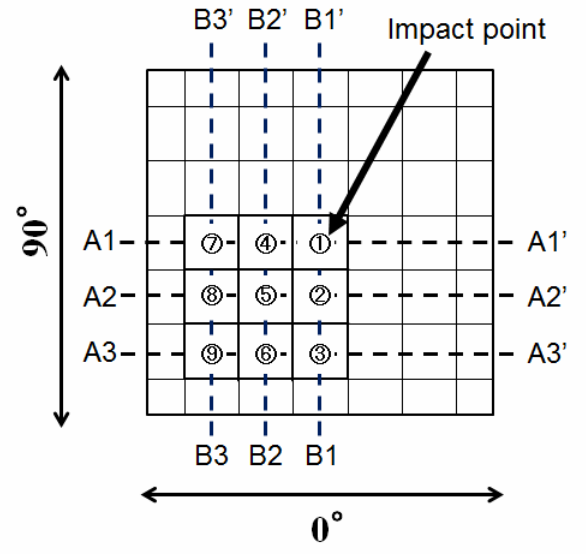


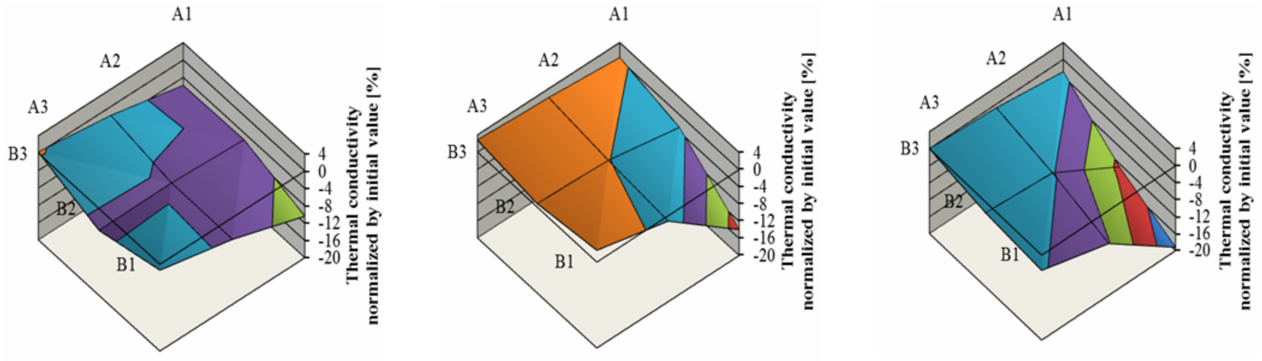
Figure 2. Positions of measuring thermal conductivity and observing cross sections.

2.3. Evaluation of internal damage

Specimens are cut in two directions as shown in Fig. 2. They are named A-direction and B-direction. A-direction coincides with 0^{o} which is orientation of fiber alignment directly under cloth layer. Three cross sections in each direction (for instance, A1-A1', A2-A2' and A3-A3' in A-direction) are observed by an optical microscope. Specimens are embedded in resin and they are cut by diamond saw for the observation. After cutting, cross sections are polished. A couple of specimens subjected to the same impact loading are prepared for observation in A-direction and B-direction. In order to evaluate internal damage due to impact loading, photographs of cross sections are captured into a personal computer, and length and number of delamination and transverse cracks are evaluated.

3. Experimental Results

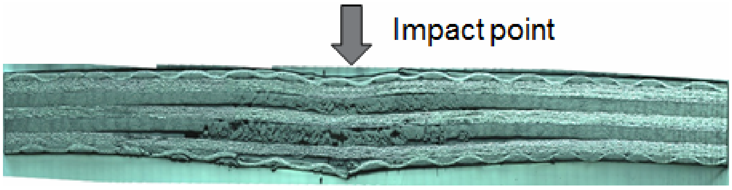
Figs. 3 show distribution of thermal conductivity in a quarter of specimen subjected to impact energy of (a) 5.1J, (b) 9.9 J and (c) 21.0 J. Thermal conductivity is normalized by the initial value. Coordinate point of A1 and B1 is a position of impact loading. As shown in the figures, reduction of thermal conductivity is the largest at the position of impact loading. Reduction of thermal conductivity in A-direction (measuring points of No. 4 and 7) is larger than that in B-direction (those of No. 2 and 3). They are caused by anisotropy of specimens. Stacking sequence of specimens is [cloth/0^o/90^o/0^o/90^o/0^o/cloth] and internal damage is more significant at opposite side of impact point. The layer directly under cloth layer is important for damage development and anisotropy is caused by the orientation of fiber alignment in the layer.



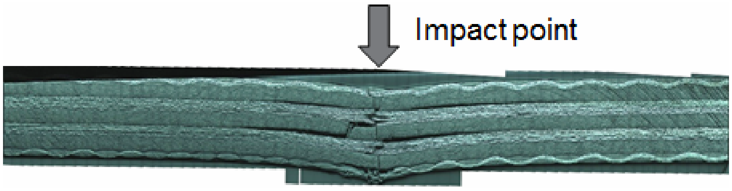
(a) 5.1 J (b) 9.9 J (c) 21.0 J

Figure 3. Distribution of thermal conductivity in a quarter of specimen subjected to impact energy of (a) 5.1J, (b) 9.9 J and (c) 21.0 J. Thermal conductivity is normalized by the initial value. The A1-B1 point is a position of impact loading.

Figs. 4 show photomicrographs of cross sections for specimens subjected to impact energy 21.0 J on (a) A1-A1' cross section and (b) B1-B1' cross section. As shown in the figures, delamination and transverse cracks are observed on the cross sections. Internal damage expands from impact point and it is significant near opposite side of impact point. By comparing both photomicrographs, anisotropy on internal damage is found clearly.



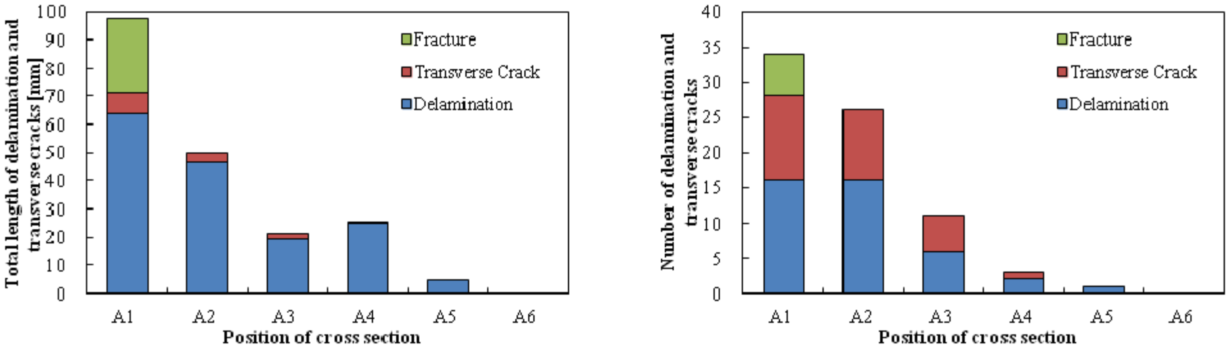
(a) A1-A1' cross section



(b) B1-B1' cross section

Figure 4. Photomicrographs of cross sections for specimens subjected to impact energy 21.0 J on (a) A1-A1' cross section and (b) B1-B1' cross section.

On the basis of photomicrographs, length and number of delamination and transverse cracks were measured. Figs. 5 show internal damage on each cross section of specimen subjected to impact energy of 21.0 J. Fig. 5(a) shows total length of delamination and transverse cracks plotted as internal damage, and Fig. 5(b) shows number of delamination and transverse cracks plotted as internal damage. In the figures, "fracture" means that damage is significant and it is difficult to distinguish between delamination and transverse cracks. Internal damage reduces as position is apart from impact point, and internal damage in A-direction is larger than that in B-direction. It is also found that ratio of delamination to transverse cracks with respect to total length in Fig. 5(a) is about 9 to 1 at any positions while the ratio with respect to number in Fig. 5(b) is about 6 to 4.

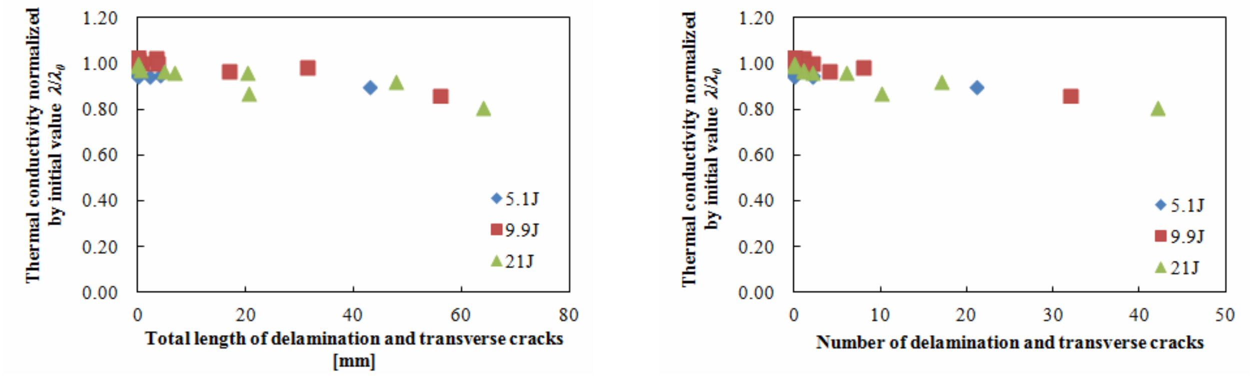


(a) Total length of delamination and transverse cracks

(b) Number of delamination and transverse cracks

Figure 5. Internal damage on each cross section of specimen subjected to impact energy of 21.0 J. (a) Total length and (b) number of delamination and transverse cracks are plotted as internal damage.

Figs. 6 show the relationship between thermal conductivity and internal damage. Thermal conductivity is normalized by the initial value. Total length and number of delamination and transverse cracks are adopted as internal damage. The total length and number of delamination and transverse cracks are summation of those in A-direction and B-direction, and the summation is carried out on the same area as thermal conductivity is measured. As shown in the figures, thermal conductivity reduces as internal damage increases. The relationship was clarified experimentally in the present research.



(a) Total length of delamination and transverse cracks

(b) Number of delamination and transverse cracks

Figure 6. Relationship between thermal conductivity and internal damage. (a) Total length and (b) number of delamination and transverse cracks are adopted as internal damage.

4. Concluding Remarks

The objectives of the present research are to improve the resolution of non-destructive inspection for CFRP by infrared pulse thermography. For the purpose of the improvement, assistance of numerical simulation is necessary. Therefore, in the present paper, in order to simulate distribution of temperature due to variation in thermal conductivity on CFRP plates including internal damage, the relationship between thermal conductivity and internal damage due to impact loading was investigated experimentally.

Conclusions of the present paper are summarized briefly as follows:

(1) Distribution of thermal conductivity in the thickness direction on CFRP plates including impact damage was clarified, and it was indicated that the distribution depends on the level of impact energy.
(2) By observation of cross sections of CFRP plates, length and number of delamination and transverse cracks were measured as internal damage. The internal damage has anisotropy with respect to the fiber orientation directly under cloth layer, and it was found that the ratio of delamination to transverse cracks has constant value.
(3) By combining results of measurement for thermal conductivity with results of evaluation for internal damage such as length and number of delamination and transverse cracks, the relationship between thermal conductivity and internal damage was clarified experimentally.

As next steps, internal damage is described by a damage variable on the basis of the continuum damage mechanics [9, 11], and development of internal damage is formulated as an evolution equation of the damage variable as a function of impact energy and distance from impact point. Using the relationship between thermal conductivity and internal damage, variation in thermal conductivity is calculated by the damage variable and distribution of temperature is simulated by taking into account the development of internal damage. By utilizing inverse analyses, internal damage could be predicted inversely from distribution of temperature which is measured by infrared pulse thermography, in future.

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