Damage Monitoring of Al_2O_3/Epoxy Laminates with Luminance Change of Transmitted Light from EL Device

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ABSTRACT

Authors have proposed a new damage monitoring system that employs luminance of Electro Luminiscent (EL) backlight for transparent composites such as glass/ epoxy composites. For the transparent composites, damage is easily found by visual inspections. In cases where the structures are sealed or are large structures, however, the visual inspections are difficult to perform. The present paper describes a system using system using change of luminance of transmitted light. When the composite structures are damaged, the damage reduces luminance of the transmitted light from the backside. The present study uses an EL device as the backlight. For Al_2O_3/epoxy composites, the transparency itself is quite different from that of glass/ epoxy. The damage silhouette is also quite different from that of glass/epoxy composites. In the present study, therefore, the method is applied on the uni-directional Al_2O_3/epoxy composites made of unidirectional prepreg in order to check the effectiveness of the method. Specimens were made of unidirectional and cross-ply laminates. Tensile tests are conducted using rectangular specimens with an open hole fabricated from cross-ply and unidirectional Al_2O_3/epoxy. The luminance of the transmitted light of the EL device increases with the increase of the elastic deformation of the transparent composites by tensile loading. The damage is monitored with measurements of the luminance of transmitted light of the EL device.

Key Words: Damage, Matrix crack, Luminance, EL, Monitoring, Al_2O_3/epoxy.

1. INTRODUCTION

For transparent or semi-transparent composites like glass/epoxy or aluminum-oxide-ceramic-fiber/epoxy (Al_2O_3/epoxy), damage reduces visual transparency due to the scattering of light transmitted through the thickness. Damage like matrix cracking and fiber breakage can be found visually. For super conductive coil support structures of MAGLEV, which are made of Al_2O_3/epoxy composites, however, visual inspections are sometimes quite difficult because the structure of the coil is completely sealed in order to obtain high thermal insulation. For large glass/epoxy composite fans of wind turbines, the fan blade itself is too large, and the visual inspections of damage after dismantling the fan blades are not cost-effective. Recently, to detect damage to composite structures, health-monitoring systems using embedded fiber optic sensors have been attempted /1-3/. The health-monitoring systems using fiber optic sensors measure strain data at multiple points. Damage, however, cannot be detected without loading or relief of residual stresses. This means that damage to the coil support structures of MAGLEV cannot be detected before running or before the creation of a large amount of damage. Although these problems are not crucial for fiber optic sensors, they do require additional cumber-

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some approaches. Furthermore, some researchers have reported that embedding some kinds of fiber optic sensors may cause strength reduction /4,5/.

For transparent or semi-transparent plastic materials and composites, a luminance pattern of light transmitted through the thickness direction is a very helpful approach to detect damage at low cost /6-8/. Since the micro cracks cause scattering of the transmitting light, the damaged zones can be easily identified visually as a silhouette in the composites. Aoyama *et al.* /8/ have revealed that the brightness pattern of the transmitted light can be used on a new non-destructive inspection tool using a CCD camera and proposed a pattern recognition system for coil support components of MAGLEV. The method is very simple and easy to handle, but CCD cameras are not always available for health monitoring systems. Moreover, uniform light sources are very difficult for complicated or curved structural components.

Electro luminescent (EL) devices can emit uniform-plane-light, and the stiffness of the device is very low and flexible. The EL devices are usually used in backlight sources of liquid crystal displays such as pocket bells and cellular phones. The thickness is less than 0.5 mm, and it emits uniform-plane-light by means of charging alternating current to the devices. The size is not limited and the configuration is changeable. A thin EL device (250 μm) is very flexible, and can be mounted on curved surfaces.

In our previous study /9/, a new damage monitoring system that uses change of luminance of light transmitted from an EL backlight was proposed. The system uses the EL devices as a backlight source for static and fatigue damage monitoring of fabric glass/epoxy composites. An EL device is mounted on a surface of a rectangular specimen with an open-hole notch, and the luminance of the transmitted light is measured from the other side of the specimen. The luminance of the transmitted light is measured with optical sensors, and the damage at the notch right is monitored by the change of measured luminance of the transmitted light.

In our following study /10/, the proposed system was applied to glass/epoxy laminates made of unidirectional prepreg. For those composites that are made of unidirectional prepreg, matrix cracking is a major damage observed before fracture, and a matrix crack is just a silhouette of a single crack line. This is difficult to detect by means of the luminance change of transmitted light. The method has, therefore, been tested for the unidirectional and cross-ply laminates of glass/epoxy composites made of unidirectional prepreg in order to check the effectiveness of the method. The method is experimentally shown to be effective even for the damage monitoring of glass/epoxy composites made of unidirectional prepreg although the luminance change mechanism in the elastic deformation region has not yet been clarified.

In the present study, the same monitoring system using luminance change from EL backlight is applied to unidirectional and cross-ply Al_2O_3/epoxy composite laminates. Since the Al_2O_3 fiber is not transparent at all, the transparency of Al_2O_3/epoxy composite laminates is less than that of glass/epoxy composites. Matrix cracking of the Al_2O_3/epoxy composite laminates is usually difficult to observe visually. For the structural health monitoring of MAGLEV, it is indispensable to investigate the effectiveness of the method for Al_2O_3/epoxy composites. The Al_2O_3/epoxy laminate is, therefore, used here. The unidirectional and cross-ply laminates are made of stacking unidirectional prepreg sheet, and the rectangular specimens are cut from the laminates. An EL device is mounted on a rectangular plate specimen, and the luminance of the transmitted light is measured with optical sensors during a static tension test. With the unidirectional laminates, luminance change during elastic loading is measured.

Luminance decrease due to increase of damage silhouettes is measured by means of an open-hole notched specimen of cross-ply laminate. An EL device is mounted at the end of the open-hole notch, and an optical meter is also attached at the other side of the surface to measure the luminance of the light transmitted through the thickness direction. Luminance images of the open-hole notched specimen are also recorded to confirm damage silhouettes.

2. HEALTH MONITORING SYSTEM

2.1. Electro Luminescent Devices

Two kinds of electro luminescent materials are available: inorganic and organic. A widely used, commercially available EL device is an inorganic EL device. The typical component of the inorganic EL is ZnS, which, with some impurities such as Al and Cu, is a kind of semi-conductor material. By charging AC current between the two electrodes, the luminescent layer emits cold light through the transparent electrode layer. In the case of the soft electrode layer, the total stiffness of the EL device is soft, just like a sheet of paper. EL devices can emit almost uniform plane light, but the luminance of the EL device is affected by aging. The luminance decreases with the increase of luminescent time. EL devices used for pocket bells are shown in Figure 1.

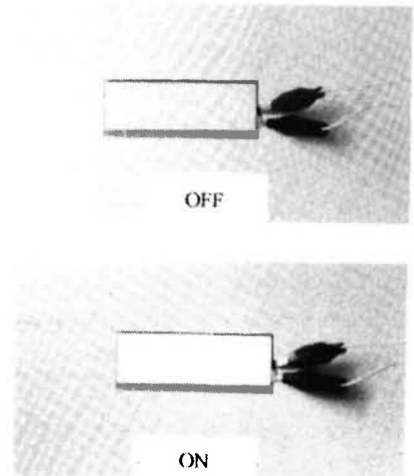


Fig. 1: EL devices

2.2. Monitoring System with EL Backlight

A new damage monitoring system for transparent composites has been proposed in the previous study /9/, and the schematic image is shown in Fig. 2. In this figure, a notched plate specimen is shown as an example for structural health monitoring. An EL device is attached to one of the specimen surfaces. On the other surface, light transmitted from the EL at the point where damage is monitored is transferred using a plastic large-core optical fiber to a luminance meter (optical sensor), and the luminance of the transmitted light is measured using the luminance meter. Since the luminance of the EL device is not constant due to aging of the EL device, reference light is also measured, as shown by an optical fiber B in Fig. 2. The reference point must be selected from the points where damage is not created. If there is no such place, we can adopt a dummy specimen that is made from the same composite plate and is not loaded. By comparing the difference of luminance between

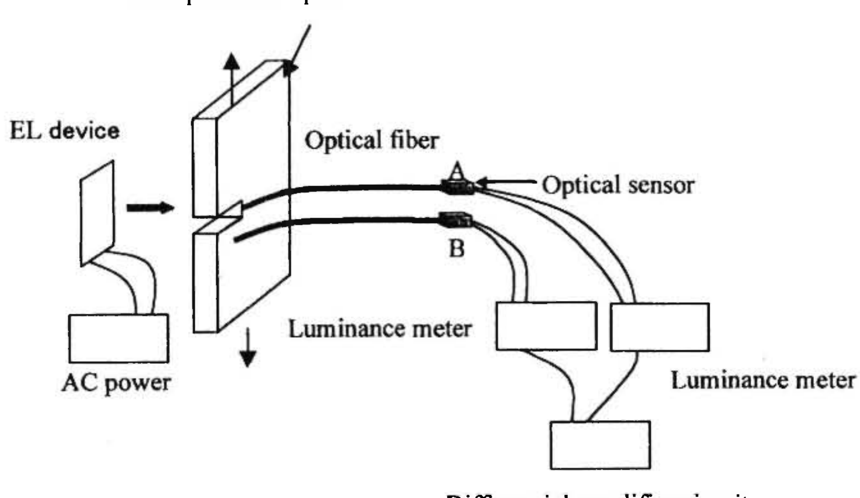


Fig. 2: Damage monitoring system with EL backlight.

these two points, we can detect the change of luminance of light transmitted from the other side of the specimen. Since the reference light is adopted in the system, we can recognize the luminance change due to the damage even if aging reduces the transparency of transparent composites.

As described previously, the EL device is very flexible, and can be adapted to curved surfaces like shell structures. Since the EL devices do not generate heat, this system can be applied to cryogenic structures such as super conductive coil support structures for MAGLEV. All instruments required are inexpensive, and, therefore, the system is very attractive for semi-transparent composites for damage monitoring.

In our previous study /9/, the system was used to monitor fatigue damage around an open-hole notch of fabric glass/epoxy composites. The results showed that the luminance of the transmitted light decreases with the increase of the applied tensile stress in the elastic deformation region, which in turn increases with the increase of applied compressive stress even in the elastic deformation region as shown in Fig. 3. This variation of the luminance of the transmitted light due to the applied stress compelled us to monitor the damage at unloaded condition. Figure 4 shows the silhouette produced by the fatigue damage with the EL backlight. Fatigue damage of the fabric glass/epoxy composites is observed as silhouettes on both ends of the open-hole notch.

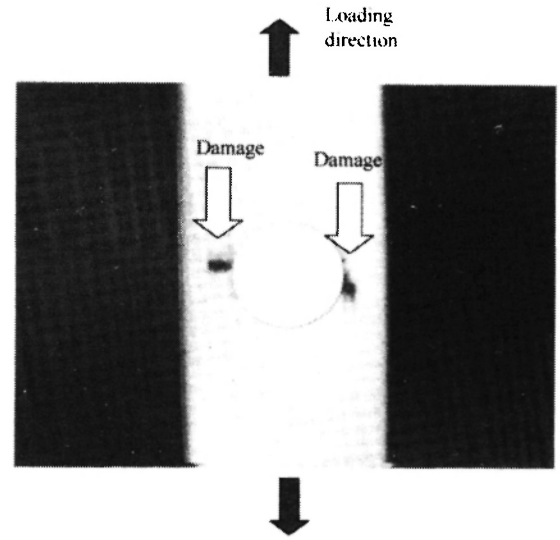


Fig. 4: Typical fatigue damage observed in the test of σ = 100 MPa at N/N_f = 99% fabric glass/epoxy taken from reference /9/.

In another paper /10/, the system was applied to glass/epoxy composite laminates made of unidirectional prepreg to investigate applicability of the system to unidirectional composites. Although the silhouettes of the matrix cracks are just lines, as shown in Figure 5, the system has successfully monitored the increase of the matrix crack density of the glass/epoxy laminates made of unidirectional prepreg.

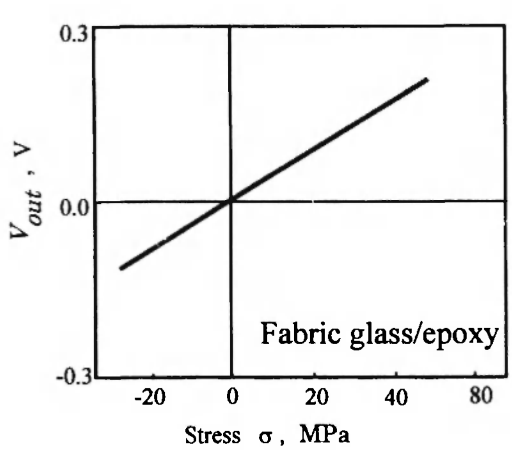


Fig. 3: Luminance change of fabric glass/epoxy laminates due to loading in static tension and compression tests taken from reference /9/.

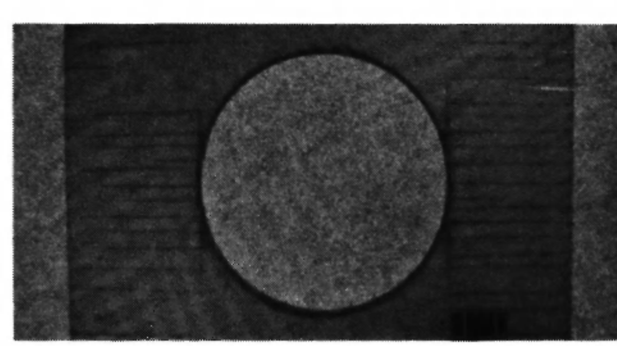


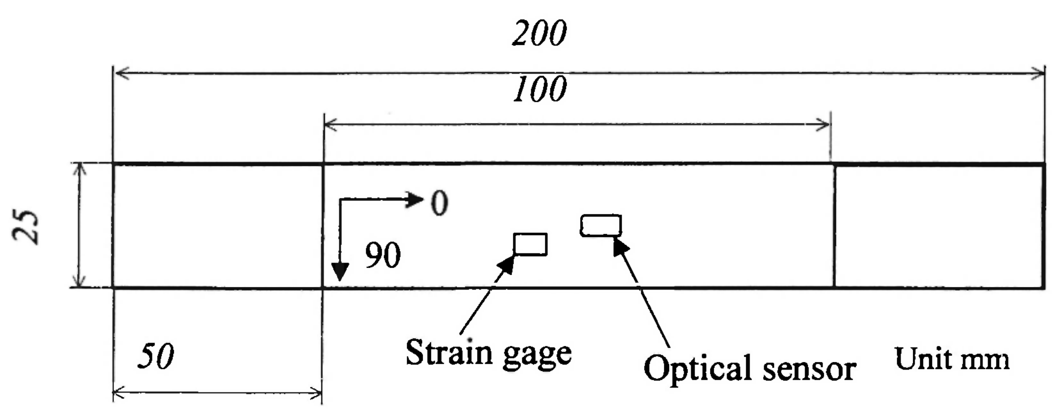
Fig. 5: Typical matrix crack damage observed in the tensile test with glass/epoxy laminates made from unidirectional prepreg.

3. EXPERIMENTAL METHOD

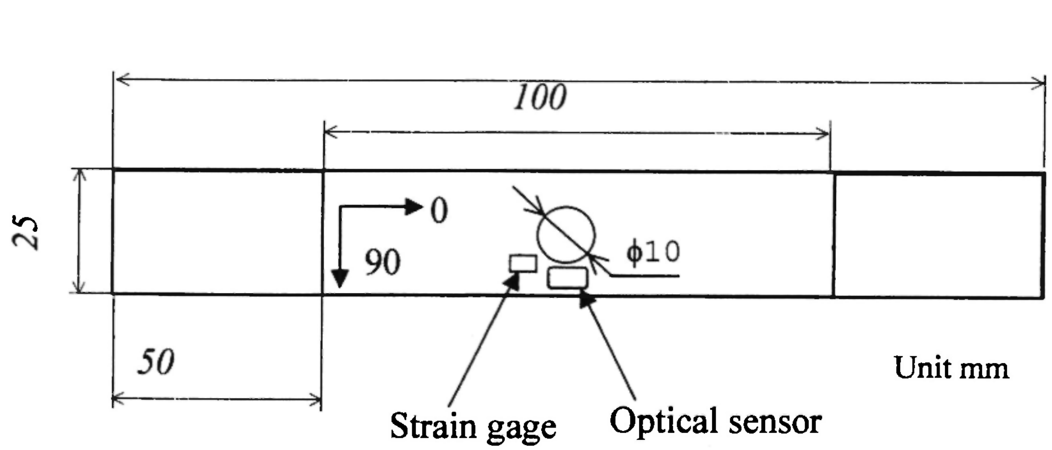
3.1. Specimens

The material used is unidirectional Al_2O_3/epoxy prepreg. The stacking sequence of specimens is $[0]_T$, $[90]_T$ and $[0_2/90_2]s$. Curing condition is 120°×2hr. After the curing, rectangular specimens are fabricated: 200 mm length, 25 mm and width 0.5 mm. Thickness of the cross-ply specimen of 8 plies is approximately 1 mm, and the thickness of the single-ply specimen is approximately 0.125 mm. The material properties of this Al_2O_3/epoxy composite are measured using the rectangular specimens, and the results are as follows: $E_L = 94.1$ GPa, $E_T = 10.0$ GPa, $\nu_{LT} = 0.3$, $\sigma_L = 992$ MPa, $\sigma_T = 60.7$ MPa.

Both types of specimen configurations are shown in Figure 6. The unidirectional tensile specimen shown in Figure 6 (a) is used for a single-ply specimen made from $[0]_T$ or $[90]_T$ and for a cross-ply specimen. Using the specimen, luminance from the EL backlight during tensile strain in the elastic deformation region is measured to confirm luminance change due to the elastic deformation observed in glass/epoxy composites /9, 10/. The open-hole-notched specimens are used for measurements of the luminance change due to damage during tensile tests. The open-hole notched test is performed to confirm the applicability of the method for the Al_2O_3/epoxy composites. For all specimens, an EL device is mounted on one side of the specimen surface, and an optical sensor to measure the luminance of the



(a) Unidirectional tensile test specimen



(b) Cross-ply laminate specimen with open-hole notch

Fig. 6: Specimen configuration for tests of matrix crack density.

transmitted light is mounted on the other side of the specimen. For the open-hole specimen, the EL device and the optical sensor are attached near the open-hole notch. A strain gage is also attached near the open hole, as shown in Figure 6, to detect the damage initiation with high sensitivity.

3.3. Test procedure

In the present study, static tension tests were performed at room temperature. To measure the luminance change of transmitted light, an EL device was mounted on the specimen surface with adhesive, and an optical sensor was directly attached to the other surface. Tension tests were conducted with measurements of the luminance of the transmitted light with an optical sensor, described later. These tests were conducted using a closed-loop material-testing machine produced by MTS under displacement control of 1.5 mm/min.

Photo-diodes of BS500B by Sharp Co. were used for the optical sensors here. To measure the luminance of transmitted light using the photo-diodes, a luminance meter circuit, shown in Figure 7, was employed. Using this circuit, change of luminance was converted to electric voltage change. The actual output signal was input into an amplifier, and the magnitude of the amplifier was adjusted at 500 times. The increase in the output, therefore, means the increase of the brightness of transmitted light in the present study.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Transparency check

First of all, transparency of Al_2O_3/epoxy composites was compared with that of glass/epoxy composites using the same EL backlight. The results are shown in Figure 8. In these figures, a rectangular shaped EL device is attached to the specimen surface at the bottom of each specimen. For each specimen, transmitted light can be seen as a bright region in the middle of each specimen. As easily seen in Figure 8, the transparency of Al_2O_3/epoxy composites (see Figure 8 (b)) is very poor when it is compared with that of glass/epoxy (see Figure 8 (a)). Since the silhouette of matrix cracks can

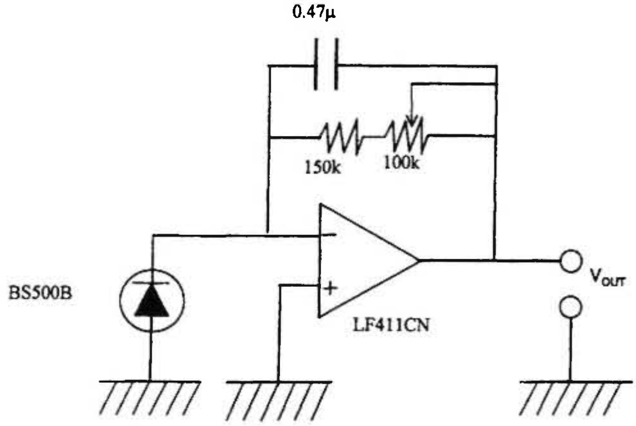
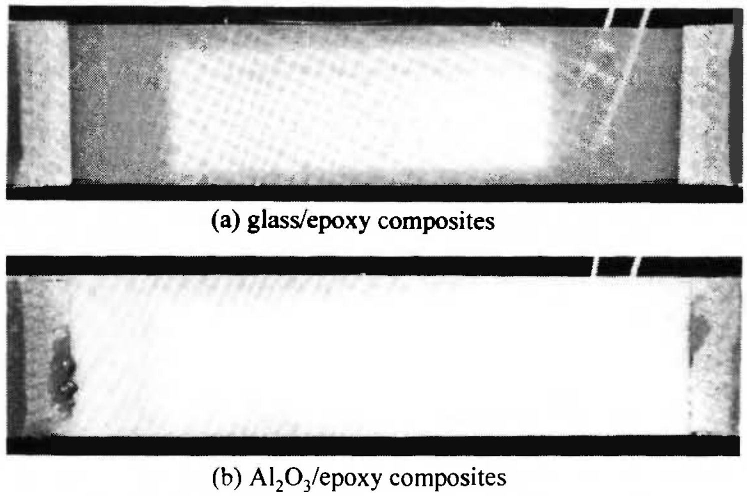


Fig. 7: Optical power meter circuit.

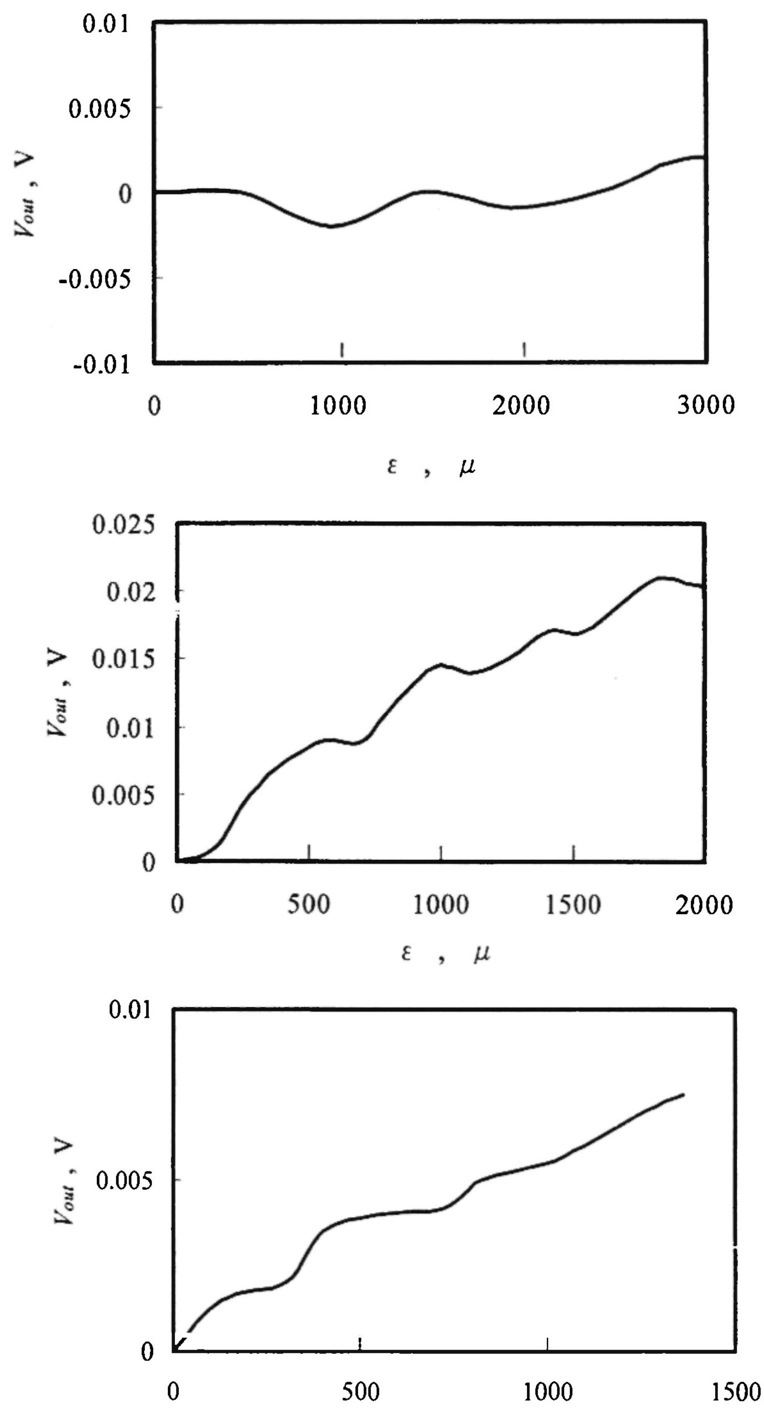


(a) glass/epoxy composites

(b) Al_2O_3/epoxy composites

Fig. 8: Comparison of transparency using EL backlight.

composites at the same load is approximately 0.01 V as shown in Figure 9 (b). Moreover, the measured V_{out} shows larger variations, although the luminance of glass/epoxy composites increased linearly in the previous paper /10/. Since the luminance change is very small, this change may be due to larger experimental errors compared to that of glass/epoxy composites. The measured luminance of the cross-ply laminates increased with the increase of applied strain, as shown in Figure 9 (c).



(a). 0° unidirectional single-ply specimen

(b) 90° unidirectional single-ply specimen

(c) cross-ply specimen of $[0_2/90_2]$s without

Fig. 9: Luminance change during tensile test of Al_2O_3/epoxy composites

In our previous paper /10/, the luminance change in the elastic deformation region is explained on the basis of two mechanisms: a thickness change model and a fiber spacing change model. This mechanism has not yet been proved, and is the subject of our future work. Despite this, the luminance change during the elastic deformation region makes it possible to measure strain of Al_2O_3/epoxy composites by means of luminance change of EL backlight.

4.3. Luminance change due to damage of open-hole specimen

The measured luminance change of the open-hole specimen is shown in Figure 10. In this figure, the abscissa is the applied strain, and the ordinates are measured V_{out} and applied stress. As with Figure 9 (c), the luminance of the transmitted light increases with the increase of applied strain almost linearly up to the applied strain of 3000 μ. Over this value, the luminance decreases suddenly with the increase of applied strain. In the stress-strain curve, a linear relationship is observed up top approximately 3000 μ. Over this value, a non-linear relationship is observed, as shown in Figure 12. This means that the luminance decrease over the 3000 μ is caused by the damage.

To confirm the damage, luminance images during tensile testing are taken as illustrated in Figures 11 (a) to (d). Figure 11 (a) shows the initial image with the EL backlight. Figure 11 (b) shows the image around the open-hole notch before damage initiation. As shown in this figure, no damage is observed around the open-hole notch. Figure 11 (c) shows the image around the open-hole notch after the initiation of damage. As easily seen, a slight dark shadow can be observed at the notch roots be distinguished by means of difference of luminance, the low transparency means monitoring of matrix cracks for Al_2O_3/epoxy composites is more difficult than that for glass/epoxy composites.

4.2. Luminance change due to elastic deformation

Measured luminance change during elastic loading of $[0]_T$, $[90]_T$ and $[0_2/90_2]s$ specimens are shown in Figure 9 (a) to (c) respectively. In all of these figures, the abscissa is tensile load strain measured with the attached strain gage, and the ordinate is output voltage (V_{out}) from the optical meter circuit. Increase of V_{out} means an increase of luminance of transmitted light here. As shown in Figure 9 (a), almost no luminance change is observed in the single-ply specimen of $[0]_T$, and approximately linear increase of luminance with the increase of tensile strain in the single-ply specimen of $[90]_T$. The increase in luminance during tensile loading of the unidirectional specimen of $[90]_T$ during elastic deformation was also observed in previous papers /9,10/ using glass/epoxy composites. For example, V_{out} of unidirectional glass/epoxy of $[90_8]_T$ at applied tensile

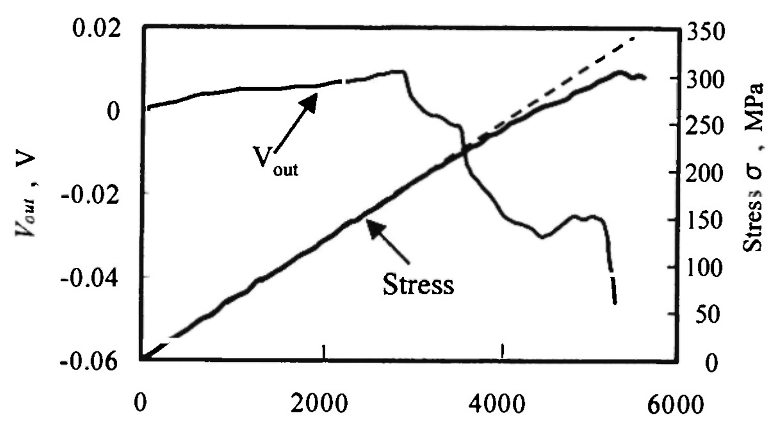
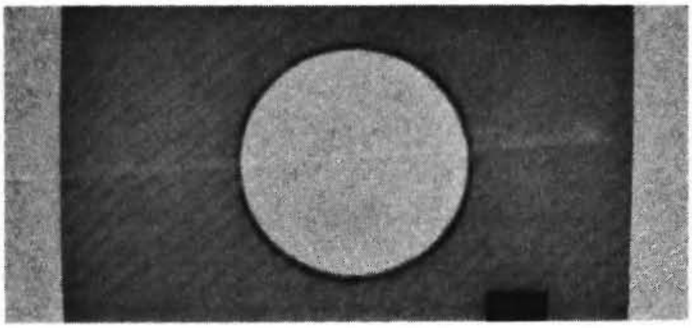
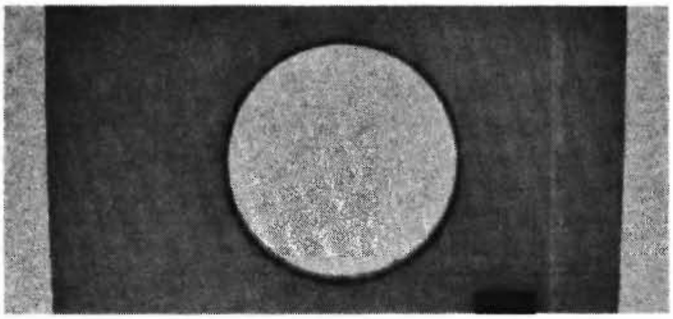


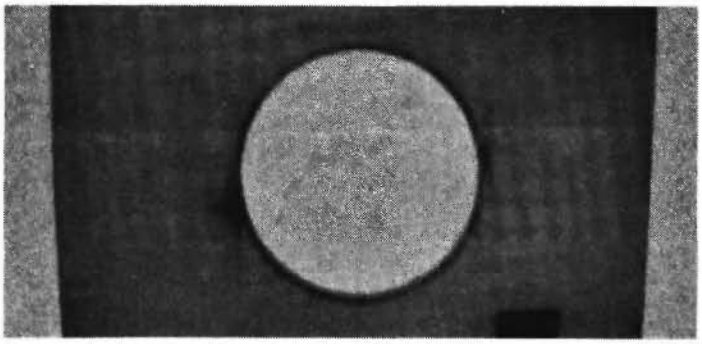
Fig. 10: Measured luminance change during tensile test of Al_2O_3/epoxy composites of cross-ply specimen of $[0_2/90_2]s$ with an open-hole notch.



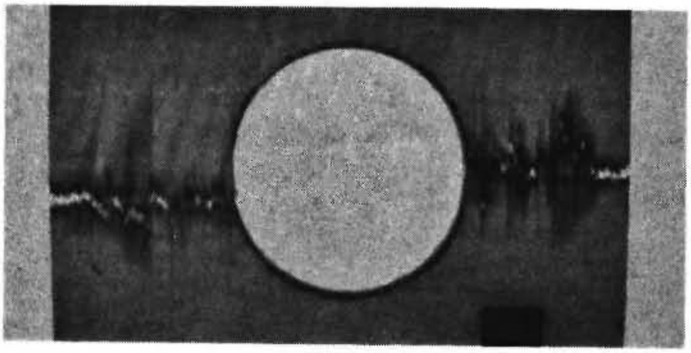
(a) Before loading



(b) Loading of 2500 μ



(c) Loading of 3500 μ



(d) After fracture

Fig. 11: Luminance image of open-hole specimen of cross-ply laminate.

strain of 1000 μ is approximately 0.05 V as shown in the previous paper /10/, but the V_{out} of Al_2O_3/epoxy of the open hole. Although it is quite difficult to understand the damage process from the silhouette image, the luminance image shows us the significant change due to damage around the open-hole notch. Figure 11 (d) shows the image of the fractured specimen. For the glass/epoxy composites of cross-ply laminates /10/, matrix cracks and splitting are clearly seen in the luminance image. Although the luminance image is not clear, we can conclude that the initiation and damage accumulation can be monitored by means of the luminance change of transmitted light from an EL backlight.

Figure 10 shows the increase of luminance due to elastic deformation is only 0.01 V for the open-hole notched specimen, and the decrease of the luminance due to damage is up to –0.05 V. We can conclude that the luminance change due to elastic deformation is negligible compared to the larger luminance decrease due to damage over 3000 μ. For example, if we set the limit value of decrease of luminance at –0.03 V, we can detect damage at applied stress of 250 MPa. Since the fracture stress is approximately 300 MPa, this means we can detect the damage at approximately 83% (=250/300) of the fracture stress. Since this limit value depends on the stress concentration of a structure, careful experimental investigations will be required before a decision can be made.

Since the damage silhouette does not disappear without loading, this method can be applied to unloaded structures or without loading. This means the method monitors damage before service use of the structures.

5. CONCLUSIONS

Luminance change of transmitted light from an EL backlight has been investigated using Al_2O_3/epoxy composites made of unidirectional prepreg sheet. The previously proposed damage monitoring method was applied to an open-hole notched specimen of Al_2O_3/epoxy composites. The following results were obtained:

1. Specimens made from 90°-ply and cross-ply laminates showed an increase of luminance with the increase of applied tensile strain that was the same as glass/epoxy composites in the elastic deformation region. This means that the elastic strain is measured with measuring luminance change even for Al_2O_3/epoxy composites using an EL backlight.
2. The damage monitoring method using an EL backlight is applicable even to Al_2O_3/epoxy composites, although the luminance is less than that of glass/epoxy composites.
3. Luminance decrease due to damage is larger than luminance increase due to elastic deformation for an open-hole notched Al_2O_3/epoxy composite specimen. Damage can be detected from the decrease of luminance from the initial value for the open-hole notched Al_2O_3/epoxy composite specimen.

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REFERENCES

1. R.A. Badcock and G.F. Fernando. An intensity-based optical fibre sensor for fatigue damage detection in advanced fibre-reinforced composites, *Smart Materials and Structures*, **4**, 223-230 (1995).
2. C.-C. Chang and J. Sirkis. Impact-induced damage of laminated graphite/epoxy composites monitoring using embedded in-line fiber etalon optic sensor, *Journal of Intelligent Material Systems and Structures*, **8**, 829-841 (1997).
3. C.-C. Chang and J.S. Sirkis. Design of fiber optic sensor systems for low velocity impact detection, *Smart Materials and Structures*, **7**, 166-177 (1998).

4. D.C. Seo and J.J. Lee. Effect of embedded optical fiber sensors on transverse crack spacing of smart composite structures, *Composite Structures*, **32**, 51-58 (1995).
5. D.C. Lee, J.J. Lee and S.J. Yun. The mechanical characteristics of smart composite structures ith embedded optical fiber sensors, *Composite Structures*, **32**, 39-50 (1995).
6. A.G. Efimov, V.M. Parfeev, Kh. Kurzemnieks and S. Vkharitonov. Study of damage in plastics by optical method, *Mechanics of Composite Materials*, **27** (6), 711-719 (1992).
7. H. Hyakutake and T. Yamamoto. Damage near the notch root of notched FRP plates in static load evaluation of damage by a luminance-measuring system, *4th International Conference on Localized Damage, Computational Mechanics*, 1996; pp. 417-424.
8. H. Aoyama, K. Tanaka, H. Watanabe and N. Takeda. Health-monitoring technologies for alumina-fiber-reinforced plastics, *Composite Structures*, **52** (3-4), 523-531 (2001).
9. A. Todoroki and Y. Shimamura. Damage monitoring for semi-transparent composites using luminance of EL backlight, *JSME Int. J., Series A*, **43** (1), 76-82 (2000).
10. A. Todoroki, Y. Shimamura and Y. Tanaka. Luminance change method for strain and matrix cracking monitoring of glass/epoxy composites with EL backlight. *Composite Science and Technology*, **63** (2), 273-281 (2003).