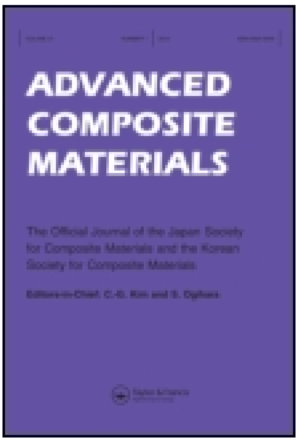

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Effects of pressure on measurement of strains in EFPI optical fiber sensors embedded in FRP laminates

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Abstract—In the authors' previous study, the internal strain measurement of GFRP laminates by using EFPI optical fiber sensors showed unreliable outputs in a cooling process of an autoclave molding. Its cause seems to be the discrepancy of the optical fiber axis in the optical fiber sensor caused by the molding pressure. In the present paper, compression and shear tests of epoxy specimens where the optical fiber sensor was embedded were conducted to investigate effects of the pressure on the internal strain output. In the experiment, the strain output was monitored under the compressive and the shear load. The stress distributions were calculated by the FEM method to know the pressure applied to the sensor. The relation between the strain output and the calculated pressure on the sensor was obtained. From the results, it was found that the load equivalent to the autoclave molding pressure almost does not affect the strain output.

Keywords: Autoclave molding; EFPI optical fiber sensor; internal strain; optical fiber axis; pressure.

1. INTRODUCTION

Recently, smart composites, which include sensors, processors and actuators, have been studied. The optical fiber sensors are suitable for the smart composites because of the advantage of small size, light weight, high strength and flexibility. An EFPI (Extrinsic Fabry-Perot Interferometer) optical fiber sensor is one of the most promising technologies to measure internal strains of materials.

In the previous study, the real-time measurement of internal strains in GFRP laminates with EFPI optical fiber sensors during an autoclave molding was conducted [1]. The experimental result of the internal strain measurement by the EFPI

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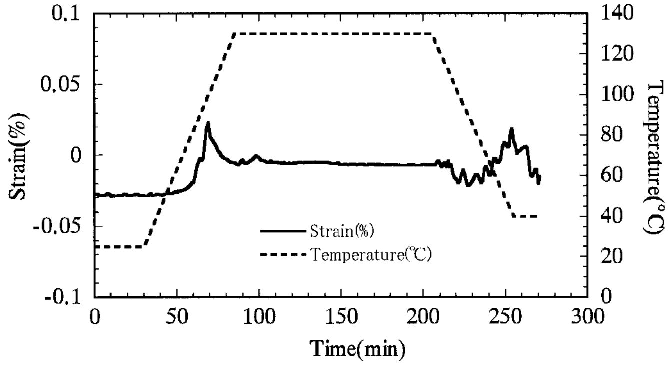

Figure 1. Result of internal strain measurement using the EFPI optical fiber sensor in the GFRP cross-ply laminate.

optical fiber sensor embedded in the GFRP cross-ply laminate along a direction perpendicular to the reinforcing fibers is shown in Fig. 1. Though compressive strains should be measured in the cooling stage, the tensile strains are monitored as shown in the figure. These tensile strains may be caused by the discrepancy of the optical fiber axis in the sensing part of the optical fiber sensor under the molding pressure. Therefore, it is necessary to investigate the effects of the pressure applied to the sensor on its output for reliable measurements to be made.

In the present paper, compression and shear tests of epoxy specimens, where the EFPI optical fiber sensor was embedded, were conducted to examine the effects of the pressure on the strain output. The stress distributions of the specimens under the compression and the shear test were calculated by the FEM method to evaluate the pressure applied to the sensor.

2. EXPERIMENTAL

2.1. EFPI optical fiber sensor

The constitution of the sensing part of the EFPI optical fiber sensor used in this study is shown in Fig. 2. The sensing part is covered with a silica glass tube. The gage length is about 1.1 mm and the diameter is about 310 μm. A phase difference between the light from (A) and that from (B) changes with the length variation of the air gap.

2.2. Specimens

Because the sensing part of the optical fiber sensor is very small (about 310 μm diameter and about 5 mm length) and fragile, it is difficult to load the surface of the optical fiber directly. Therefore, thin epoxy specimens where the optical fiber sensor was embedded were made and were used for the compression and the shear test. A bisphenol A type epoxy and a modified cycloaliphatic polyamine were used

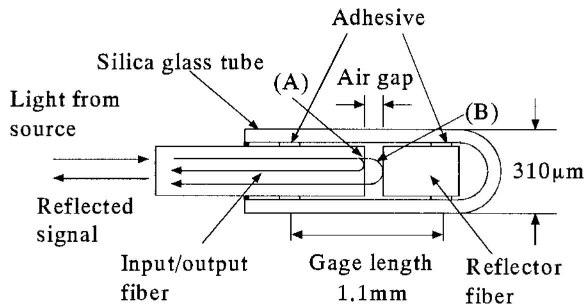

Figure 2. Sensing part of the EFPI optical fiber sensor.

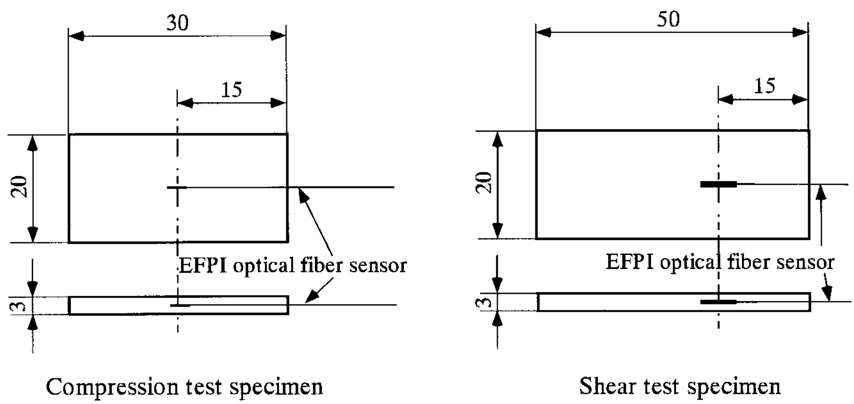

Figure 3. Shape and dimensions of the compression and the shear test specimen.

for the specimens. They were cured at 60°C for 3 hours. The shape and dimensions of the compression and the shear test specimen are shown in Fig. 3.

2.3. Shear and compression tests

The loading jigs for the shear test are shown in Fig. 4. The position of the air gap of the optical fiber sensor is adjusted to the edge of the jig A, and the specimen is fixed. The jig A is placed in the jig B, and is fastened by flat plates. In the loading test, as shown in Fig. 5, when the tensile load is applied to the jigs, a shear deformation is applied to the sensing part of the optical fiber sensor through the specimen. In the compression test, the specimen was set between two disc jigs in the test machine and the load was provided.

An Instron type tensile test machine (Shimadzu Corp: Autograph AG-5000C) was used in these tests. The test speed was 0.01 mm/min. The output of the optical fiber sensor was monitored by FTI-Buss500 strain measurement system (FISO Technologies Inc.). The displacement was measured by a video-style noncontact extensometer, and the load was measured by a load cell.

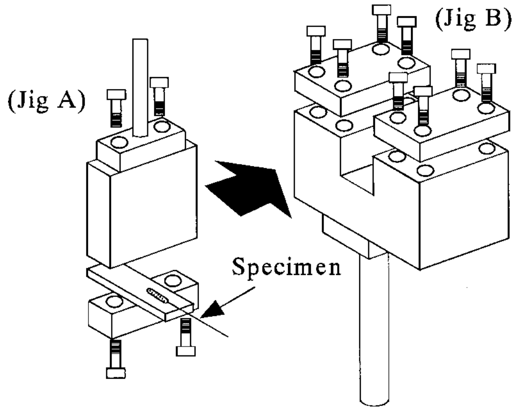

Figure 4. Shear test jigs.

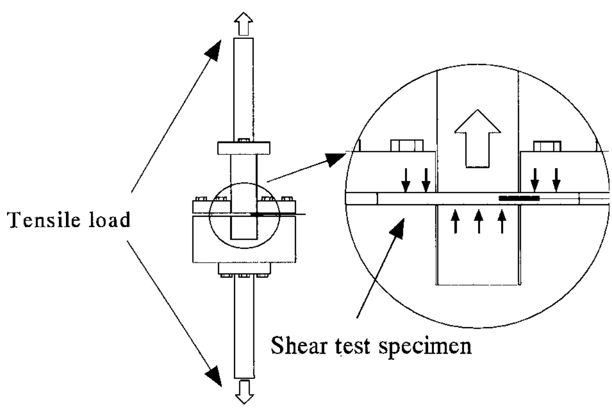

Figure 5. Loading setup for the shear test specimen.

3. RESULTS

Typical results from the shear test are shown in Figs 6 and 7. In Fig. 6, the internal strain is plotted against the load. In Fig. 7, the displacement is plotted against the load. The specimen is loaded up to about 3000 N. Figure 6 shows that the strain increases with the shear load. The strain is too small to be detected under the load of 300 N. As shown in Fig. 7, the displacement curve has a linear relation with the applied load up to about 2500 N; but the relation between the strain output and the load is nonlinear. In Fig. 8, the internal strain obtained from the compression test is plotted *versus* the mean compressive stress applied to the specimen. The strain curve is almost expressed by two straight lines having different inclinations with the exception of an initial nonlinear part.

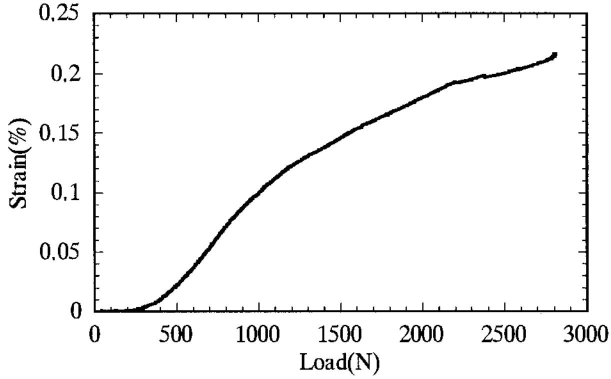

Figure 6. Strain output *versus* load applied to the specimen for the shear test.

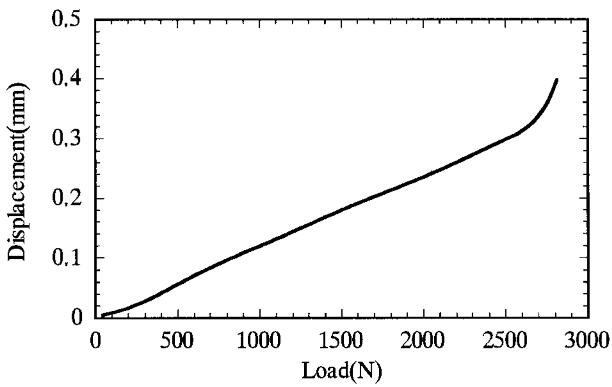

Figure 7. Load *versus* displacement curve for the shear test.

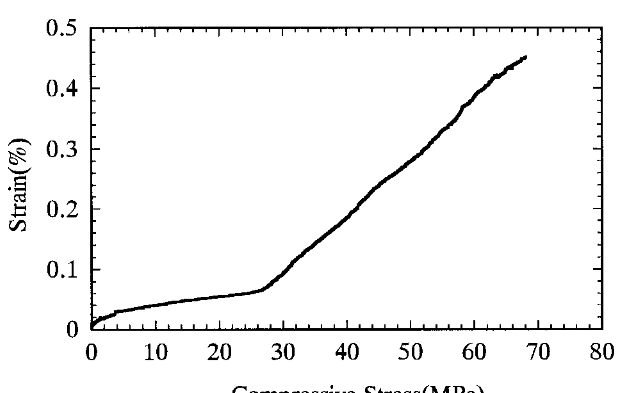

Figure 8. Strain output *versus* mean compressive stress applied to the specimen for the compression test.

4. EFFECTS OF THE PRESSURE

Our interest is in the effect of the pressure on the strain output of the EFPI sensor. In order to obtain the pressure applied to the sensor, the stress distributions of the specimens under the applied compressive and shear deformations were calculated by the FEM method. To obtain material properties of the specimen, its tensile tests were conducted. Figure 9 shows the representative stress–strain curve obtained from the tests. The curve has a non-linearity over 0.8% strain. With use of this stress–strain curve, the elastoplastic analyses of the specimens were performed. The FEM model for the shear test is shown in Fig. 10. The ε_z strain component along the center axis of the optical fiber is so small, as compared with the strain output, that its contribution to the strain output is negligible. It means that only the share deformation affects the strain output. The average of σ_y stress components of elements adjacent to the surface of the sensing part (in Fig. 11) is considered as a representative value to evaluate the effect of the molding pressure. Accordingly, the strain output for the shear test is plotted against the σ_y stress in Fig. 12. The shape of the output curve is the same as that in Fig. 6. From this result, it is found that the stress equivalent to the autoclave molding pressure (0.5 MPa) hardly affects the strain output. The result for the compression test is shown in Fig. 13. In the figure, the strain in the sensing part of the EFPI sensor calculated by FEM is also shown,

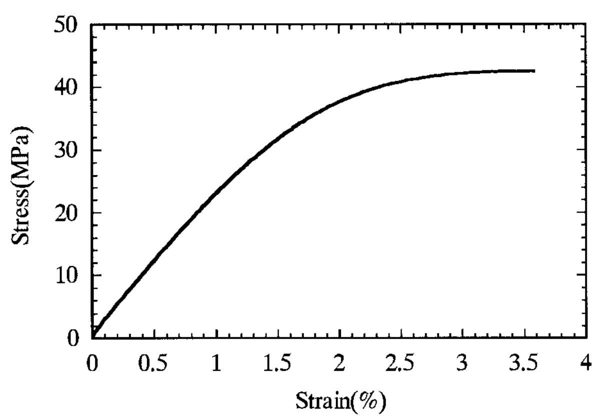

Figure 9. Strain *versus* stress curve of the epoxy used for the specimen.

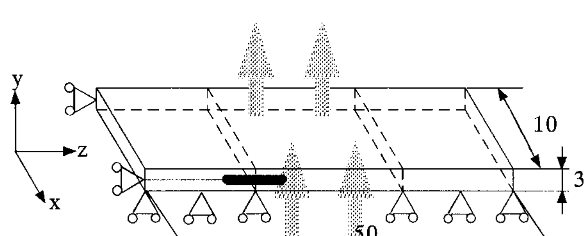

Figure 10. FEM model for the shear test.

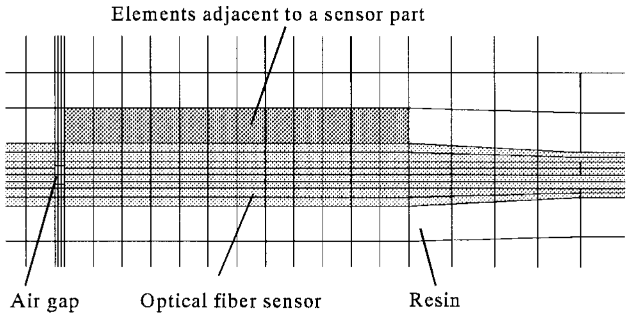

Figure 11. Sensing part of the optical fiber sensor in the FEM model.

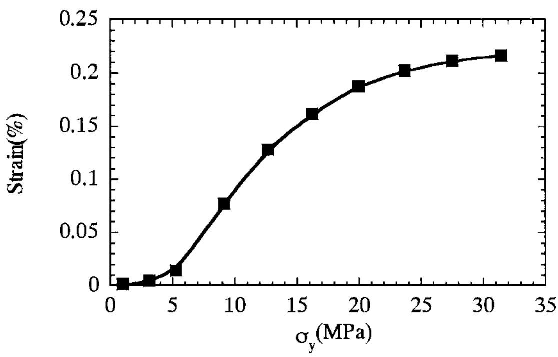

Figure 12. Relation between the calculated σ_y and the experimental strain output for the shear test.

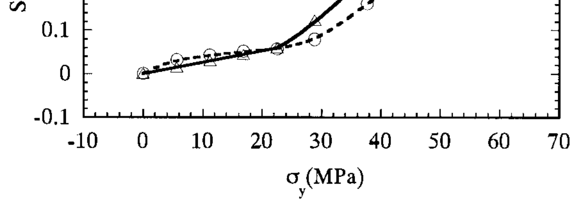

Figure 13. Relation between the calculated σ_y and the experimental strain output for the compression test.

together with the strain output from the sensor. The strain output shows a little higher value than the calculation under 22 MPa, and smaller strains are detected up to 60 MPa. The cause of these differences between the detected and calculated strains seems to be effects of situations of the embedded sensor and restrictions of the deformation in the sensing part of the sensor by the pressure; but an exact cause should be examined in detail. In the compression test, it is also found that the stress equivalent to the autoclave molding pressure (0.5 MPa) hardly affects the strain output.

From both the shear and the compression test, it was found that the stress equivalent to the autoclave molding pressure (0.5 MPa) hardly affects the strain output. Therefore, in the cooling stage of the autoclave molding, the strain output of the optical fiber sensor embedded in the FRP laminate may be affected by the stress concentration due to a heat shrinkage and a nonuniform distribution of the reinforcing fibers. To discuss quantitatively, it is necessary to investigate an optical behavior of interference light of the EFPI optical fiber sensor when the shear deformation is applied.

5. CONCLUSIONS

The compression and the shear test of the thin epoxy specimens where the EFPI optical fiber sensor was embedded were conducted to evaluate the effects of the pressure on the strain output. From the experimental results, it was found that the strain output is affected by the shear deformation. In order to obtain the pressure applied to the sensor, the stress distributions of the specimens were calculated by the FEM method. The strain output *versus* the stress applied to the sensor, which was calculated from the stress analysis, was obtained. From this relation, it was found that the compressive and the shear deformation caused by the autoclave molding pressure hardly affect the strain output. Therefore, in the cooling stage of the autoclave molding, the strain output may be affected by the stress concentration due to a heat shrinkage and a nonuniform distribution of the reinforcing fibers.

Acknowledgements

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