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Luminance change method for strain and matrix cracking monitoring of glass/epoxy composites with EL backlight

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Abstract

Authors have proposed a new damage monitoring system that employs luminance of EL backlight for transparent composites such as glass/epoxy composites. For the transparent composites, damage is usually easily found by visually. In the case of the sealed structures or huge structures, however, the visual inspections are difficult to perform. The previous paper adopts a system using change of luminance of transmitted light for damage monitoring of fabric glass/epoxy composites. When the composite structures are damaged, the damage reduces the luminance of the transmitted light emitted from the backside. The study adopts an electro luminescent device (EL) as the backlight similarly. In the present study, the previously proposed method is newly applied to glass/epoxy composites fabricated from unidirectional prepreg sheet to confirm availability of the method to monitor matrix cracking. Specimens are made from unidirectional plies and cross-ply laminates. Tensile tests are conducted using the specimens fabricated with measuring the luminance change of the EL backlight. In the elastic deformation region, the luminance of the transmitted light changes with the applied strain. After the creation of the matrix cracks, the luminance decreases with the increase of the loading. As a result, the method is confirmed to be available to monitor the matrix cracking for glass/epoxy laminates fabricated from unidirectional prepreg.

Keywords: A. Glass fibers; A. Smart materials; B. Matrix cracking; Strain; EL; Luminance

1. Introduction

Damage of transparent composites such as glass/epoxy composites and aluminum-oxide-ceramic-fiber/epoxy composites reduces their visual transparency owing to the scattering of transmitted light caused by the damage like matrix cracking, delaminations and fiber breakages. The damage, therefore, can easily be detected visually. For super conductive coil support structures of MAGLEV, however, the visual inspections are sometimes quite difficult because the structure of the coil is completely sealed to obtain good thermal insulation. For large glass/epoxy composite fan blades of wind turbine plants, the fan blade itself is too large, and the visual inspections of damages are not cost effective. To detect damage of composite structures, recently, 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 strain changes for the fiber optic sensors. This means that the damage detections of the coil support structures of MAGLEV before running are very difficult, and the damage detections of the fan blades for wind turbine plants are also very difficult when the wind turbine plants are stopped for inspections. Although these problems are not fateful for fiber optic sensors, the problems surely require additional cumbersome approaches. Furthermore, some researches have reported that embedding fiber optic sensors may sometimes cause strength reduction [4,5].

For transparent or semi-transparent plastics and composites, a luminance pattern of transmitted light through the thickness is a very helpful approach to detect damage [6–9]. Since the micro cracks cause scattering of the transmitting light, the damaged zones can be easily identified visually as a dark area for such composites. Aoyama et al. have revealed that the brightness pattern of the transmitted light are applicable for a new non-destructive inspection tool using a CCD camera and they proposed a pattern recognition system

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for the coil support components of MAGLEV [8]. 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 curved complicated structural components.

Electro luminescent (EL) devices emit uniform-plane-light, and the stiffness of the device is very low and flexible. The EL devices are usually applied to backlight sources of liquid crystal displays such as pocket bells and cellular phones. The thickness is less than 0.1 mm, and can emit uniform-plane-light by charging an alternative current of 50 Hz to the devices. The size is not limited and the configuration is changeable just by cutting a sheet of the EL device. The thinnest EL device is very flexible, and can be mounted on curved surfaces.

In our previous study [10], a new damage monitoring system which employs change of luminance of transmitted light from an EL backlight has been proposed. The system adopts 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 of fiber breakages and matrix cracking at the notch root is monitored by the change of measured luminance of the transmitted light.

In the present study, this system is applied to cross-ply glass/epoxy composite laminates fabricated from unidirectional prepreg to confirm availability of the system for monitoring matrix cracking of unidirectional composites. Rectangular plate specimens are fabricated 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. In the previous study, luminance change during elastic deformation region has been observed using the fabric glass/epoxy composites. In the present study, therefore, luminance change during elastic loading is also measured with the unidirectional laminates, and the mechanism of luminance change during elastic loading is investigated here. Matrix crack density is measured during tension tests, and the relation between the matrix crack density and the luminance of the transmitted light of the EL device is experimentally obtained. The present method for detection of the matrix cracking is discussed in detail.

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 a ZnS particle that is a kind of semi-conductor materials. The luminescence of EL devices does not generate heat and emission gas. By charging alternative current between the two electrodes, the luminescent layer emits cold light through the transparent electrode layer. The EL device emits almost uniform plane light, but the luminance of the EL device is not permanently constant. The luminance decreases with the increase of luminescent time. EL devices used for pocket bells are shown in Fig. 1.

2.2. Monitoring system using EL backlight

A new damage monitoring system was proposed in the previous study [10], 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 mounted on one of the specimen surfaces. On the other surface, transmitted light at the point where damage is monitored is transferred using a large-core plastic-optical fiber to a luminance meter (optical sensor), and the luminance of the transmitted

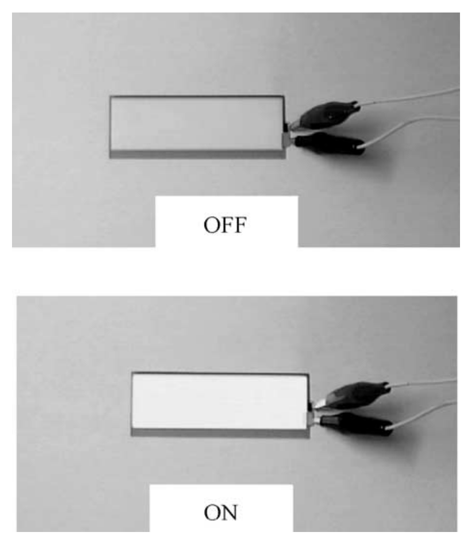

Fig. 1. EL devices.

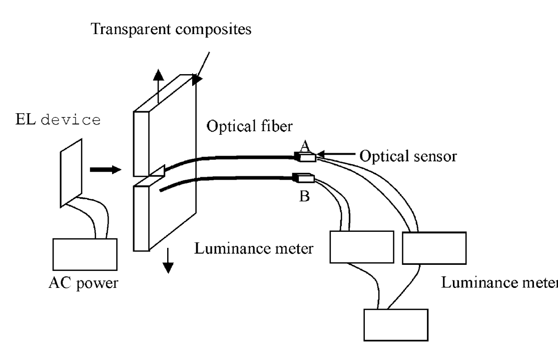

Fig. 2. Damage monitoring system with EL backlight.

light is measured with the luminance meter. Since the luminance of the EL device is not constant owing to aging of the EL device, reference light is also measured as shown by 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 a place, we can adopt dummy specimen that is made from the same composite plate and is not loaded. By comparison of the difference of luminance between these two points, we can detect change of luminance of the transmitted light. Since the reference light is adopted in the system, we can recognize the change owing to the damage even if aging reduces the transparency of semi-transparent composites.

As described before, the EL device is very flexible. This system, therefore, can be applied 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 not expensive. This system is very attractive for transparent composites for damage monitoring.

In our previous study [10], the system was applied to monitor fatigue damage around an open hole notch of fabric glass/epoxy composites. The results has shown that the luminance of the transmitted light is decreased with the increase of the applied tensile stress in elastic deformation region, and that is increased 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 owing to the applied stress forced us to monitor the damage under the unloaded condition in the previous study. Fig. 4 shows the fatigue damage shadow observed using the EL backlight. Fatigue damage of the fabric glass/epoxy composites is observed as dark shadows on both ends of the open hole notch. As a result, the luminance decreased during fatigue cycling, and the fatigue damage has been detected from the luminance change in the previous study.

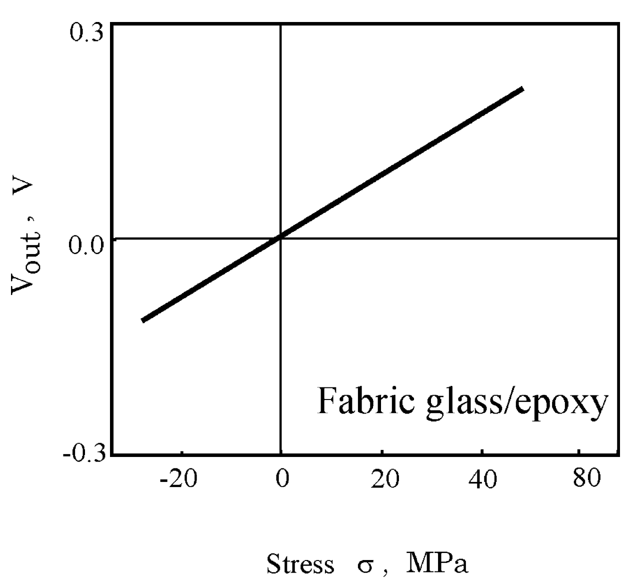

Fig. 3. Luminance change of fabric glass/epoxy laminates due to loading in static tension and compression tests after [10].

3. Experimental method

3.1. Specimens

Material used is unidirectional glass/epoxy prepreg: GE0750-433H (0201) Nippon Steel Chemical Group. Stacking sequences of specimens are $[0_8]_T$, $[0_{12}]_T$, $[0_{16}]_T$, $[90_8]_T$, $[90_{12}]_T$, $[90_{16}]_T$ and $[0_2/90_2]s$. These unidirectional laminates of 0°-ply and 90°-ply are employed for investigations of luminance change owing to applied strain in the elastic deformation region to clarify the mechanism of luminance change. Curing condition is 130°×2 h. After the curing, rectangular specimens are fabricated: 200 mm length, 25 mm and width 0.5 mm. Thickness of the laminates of 8 plies is approximately 0.5 mm, thickness of the laminates of 12 plies is approximately 0.75 mm and the thickness of the laminates of 16 plies is approximately 1 mm. The material properties of this glass/epoxy composites are as follows: $E_L = 33.6$ GPa, $E_T = 14.2$ GPa, $G_{LT} = 3.14$ GPa, $\nu_{LT} = 0.32$, $\sigma_L = 924$ MPa, $\sigma_T = 49.6$MPa.

Specimen configurations are shown in Figs. 5 and 6. The rectangular plate specimen shown in Fig. 5 is adopted for the measurements of luminance change owing to applied strain in the elastic deformation region. The rectangular specimen is also adopted for the measurements of the relation between matrix crack

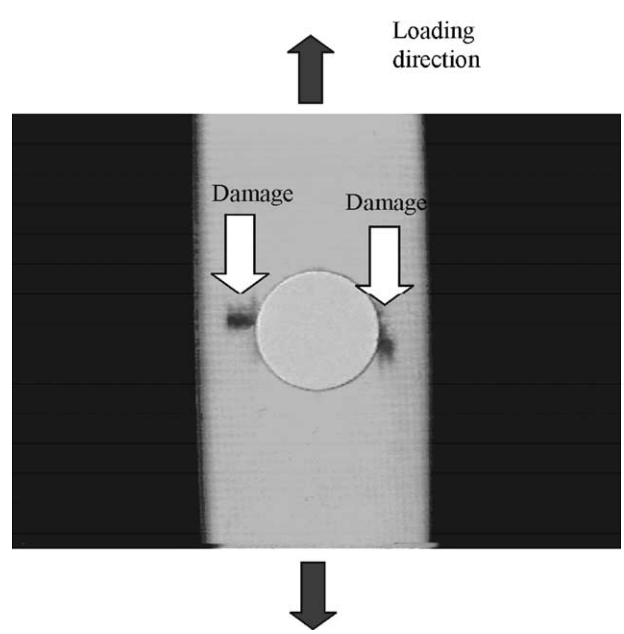

Fig. 4. Typical fatigue damage observed in the test of $\sigma = 100$ MPa at $N/N_f = 99\%$ fabric glass/epoxy after [10].

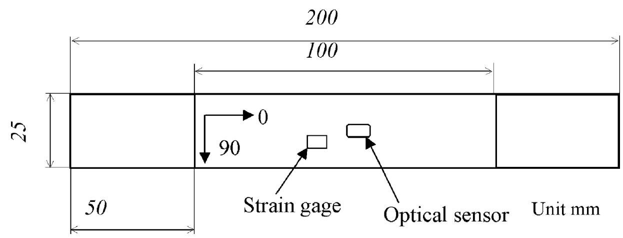

Fig. 5. Specimen configuration for tests of matrix crack density.

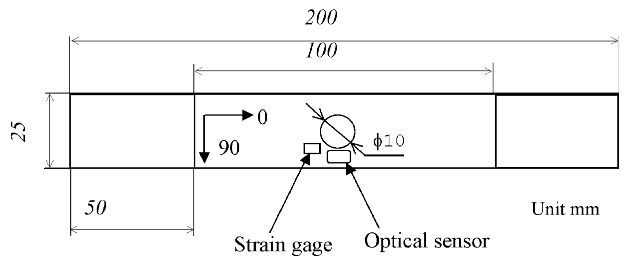

Fig. 6. Specimen configuration of open hole notch.

density and luminance change of the transmitted light of an EL device. The open-hole-notched specimens are adopted for confirmation of the method for damage monitoring of stress concentrated region. This test is performed to confirm the applicability of the method for the non-uniform matrix cracking around the stress concentrated region.

3.2. Test procedure

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

Three kinds of tests are performed in the present study here. The first test is to investigate the luminance change of transmitted light owing to tension load in the elastic deformation region of the unidirectional and cross-ply laminates. The second test is performed to investigate the applicability of the method for monitoring matrix crack density. For these two kinds of the tests, the EL device is mounted on a specimen surface, and an optical sensor is attached on the opposite side of the surface without using optical fiber to simplify a test process. For measurements of the matrix rack density, video image of the luminance of the transmitted light is also recorded from the specimen surface where the sensor is attached. The matrix crack density is measured by counting the number of matrix crack between the gage length of 20 mm. The last test is damage detection near the stress concentrated area during a static tension test. For the damage detection test, a specimen with an open-hole notch is adopted: the diameter of the hole is 10 mm, and the hole locates in the center of the specimen. The specimen configuration with an open-hole notch is shown in Fig. 6. An EL device is mounted near the open-hole notch, and an optical sensor to measure the luminance of the transmitted light is mounted on the edge of the open-hole notch. Strain gage is attached near the open-hole notch as shown in Fig. 6 to detect the damage initiation with high sensitivity.

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

4. Results and discussion

4.1. Luminance change owing to elastic deformation

Fig. 8 shows the results of the luminance change during the tension tests of the unidirectional 0°-ply laminates. The abscissa is the applied strain and the ordinate is the measured luminance change (V_{out}). Fig. 9 shows the results of the luminance change during the tension tests of the unidirectional 90°-ply laminates. The abscissa and the ordinate are the same as those of Fig. 8. Fig. 10 shows the results of the luminance change of the cross-ply laminates of $[0_2/90_2]$s.

Comparing the luminance change of the 0°-ply laminates (Fig. 8) to that of the 90°-ply laminates (Fig. 9) or the cross-ply laminates (Fig. 10), the luminance change of the 0°-ply laminates is almost constant against the

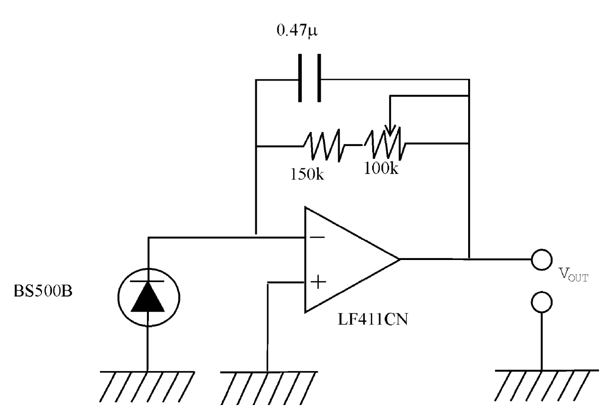

Fig. 7. Optical power meter circuit.

increase of the applied strain. The increase of the fabricated specimen thickness does not affect the luminance change. For the 90°-ply laminates, the luminance change increases with the increase of applied strain, and the thickness of the laminates does not affect the luminance change similarly. The luminance change of the cross-ply laminates is similar to that of the 90°-ply laminates. It can be concluded that the luminance change of the 90°-ply laminates contributes to the luminance change of the cross-ply laminates.

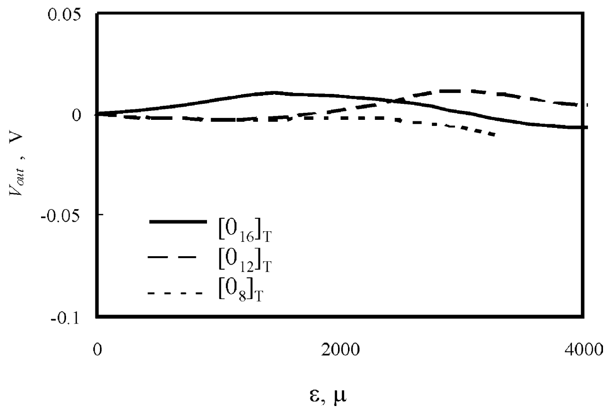

Fig. 8. Luminance change due to applied strain of unidirectional laminates (0°-Ply) in elastic deformation region.

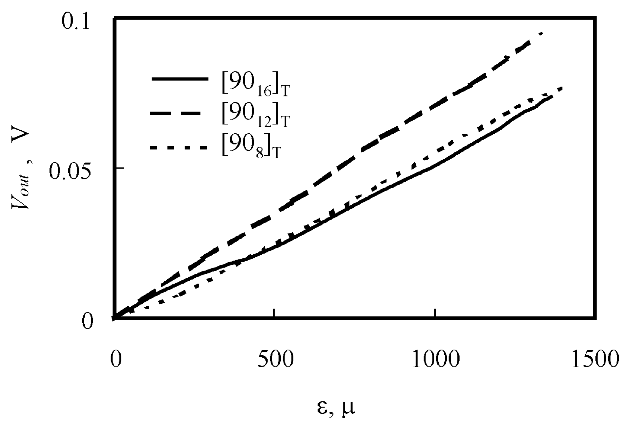

Fig. 9. Luminance change due to applied strain of unidirectional laminates (90°-ply) in elastic deformation region.

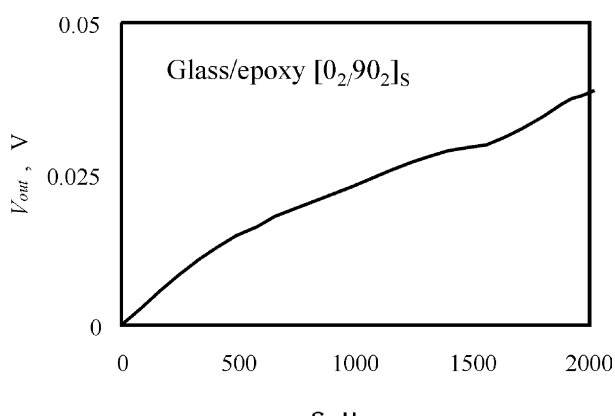

Fig. 10. Luminance change of $[0_2/90_2]_S$ during tension test.

As shown in the previous study [10], the luminance increase with the increase of the applied tensile strain and it decreases with the increase of applied compressive strain. This means the luminance change in the elastic region was not the result of a photo-elastic effect. Two models to explain the luminance change owing to the applied elastic deformation has been proposed in the previous paper, and the two models are investigated here. The first model is the effect of the thickness decrease with the applied strain due to Poisson's effect as shown in Fig. 11 (thickness-reduction model). The second model is the effect of the spacing change of fibers owing to the applied strain as shown in Fig. 12 (fiber-spacing model). Although the spacing is not constant for practical composites, this spacing change means the statistical change of average spacing.

The thickness-reduction model explains that the luminance increase with the increase of the applied strain is caused by the decrease of the thickness owing to the elastic deformation. Tensile elastic loading causes the decrease of the thickness owing to Poisson's effect. Since the reduction of the luminance of the transmitted light is proportional to the thickness, the decrease of the thickness causes the increase of the luminance. Both the 0°-ply laminates and the 90°-ply laminates has positive Poisson's ratio to the thickness direction. The positive Poisson's ratio makes reduction of the thickness in tensile tests for both laminates. This means that the luminance have to increase with the increase of the tensile strain for both laminates as shown in Fig. 13(a). The inclinations of the 0°-ply laminates are, however, almost zero. This means, at least, that the luminance change in the

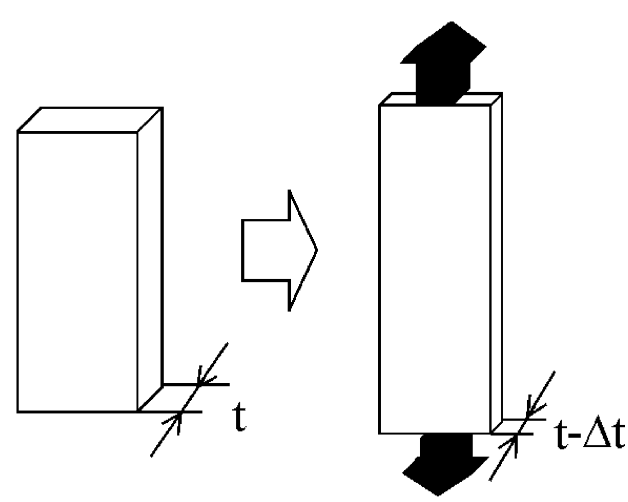

Fig. 11. Thickness change model due to applied strain of in elastic deformation region.

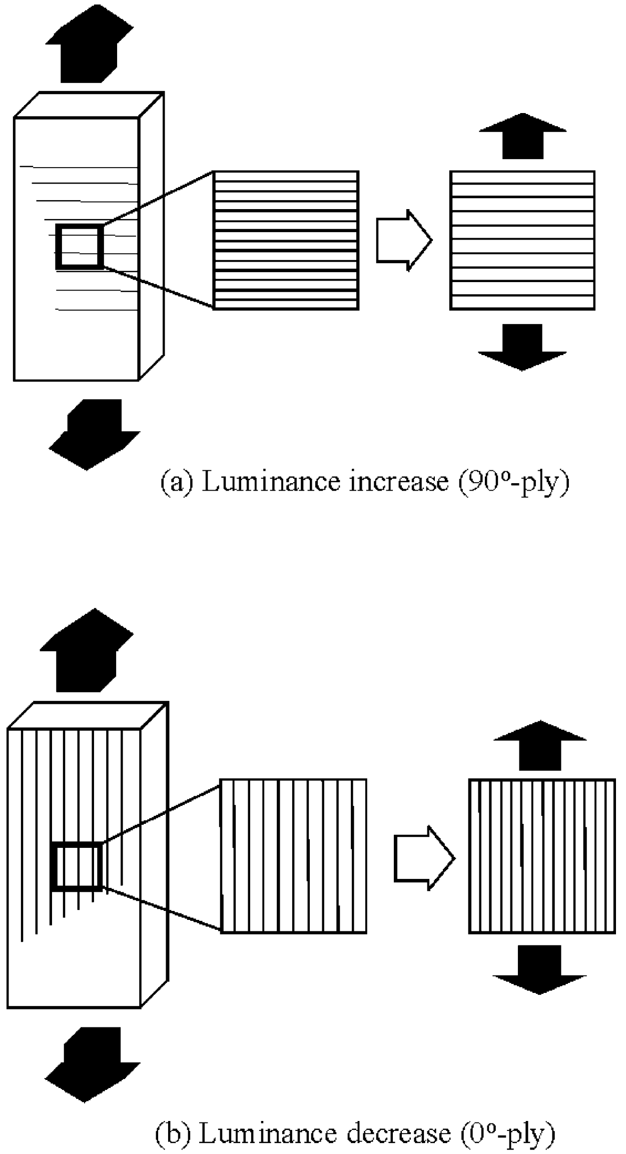

Fig. 12. Fiber spacing model due to applied strain of in elastic deformation region.

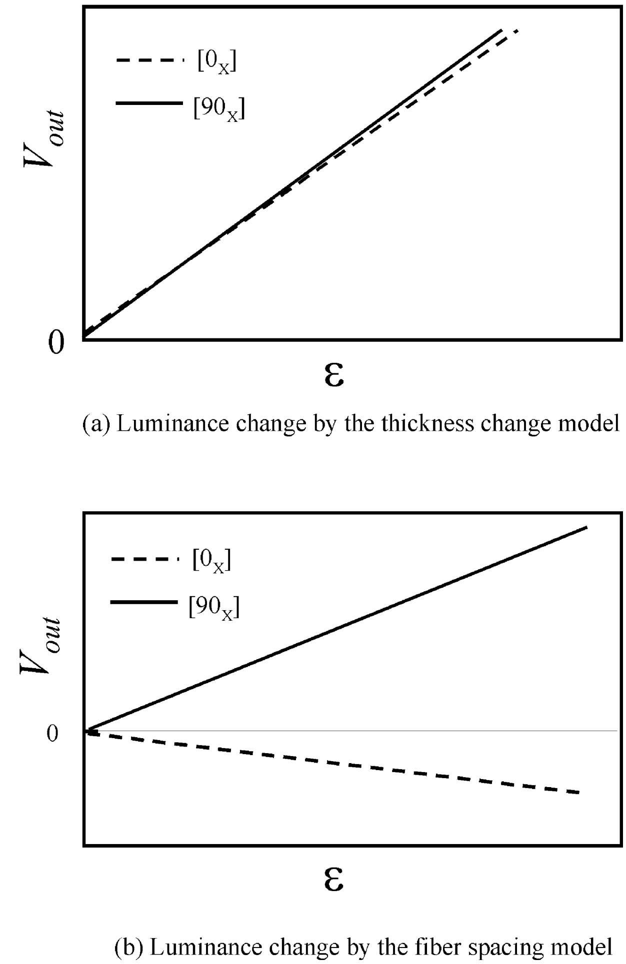

Fig. 13. Schematic luminance change due to applied strain of in elastic deformation region.

elastic deformation region cannot be explained using the thickness reduction model alone.

The fiber-spacing model explains that the luminance with the increase of the applied strain is caused by the increase of the fiber spacing in the elastic deformation region. When the tensile elastic strain is applied to the 90°-ply laminates, the glass fiber spacing increases with the applied strain. Since the transmitting light scatters owing to the glass fibers, the increase of the spacing means the light of an EL device can transmit inside the glass/epoxy composites without scattering. This reduction of scattering causes increase of the luminance when tensile strain is loaded on the 90°-ply laminates. When the tensile strain is loaded in the 0°-ply laminates, the spacing of the fibers decreases with the increase of the tensile load owing to the effect of Poisson's ratio. This decrease of the spacing could cause the decrease of the luminance as shown in Fig. 13(b). The luminance change of the 0°-ply laminates, however, is almost constant. This means that the luminance change cannot be explained using the fiber-spacing model alone.

Measured luminance change of the 0°-ply laminates is almost constant against the increase of the applied strain as shown in Fig. 8. This cannot be explained using both models as described before. Simple sum of both model effects of the 0°-ply laminates, however, explains constant against the increase of the applied load: when the effect of the thickness-reduction and the effect of the fiber-spacing are almost the same magnitude, the luminance shows no change with the increase of applied strain. It may be concluded, therefore, that both models may have significant effects on the luminance change in the elastic deformation region. Otherwise, the applied stress may affect the index of reflection of glass fibers and epoxy matrix, and this change of the index of reflection may cause the change of the transparency of the glass/epoxy composites. This must be our future work.

The luminance change in the elastic deformation region can be applied to measure local elastic strain of glass/epoxy composite structures. It is, however, very difficult to measure dynamic strain using this method because the inorganic EL device emits the blinking light of 50 Hz owing to the applied alternating current. This can be overcome using an organic EL device that emits light by charging direct current or a LED. The organic EL device is, however, currently under developing and quite expensive. This is also our future work.

4.2. Matrix crack measurement

Fig. 14 shows an example of an image of the test of the matrix crack density. An EL device is mounted on the opposite side of the specimen surface, and the optical sensor is attached on the surface. As shown in Fig. 14, matrix cracks are visible as dark horizontal lines. Fig. 15 shows the schematic mechanism of the decrease of luminance owing to the matrix cracking. In this figure, an EL device is attached on the right surface of the specimen, and an optical sensor is mounted on the left surface of the specimen of stacking sequence of [0/90]s. Almost uniform light is emitted from the surface of the EL device. Matrix cracks are perpendicular to the loading direction, and this means the matrix cracks are normal to the direction of the EL device. The matrix cracks disturb the light emitted from the EL device. This disturbance around the matrix crack makes a dark image of the matrix crack from the opposite surface (the left surface in Fig. 15). Although the decrease of luminance owing to the single matrix crack is small, accumulation of the matrix causes a decrease of the luminance of transmitted light.

Fig. 16 shows the results of the measured luminance and the matrix crack density. The abscissa is applied strain, and the ordinates are the luminance and the matrix crack density. In the lower applied strain regionless than 5000 μ, the measured luminance V_{out} is almost linearly increasing. As shown in Fig. 16, no matrix cracking occurs under the applied strain of 5000 μ. The linear increase of luminance corresponds to the effect of the increase of the luminance owing to the applied elastic tensile strain.

Over the applied strain of 5000 μ, matrix cracking is observed, and the matrix crack density increases as the increase of the applied load. Measured luminance is

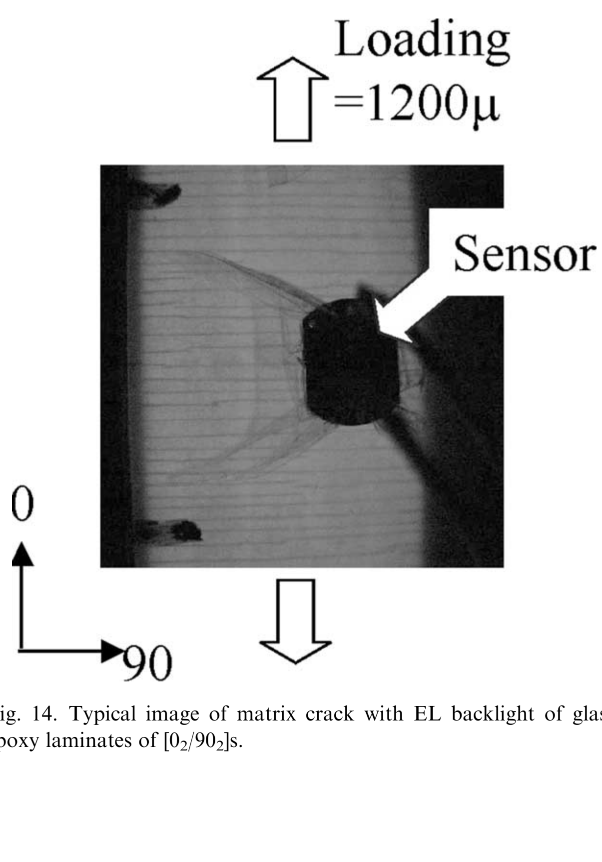

Fig. 14. Typical image of matrix crack with EL backlight of glass/epoxy laminates of $[0_2/90_2]$s.

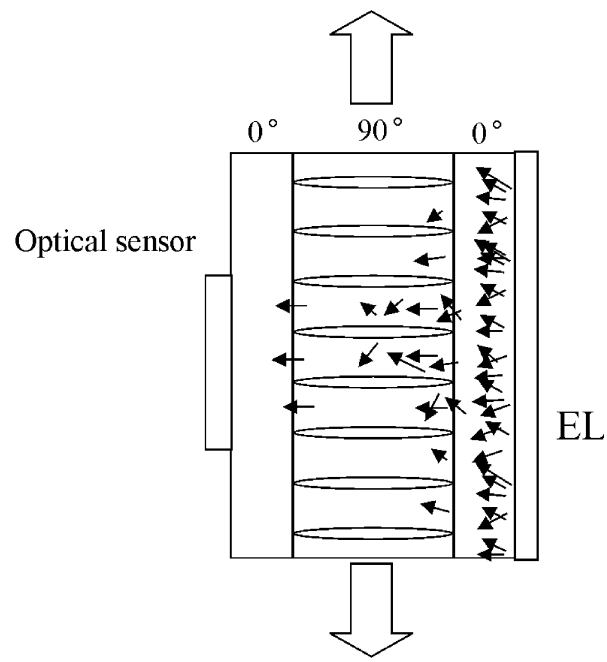

Fig. 15. Schematic image of decrease of luminance due to matrix cracking of glass/epoxy.

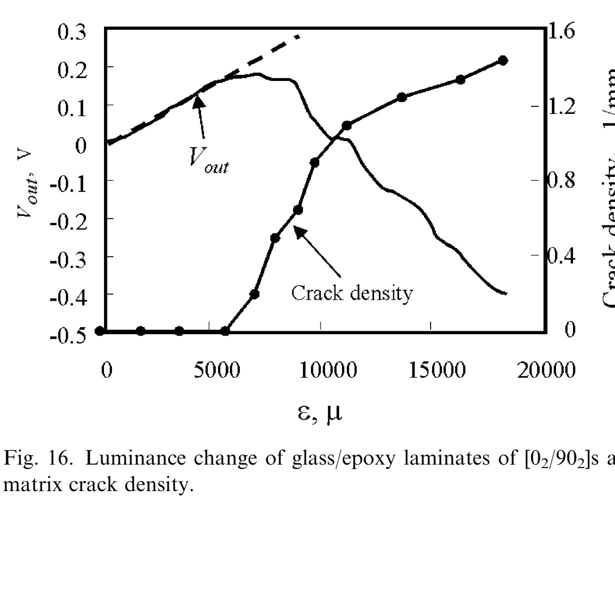

Fig. 16. Luminance change of glass/epoxy laminates of $[0_2/90_2]$s and matrix crack density.

decreasing with the generation of the matrix cracking. This figure shows that the matrix cracking causes decrease of the luminance, and the figure implies that the deviation from the linear increase of luminance corresponds to the initiation of the matrix cracking.

For example, we can obtain a linear relation between the luminance V_{out} and the applied strain ε as shown in Fig. 16 (dashed straight line). The linear relation is written as follows:

$$\varepsilon \approx 0.33 V_{out} \tag{1}$$

At the deviation point from this linear relation, the matrix cracking can be monitored. The point is approximately 5000 μ in the present study. Subtracting the luminance V_{out} owing to the elastic deformation, we can estimate matrix crack density from the measured luminance. The applied stress of the rest of the undamaged area of the 90°-ply, however, decreases owing to the existence of matrix cracks as described by Hashin [11].

$$\sigma_x = \sigma_1(1 - \phi) \tag{2}$$

where σ_1 is applied nominal stress and σ_x is stress at the 90°-ply [11]. ϕ Is calculated from the elastic modulus of the composites and thickness of the 90°-ply and the thickness of the 0°-ply. At the saturated characteristic damage stage, the calculated value of mean stress almost equals to 0.54 of the applied stress. Although the matrix cracking is not completely saturated even at the maximum strain of 1800 μ here, that approximately means the increase of the luminance V_{out} owing to applied elastic stress is reduced to almost half of the applied stress. This stress reduction effect is schematically illustrated in Fig. 17 as a dash-dotted curve. The dash-dotted curve represents the approximated qualitative estimation of the increase of the luminance owing to the applied elastic tensile stress with considering stress reduction caused by matrix cracking. The matrix cracking reduces the luminance to the solid curve. The difference between the dash-dotted curve and the measured luminance V_{out} (solid curve in Fig. 17) approximately implies the luminance change due to the matrix cracking, and this will become residual luminance change of the transmitted light when the specimen is completely unloaded. The estimated unloading curve from the point A is schematically illustrated using a dotted curve in Fig. 17. Measurements of the residual luminance under the unloading condition may enable monitoring of the matrix crack density without loading.

4.3. Open hole specimen

Typical images of the specimen with an open hole with an EL device attached are shown in Fig. 18. This specimen is to observe the damage around the open hole notch. The measured stress–strain curve of the specimen with an open hole notch is shown in Fig. 19. The abscissa is applied strain measured with an attached strain gage, and the ordinate is applied stress. The luminance of the transmitted light is shown in Fig. 20. The abscissa is applied strain and the ordinate is the measured output of the optical sensor V_{out}.

Under the applied strain of 5000 μ, the stress–strain relation is linear, and no damage was observed. This region is a complete elastic deformation region, and the luminance of the transmitted light is also linearly

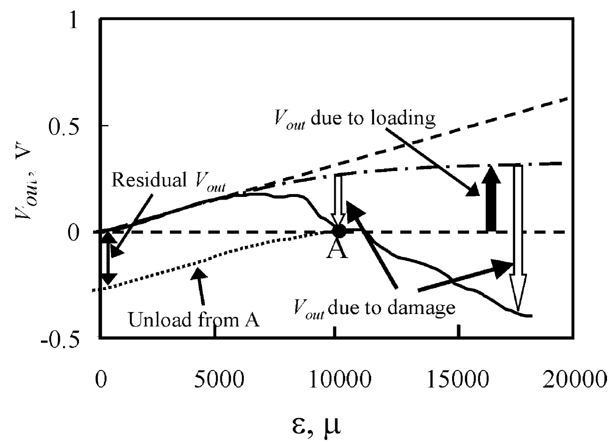

Fig. 17. Luminance change analysis of glass/epoxy laminates $[0_2/90_2]$s.

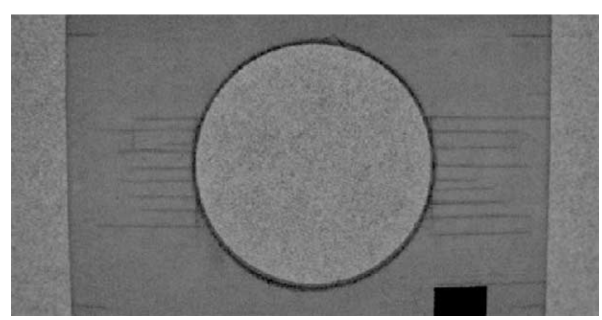

Fig. 18. Typical image of matrix crack and splitting of an open hole specimen with EL backlight (applied strain = 980 μ).

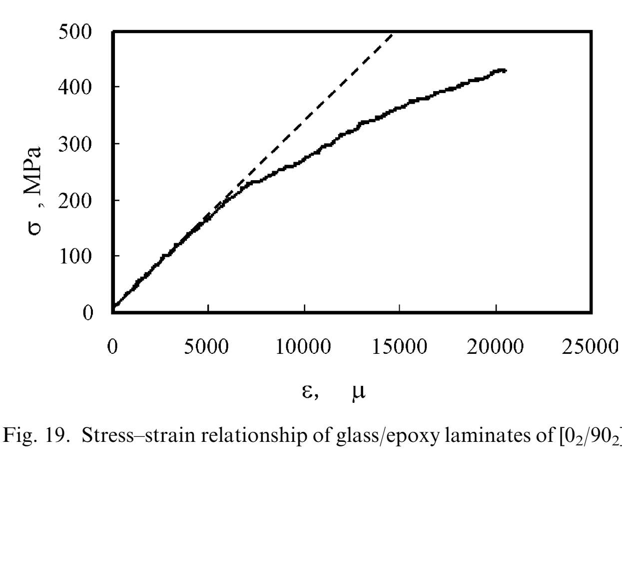

Fig. 19. Stress–strain relationship of glass/epoxy laminates of $[0_2/90_2]$s.

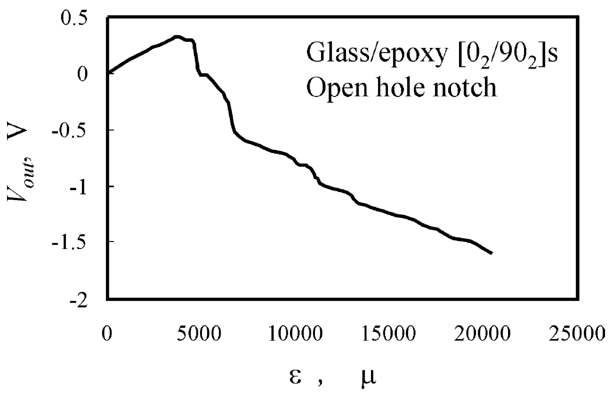

Fig. 20. Luminance change of notched glass/epoxy laminates of $[0_2/90_2]$s.

increasing at the same as the previous test results in the elastic deformation region. The inclination between the applied strain ε and V_{out} is, however, different from Fig. 12. This is because of the stress concentration around the open hole. The applied strain is measured apart from the end of the notch, and the luminance change is measured at the ligament of the open hole notch. The difference of the measured position makes this difference.

Over the applied strain of 5000 μ, the stress–strain curve deviates from the linear relation. This deviation is caused owing to the matrix cracking generated from the ends of the open hole notch as shown in Fig. 18. This matrix cracking significantly reduces the luminance of the transmitted light V_{out} as shown in Fig. 20.

These results clearly show that the matrix cracks around the stress concentration points can be detected with the luminance change of the transmitted light using an EL backlight. Since the matrix crack does not vanish even when the applied load is completely unloaded, this method can detect the damage without loading.

5. Concluding remarks

A previously proposed method with the luminance change of the transmitted light of an EL backlight is applied to detect matrix cracks for cross-ply laminates of unidirectional glass/epoxy composites. Three kinds of tests have been performed; a tensile test to obtain the relation between elastic strain and the luminance of the transmitted light, a tensile test to obtain the relation between matrix crack density and the luminance of the transmitted light, and a tensile test of an open hole to detect the matrix crack around the stress concentration with the luminance of the transmitted light. The results obtained are as follows: Even for the cross-ply laminates of unidirectional glass/epoxy composites, the luminance of transmitted light of an EL backlight increases with the increase of applied tensile load in the elastic deformation region. This is caused owing to the cooperative work with both mechanisms of the thickness-reduction model and the fiber-spacing model. After the matrix cracking, the luminance of the transmitted light decreases with the increase of matrix crack density. This method is applicable to detect matrix cracking at the stress concentration points of transparent composites.

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