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A system that detects fiber reinforced plastic (FRP) erosion automatically is important. To achieve such a system, this study proposed an FRP erosion detecting sensor using an optical fiber (OF). The relationship between the erosion characteristics of OF alone and the attenuation of light was investigated, and it was found that this relationship can be applied to an erosion detecting sensor. The sensor feasibility was confirmed by investigating the erosion characteristics of FRP with an embedded OF and conducting tests to detect abrasion based on the light attenuation. Four-point bending tests were conducted on an FRP laminated plate with an embedded OF, and the mechanical characteristics of the plate were examined. The results indicated that the embedded OF did not degrade the FRP rupture strength. The proposed erosion monitoring system effectively predicts FRP erosion.

Keywords: FRP; optical fiber; sensor; erosion; prediction; measurement; bending characteristics

1. Introduction

Fiber reinforced plastics (FRPs) are currently used as alternative materials for metals in many fields, including the aerospace industry, because of its high specific strength, high comparative rigidity, and multifunctionality. Representative examples include the bodies and wings of space shuttles and private airplanes, and the propellers of aero-generators [1]. However, space shuttles and propellers and airplanes will be hit by dust and particles in the air, and their surface layers will become worn. This material wear by particles is called erosion.

Many results have been obtained from basic studies of erosion in structural materials, primarily metals and inorganic materials, conducted by Hashimoto et al. over a long period [2,3]. Application of such studies has contributed much to industry. Recently, dry sand erosion of FRP has been studied vigorously in response to industry requests. After 1986, studies of the erosion resistance of materials were conducted by Pool [4] over a range of metals, polymers, and their compounds. Thereafter, Harsha et al. [5], Barkoul et al. [6], and others investigated the influence of the angle of impact, the impact speed and form of particles, and the erosion resistance of the matrix resin for carbon fiber reinforced plastics (CFRP) and glass fiber reinforced plastic (GFRP) etc. which are frequently used for industrial purposes. The erosion resistances of CFRP and GFRP were lower than that of the matrix resin, so they were found to be unsuitable for uses that involve collisions of particles. We found that an FRP

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material that has a high specific strength and high erosion resistance can be achieved by using a super fiber [7]. Furthermore, we investigated the erosion resistance of hybrid FRP and proposed an erosion-accumulation theory that enables predicting the erosion resistance of hybrid FRP from that of FRP alone. It was successfully verified that high cost performance can be achieved by using hybrid FRP [8].

At the site, visual inspection is commonly used for checking whether or not the outer layer of material has been damaged by erosion. Therefore, to further enhance the safety and reliability of the material, a system that automatically detects erosion in FRP is required. Currently, there is no system to measure erosion of FRP automatically, and there has been no study of this.

Recently, the importance of structural health-monitoring technology to identify the position and size of damage cracks and other damages that occur when using FRP has been recognized. Many methods of achieving this, mainly by embedding optical fibers (OFs) in FRP, have been studied in Japan [9–14]. The state of a system is diagnosed by detecting the destruction of FRP or strains and cracks occurring before actual destruction as changes in light propagating in an OF. To determine the changes in mechanical characteristics due to embedding a different material, Osaka et al. [9] investigated the influence of an embedding an OF on the fatigue damage progress of FRP laminated plates. Kitade et al. [11] examined the influence of embedded OF on the shear strength between layers of FRP laminated plates. The influence was found to be small in both cases. Furthermore, Haga [12] tried to detect impact damage of FRP laminated plates using OFs.

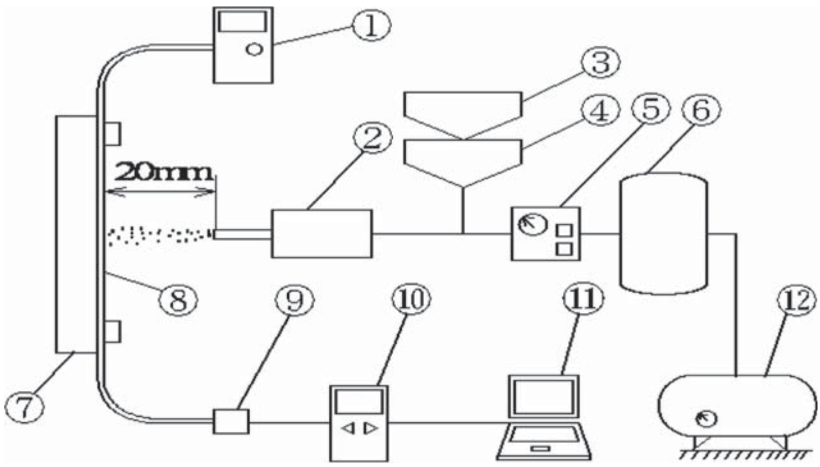
In this study, we propose an FRP erosion sensor that uses OFs. We investigate the erosion resistance and light attenuation of a coated OF alone, and examine the possibility of utilizing it as an erosion sensor. We investigate the erosion resistance of FRP with OFs embedded by conducting degree of wear detection tests based on the decrease in the amount of light, and examine the usefulness of this as a sensor. We also observe the traces of erosion wear after the test using a microscope to investigate the relation between the FRP and OF wear. Furthermore, we will investigate the changes in the mechanical characteristics of FRP due to embedding an OF in it to check whether or not OF is useful as a sensor.

2. Erosion tests on monofilament OFs

We conducted erosion tests on monofilament OFs to confirm the possibility of using an OF as a health-monitoring sensor for FRP erosion wear.

2.1. Erosion test device and outline of the test

The erosion test device is a slightly modified version of the FRP erosion device [7–8]. Figure 1 schematically diagrams the test device. Multiphase flow is produced by throwing particles fed by the microfeeder into the air compressed by the compressor and having them collide with an OF installed on the supporting stand of the test device. The pressure of the compressed air, which influences the impact speed of the particles, is adjusted by a pressure regulator. The inside diameter of the nozzle is 5.35 mm, the flow velocity is 127.4 m/s, and the impact distance is 20 mm. The particles for collision are alumina grinding material (WAF220, Showa Denko Co., Tokyo, Japan) with an average diameter of 5 μm and a particle supply weight of 2 g/min. LED light stabilized at a certain level by the light source (MODEL 370H, Hakuto Co., Tokyo, Japan; wavelength: 1310 nm) constantly flows in the OF. An optical power meter is connected to the other end of the OF to constantly measure the amount of light. When the OF suffers erosion wear due to collision of particles, the coating and cladding of the OF are damaged and the



① LED source	② Air gun	③ Hopper
④ Micro feeder	⑤ pressure regulator	⑥ Surge tank
⑦ Backing metal	⑧ Optical fiber	⑨ Connectors
⑩ Optical power meter	⑪ Computer	⑫ Compressor

Figure 1. Experiment apparatus for erosion test.

amount of light that flows in it changes; such changes are reflected in the values measured by the optical power meter. The tests were conducted in a constant temperature and humidity chamber (20 °C, 65%).

2.2. Test results and considerations

The OF used for the test (GI40/80PI, Totoku Electric Co., Tokyo, Japan) is intended for common communications and is composed of fused silica coated with polyimide resin with a core diameter of 40 μm, cladding diameter of 80 μm, and a polyimide resin coating thickness of 20 μm.

Figure 2 presents a typical measurement result. The horizontal axis represents wearing time and the vertical axis does the intensity of light as measured by the optical power meter. As depicted in the figure, the amount of light decreases immediately after 7 s.

Figure 3 depicts the surface of a worn OF as observed through a microscope. The OF lost its gloss over the entire length, after the polyimide coating was worn by alumina particles. The circled portion in the figure has been damaged particularly seriously, with the polyimide coating completely worn and the fused silica exposed. During the test, it could be confirmed with the naked eye that red LED light was leaking from the damaged point. In other words, the amount of light in Figure 2 decreased, because the polyimide coating and cladding layers were completely damaged and the internal LED light leaked out.

Here, we proposed this device as a sensor to detect wear of the OF based on the interruption of light propagation. A low-cost, large core diameter multimode OF and a wideband LED light source were used, so even minor damage to the cladding layer may cause a large loss of light.

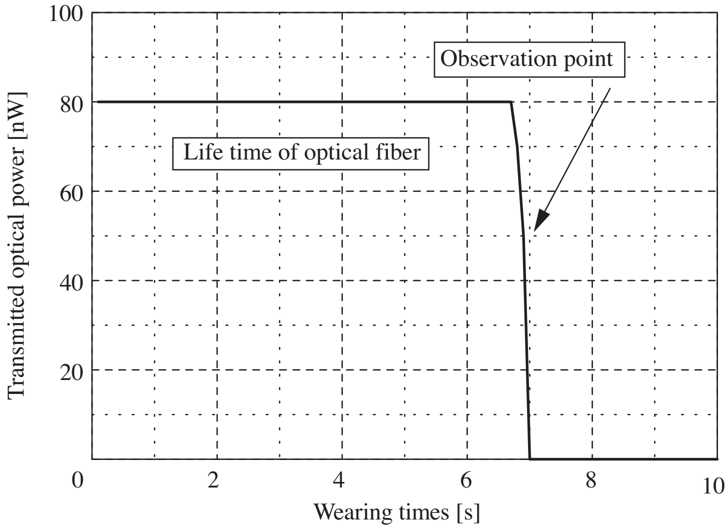


Figure 2. Relationship between transmitted optical power and wearing times.

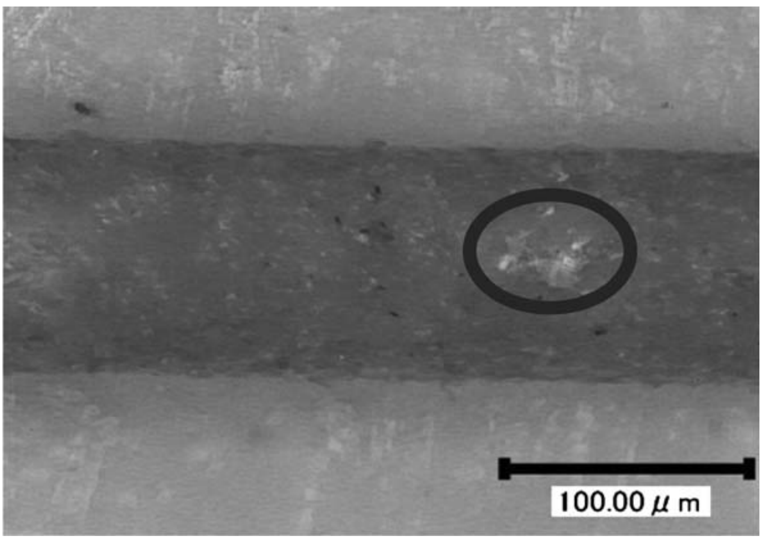


Figure 3. Enlarged image of OF wear point.

3. Erosion tests on FRP laminated plates with OFs embedded

FRP specimens with OFs embedded between layers were prepared and tested for erosion wear to check the possibility of detecting erosion.

3.1. Preparation of FRP specimens with OFs embedded

We prepared three types of FRP specimens with OFs embedded (types A, B, and C) using carbon fiber as the reinforcing fiber. For the specimens of type A (B), the OFs were arranged perpendicularly to (in parallel with) the reinforcing fibers using a carbon prepreg (Q-111E

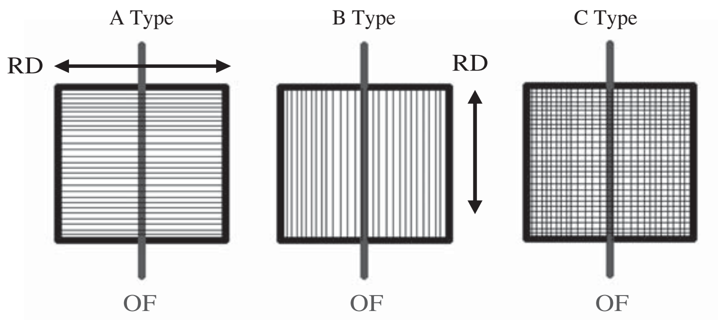


Figure 4. Test specimen pattern.

1940, Toho Tenax Co., Tokyo, Japan) as depicted in Figure 4. The specimens were molded with a hot press, and epoxy resin was used. The type C sample was hand layup molded using carbon cloth (CO6343, Toray Co., Tokyo, Japan). The resin used is unsaturated polyester (BQT158, Showa Denko Co., Tokyo, Japan).

All samples are composed of 10 layers with the thickness of each sample adjusted to 2 mm. One OF was embedded between every two layers.

3.2. Erosion detection test

Erosion detection tests were conducted using the device depicted in Figure 1. The test conditions and parameters are described in Section 2.1.

To measure the amount of light, a multiphase flow containing alumina particles was jetted from the nozzle to the subject FRP to induce erosion wear, as depicted in Figure 5. After the

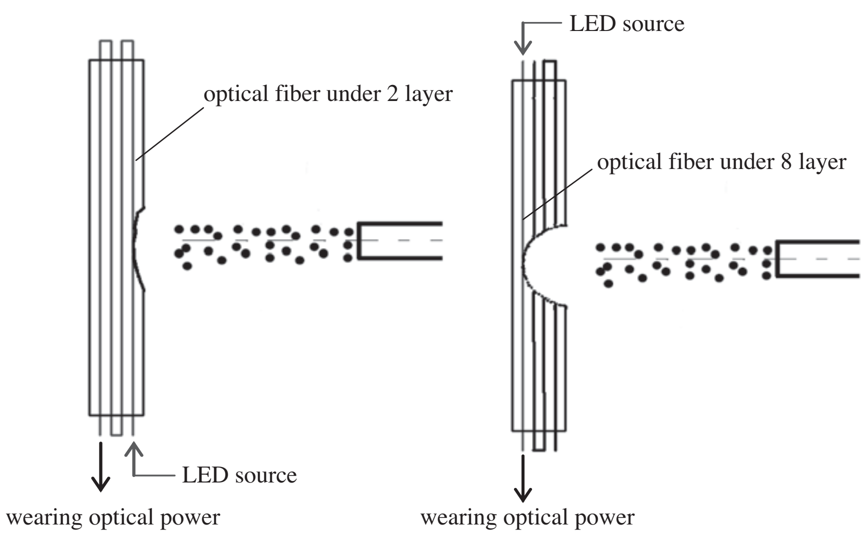


Figure 5. Diagram of experiment apparatus.

amount of light lost in the OF embedded two layers below the wear surface was confirmed, the test was stopped temporarily and the worn portion was observed through a microscope. The OF under two layers and the OF under four layers were cut and the OF embedded under four layers was connected to the LED light source. The erosion test was then restarted. The tests were repeated until the OF embedded under eight layers was worn.

Three specimens of each type (A, B, and C) were prepared, and the above test was conducted a total of nine times.

3.3. Results of erosion tests and consideration

Figure 6 depicts the worn portion as observed through a microscope after multiphase flow containing alumina particles was jetted against type A FRP to cause wear, when the decrease in the amount of light in the OF embedded two layers below the wear surface was confirmed. The exposed and worn OF can be detected. Because carbon fiber erodes more easily than resin, as reported in reference, [8] mainly resin is left around the OF.

Figure 7 depicts the relationship between the amount of light in the OFs embedded between each layer of the type A sample and the amount of jetted particles. The vertical axis represents the amount of light emitted by the LED light source and measured by the optical power meter in nanowatts. The horizontal axis represents the amount of particles jetted from the air gun (g). As depicted in the figure, the amount of light in the OF embedded under two layers measured by the optical power meter decreased rapidly when 8 g of particles were jetted, and light leaks due to damage to the OF. Also, the amounts of light in the OFs under four, six, and eight layers as measured by the optical power meter decreased rapidly when 16, 25, and 34 g of particles were jetted, respectively. The same phenomenon also occurs in type B and type C specimens, though the amount of particles varies slightly.

Since each sample consisted of 10 layers and sample thickness was adjusted to 2 mm, the positions of the OFs were estimated, and the relationships between these and the amount of

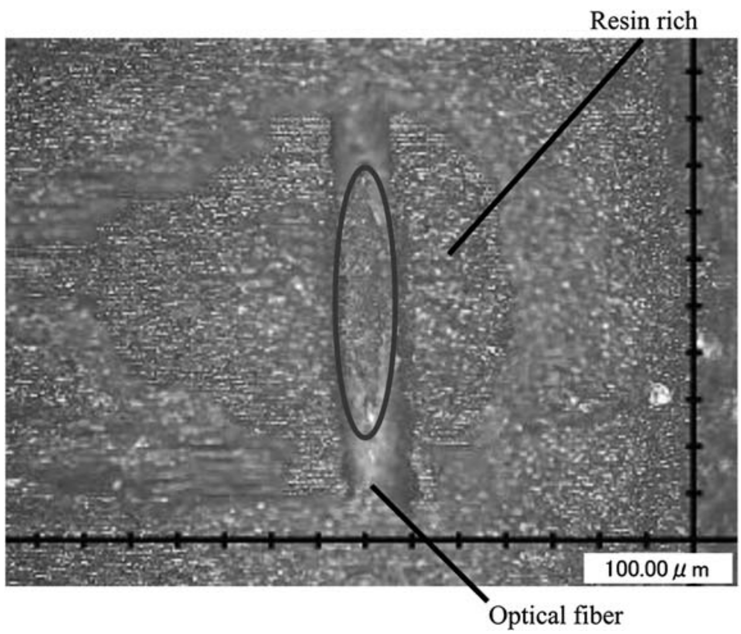


Figure 6. Enlarged image of type A specimen.

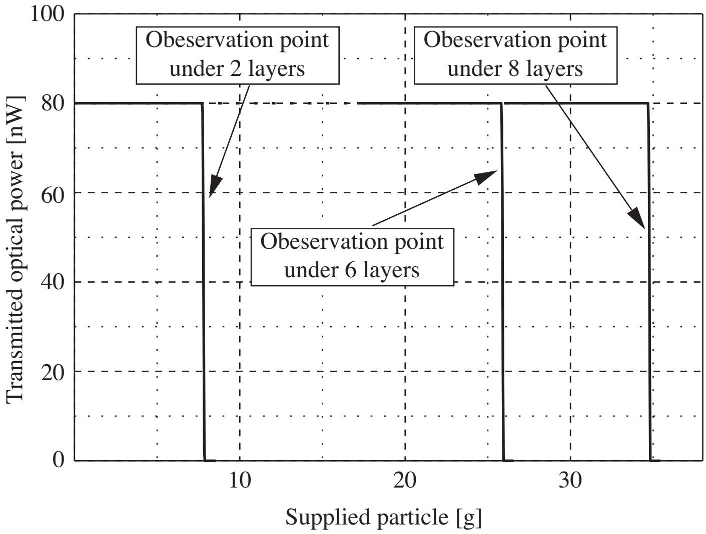


Figure 7. Relationship between the transmitted optical power and the supplied particles for type A specimen.

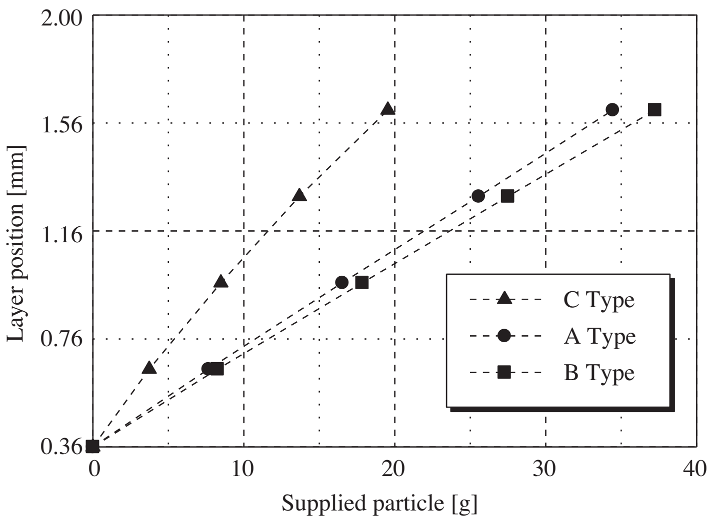


Figure 8. Relationship between layer positions of OF and supplied particle for types A–C specimens.

particles required for destroying each layer were obtained, as depicted in Figure 8. In each sample, the amount of worn FRP detected increases almost linearly in proportion to the amount of particles jetted (increase in wearing time). While the graph slope is almost equal for type A and type B samples, which are composed of unidirectional materials, it is larger in the type C specimen, which is composed of orthogonal plain-weave fabric. This study, however, emphasized investigating whether or not an OF is useful as an erosion detection sensor, so differences in erosion resistance among different types of fibers and different types of resins will not be examined here.

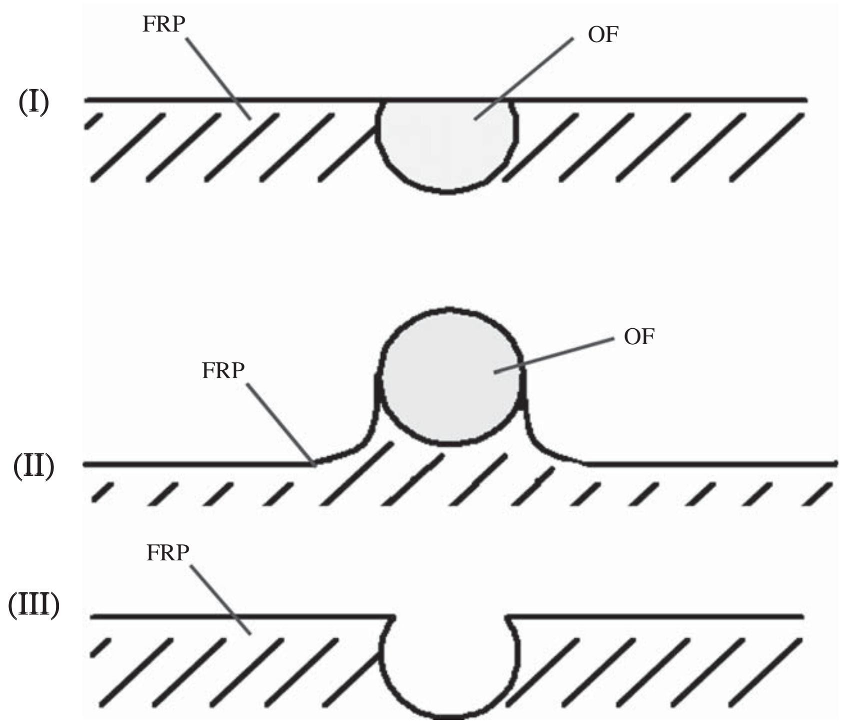


Figure 9. Schematic view of FRP with OF for erosion.

When subjected to erosion wear, FRP with OFs of different materials embedded is expected to exhibit the three of wear patterns depicted in Figure 9. First is the simultaneous wearing type, where the OF and FRP wear at the same rate and is ideal when using an OF as a health-monitoring sensor for FRP. Second is the OF residual type, and third is the OF loss type, where the erosion resistances of the OF and the FRP differ greatly from each other. A health-monitoring system for FRP that uses OFs may not be able to determine the degree of wear exactly.

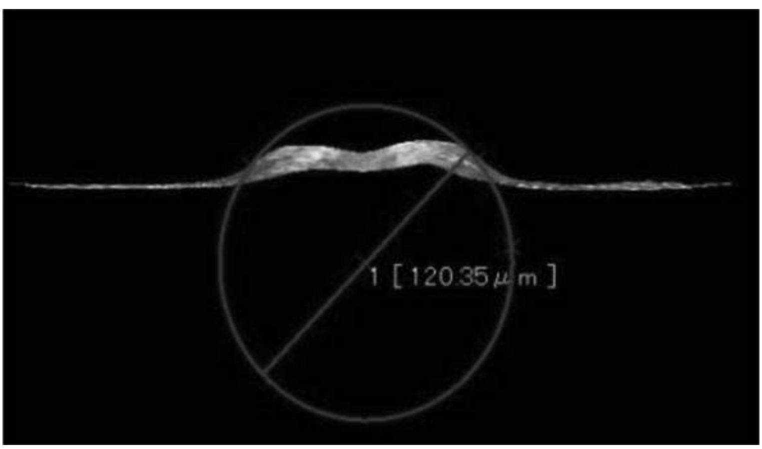


Figure 10. Cross-sectional image of type A specimen with added OF diameter circle.

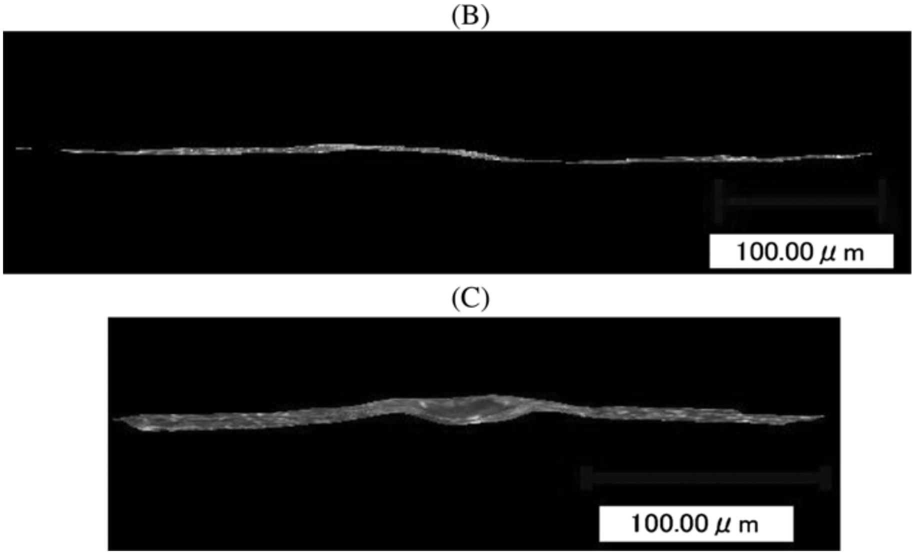


Figure 11. Cross-sectional image of type B and type C specimens.

Figure 10 is a microscope 2D-image (cross-sectional photo) of the FRP when a decrease in the amount of light was detected during the erosion test of sample A. The circle indicates the virtual diameter of the OF.

Wear progresses slightly faster in the FRP depicted in the figure. However, the difference in the progress of wear between OF and FRP is 10–20 μm or less and is effectively within the same layer, because the thickness of a layer of the specimens used in this test is 200 μm. This specimen can thus be classified as a "simultaneous wear" type. Figure 11 presents cross-sectional photos of type B and type C; all of the specimens can be classified as "simultaneous wear" types, as in the case of type A, though there are some differences.

The above results indicated that wear in CFRP can be accurately detected when an OF is used as a health-monitoring sensor for the CFRP.

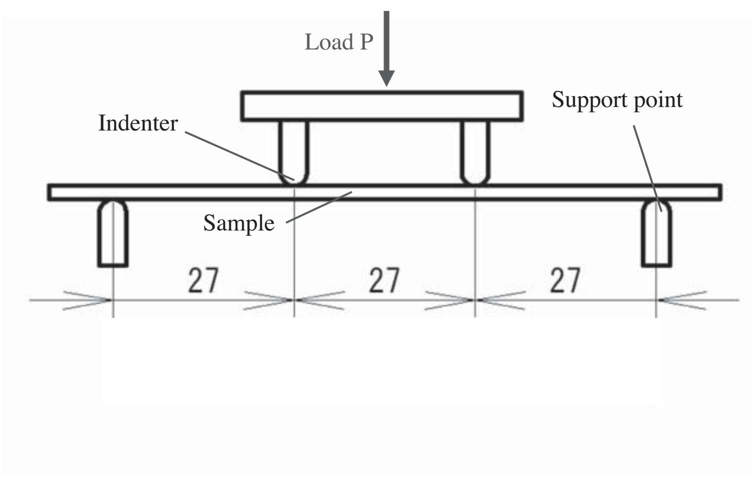


Figure 12. Diagram of bending test.

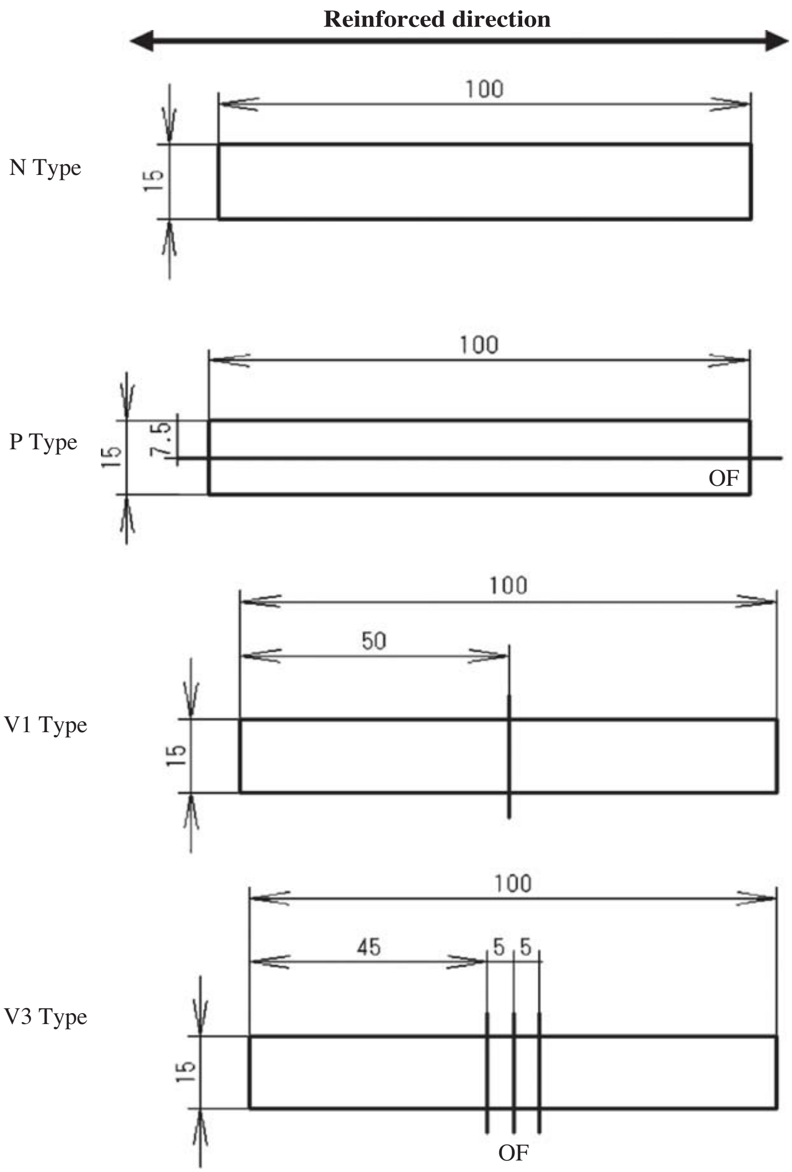


Figure 13. Embedding position of OF.

4. Mechanical characteristics of FRP laminated plates with OFs embedded

We will conduct four-point bending tests on FRP with OFs embedded to examine the changes in mechanical characteristics and the impact on actual products.

4.1. Test method and conditions

We will evaluate the mechanical characteristics of FRP laminated plates with OFs embedded by conducting four-point bending tests in accordance with JIS K7074. Since the thickness h of the specimens is 2 mm, the distance between indenters is set to 27 mm, and the distance

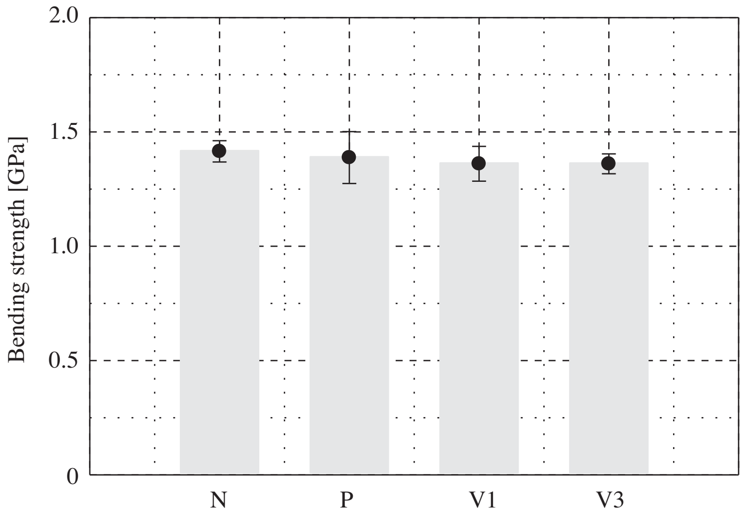


Figure 14. Relationship between bending fracture strength and number of OF.

between the support points to 81 mm. A diagram of the specimen mounting section is presented in Figure 12. The test rate is 6.89 mm/min.

The loading device was AUTOGRAPH AG-20KND (Shimazu Co., Kyoto, Japan).

4.2. *Specimens for the bending test*

To create specimens for the bending test, unidirectional laminated material was molded using carbon prepregs (Q-111E 1940, Toho Tenax Co., Tokyo, Japan) as in the case of the specimens for the erosion test. The specimen was 2 mm thick.

OFs (GI40/80PI, Totoku Electric Co., Tokyo, Japan) were embedded in four types as depicted in Figure 13. Type N has no OF. In type P, one OF is embedded in parallel with the carbon fiber at the center of the specimen. In type V1 (V3), one (three) OFs is (are) embedded perpendicular to the carbon fiber. The erosion wear of a material is measured over a wide area, so we do not believe that a fine net-like arrangement of OFs, as used for detection of cracks, is required. The maximum impact was investigated with OFs arranged as depicted in Figure 13. In all three types, OFs were embedded between the second and third layers, and the eighth and ninth layers.

Tests were conducted using five specimens under the same conditions.

4.3. *Test results and considerations*

The bending strength was calculated from the maximum load obtained from the four-point bending test. The calculation results are presented in Figure 14. Each type had almost the same bending strength of the type N specimen, where no OF is embedded, although there are some differences, indicating a small influence of the embedded OFs. This result differs from that in another paper [13] that stated that there is some influence, probably due to the small amount of OF used. Furthermore, the diameter of the OF and the presence or absence of coating may also have some influence, so we believe it necessary to examine all such influences in detail as a future task.

Enlarged images of specimens after breakage were observed through a microscope. There was no compression or shear destruction between layers from the position of the embedded OF indicating that the influence of the embedded OF is small.

5. Conclusion

Constant monitoring of FRP wear is essential for improving safety and reducing costs of FRP products. Therefore, we have proposed embedding OF in the FRP and using it as a health-monitoring sensor, and examined its feasibility.

We conducted erosion wear tests on the OF itself that is to be used as a sensor and found that the amount of light that propagates inside decreases rapidly when the coating or cladding layer in the OF is damaged. Furthermore, because this reaction occurs immediately, we found that OF can be an effective sensor.

We conducted erosion wear tests on CFRP laminated plates with embedded OFs. In the OF, a rapid decrease in the amount of light propagating inside was observed, as in the case of erosion wear tests on a monofilament OF. Furthermore, the time when the top layer of the OFs was destroyed and the time when the amount of light decreased rapidly were correlated, confirming that the FRP and OF are the “simultaneous wear” type. It was confirmed that erosion wear can be monitored regardless of the type of FRP (unidirectional or crossed materials), the direction of reinforcing fibers, or the kind of resin.

We conducted four-point bending tests on FRP laminated plates with embedded OFs and examined the changes in mechanical characteristics of such plates. No decrease in bending strength due to the embedding of OFs inside was detected.

From the above reasons, we believed that the proposed OF is useful as an erosion wear detection sensor for FRP and that an erosion health-monitoring system consisting of FRP with OFs embedded could be used effectively. Furthermore, the FRP crack health-monitoring system proposed by Takeda et al. [14] can be utilized as it is and can be used concurrently with this system. Thus, a large reduction in the system cost can be expected.

Acknowledgements

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