BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF POLYMER ENGINEERING

OPTICAL METHODS FOR HEALTH MONITORING OF COMPOSITE STRUCTURES

PHD THESIS BOOKLET

MADE BY:

GERGELY HEGEDŰS

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SUPERVISOR:

DR. TIBOR CZIGÁNY

PROFESSOR

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1. Introduction

The development of composite structures has been uninterrupted since they were first used; fiber-reinforced plastics are used in almost every part of our lives. If the components of a composite are selected carefully, it can be tailor-made and optimized for a particular purpose. Due to the large number of possibilities, composites are not made only in small sizes and small numbers; there are also large composite parts with considerable load-bearing capacity, and they can be mass-produced as well. For this reason, they are very common in the vehicle industry, too [8, 9]. The everyday use of such composites poses numerous challenges for engineers. As opposed to the homogeneous structure of metals, composites have a far more complex structure, which requires new methods for the calculation, structure optimization and manufacturing technology of parts—these methods are very different from those used with metals.

Also, composite structures behave differently from metal structures throughout their lifetime. In the complex structure of composites, the matrix and the reinforcement behave differently under load. Therefore, the health monitoring of composite structures is very important, which requires the development of new methods, especially simple non-destructive *in-situ* (during operation) health monitoring methods [7].

Most existing health monitoring procedures involve equipment independent of the part, but these procedures usually do not test the health of the part when it is built in or during operation. Built-in health monitoring systems, on the other hand, have a sensor integrated into the composite part and a possible defect is indicated by a change in the signal provided by the built-in sensor. Such built-in sensors can provide a signal continuously, making continuous health monitoring possible. In the case of fiber-reinforced composites, the electrical conductivity of carbon fibers, or the light-transmitting ability of glass fibers can be used for this purpose. With glass fibers, a change in the power of emitted light can indicate the health of the composite.

My goal was to lay the foundations for a cost-effective, non-destructive optical health monitoring technology which. I also aim to show deformation before catastrophic failure, because this can provide safety for the users.

2. Literature review, goal-setting

There are basically two kinds of methods to examine the health of composite structures. One possibility is testing with external equipment, during which the whole surface of the composite is tested, and this way, directly or indirectly, defects within the composite can be revealed. The other possibility is building sensors inside the composite structure and analyzing the signal provided by the sensors—the analysis can indicate stress, deformation and structural changes in the structure, even during operation. The two procedures can supplement each other.

With the use of optical sensors, the deformations, stresses and damage or defects resulting from these can be monitored throughout the whole lifetime of the composite structure (including lamination, curing, removing from the tool, assembly and normal operation). Another advantage of optical fibers is that they do not considerably impair the mechanical properties of the composite part. Their disadvantage is their relative complexity and narrow range of measurement. Another shortcoming is that information can only be obtained from the immediate vicinity of the fiber.

Based on the literature review, I think that among the commercially available optical health monitoring systems for composite structures, Fiber Bragg Grating (FBG) sensors are probably the most useful because this method has adequate sensitivity and resolution. For this reason, I think it is reasonable to conduct preliminary experiments with an FBG sensor and through this I can learn more about optical health monitoring equipment and the limits of application.

Although the FBG sensor is often used in the laboratory, it is not normally used in cost-sensitive industries, such as the vehicle industry, because it involves building in a relatively complex and expensive system. Based on the literature review, I think glass optical fibers used in telecommunication and the optical power meter used to characterize optical fiber networks are a more cost-effective solution for the health monitoring of polymer composite structures, although this has not been investigated by and research teams so far. Based on this, I attempt to develop an economical health monitoring system by building an optical fiber into the composite and monitoring the change in the attenuation of the fiber, and observe the stress concentration points of the composite structure. I will do it with an optical fiber built into the composite structure and an optical loss test set. If the optical fiber is built into stress concentration areas, the change in the attenuation of the fiber would enable the analysis of the deformation of the composite. This could be the basis of a cost-effective measurement method.

The disadvantage of fibers built into the composite is that they are several times thicker than the reinforcing fibers in the structure and so there is a resin-rich area near them, which damages the integrity of the structure and can negatively influence mechanical properties.

Although reinforcing fibers are different from optical fibers concerning their material, and manufacturing technology, there are publications that report that glass fiber bundles with the sizing removed can be made capable of transmitting light embedded in a resin. Sizing, however, not only keeps the fiber bundle together and protects the fibers during processing after manufacturing, but also usually improves fiber-matrix adhesion considerably, therefore its removal can impair the strength of the composite structure. I assumed that without removing the sizing, a selected fiber bundle could transmit light in a properly selected general-purpose matrix material (of lower refractive index). If a connection can be shown between the change of transmitted power and the mechanical condition of the continuous fiber-reinforced polymer composite structure, this can be a basis of a health-monitoring system that does not require the use of an external sensor because the reinforcement itself can work as a sensor without any change to the integrity of the composite structure. Such a use of reinforcement would result in a self-sensing multifunctional material, in which fibers performed both the function of reinforcement and sensor. I intend to prove the applicability of these theoretical possible procedures through experiments.

Based on the above, the goal of my PhD dissertation is:

- to prove that glass optical fiber and widely used equipment in telecommunications (optical loss test set, OTDR) can be used for the health monitoring of composite structures,
- to prove that the reinforcing fiber bundles in the composite can be used to monitor the health of the composite, and show its modes of failure.

3. Equipment and materials used in the experiments

In the case of each experiment it is true that loading was applied, and a signal processing unit measuring a parameter of transmitted light and a signal transmission unit (for connection) was used.

the light source was light of a wavelength of 1550 nm (AFL Telecommunications, OLS7 FTTH UCI and FlexScan, USA), and the power of emitted light under load was measured with an optical loss test set of a resolution of 0.01 dB (AFL Telecommunications, OPM5-4D and FLX 380 OTDR, USA). To connect optical fibers, I used a cleaver (Fujikura, CT-30, USA) and a fiber welder (Fujikura, FSM 12 S, USA).

In the reinforcement bundle tests, as a light source, I used blue, green, red and white LED light (Cree, XLamp, XP-C LEDs, USA), HeNe laser (Melles Griot, 25-LGP-193-230, UK), Nd:YAG laser (Suwtech, dpgc-2250, USA), and the light source of the optical loss test set for infrared tests (AFL Telecommunications, OLS7 FTTH UCI and OLS7-3, USA). To measure a selected parameter of transmitted light, I used a USB microscope camera (Bresser, Germany), optical power meter (Coherent, OP-2VIS, USA), a high-speed camera (Keyence, VW-600M, Japan) connected to a lens system (Keyence, VH-Z100UR, Japan), digital microscope (Keyence, VHX-6000, Japan), and a spectrometer (Ocean Optics, USB 4000, USA). For infrared tests, I used an optical loss test set (AFL Telecommunications, OPM4-4D and OPM5-4D, USA), a photodiode connected to an ammeter (Hamatsu, S1133, Japan), and a thermal imaging camera (FLIR A325sc, USA).

In some tests, I connected the fiber bundle of the specimen to the signal source and the signal processing unit with polymer optical fiber (outer diameter 1500±90 μm, core diameter 1470±90 μm, refractive index of the core 1.492, Tru Components, VD-1500, Germany) using optical couplers I developed for connection; I also used glass optical fibers (G.652.D monomodal, outer diameter 125 μm core diameter 9 μm, Corning, USA) for connection.

I loaded the specimen in a tensile testing machine (Zwick, BZ020/TN2S and BZ050/TH3A, Germany). I checked the deformation calculated from crosshead displacement with a video extensometer (Mercury Monet DIC, MCR050, Sobriety, the Czech Republic) and corrected it with the software of the equipment.

Materials and specimens used

The optical fiber in the experiments has a core diameter of 9 μm, and is more sensitive to deformation than other fibers. It has a perpendicular fiber end. When making the specimen, I put the optical fiber in a single-layer and a double-layer [0/90] glass fabric (300±5% g/m^2, RT 300 N, Kelteks, Croatia), and used unsaturated polyester resin (AROPOL M105 TB, Ashland S.p.A., Italy) as matrix material. I used hand layup. I added 1.5% initiator (PROMOX P200TX, PROMOX SRL, Italy) and cured the resin at room temperature for 24 hours.

For the reinforcement bundle tests, I used a boron-free E-CR fiber bundle (Advantex T30 R25H-1200 TEX roving, Owen's Corning, Belgium) with a refractive index of 1.56–1.57 and a density of 2.62 g/cm^3 according to the datasheet. When I tested the fiber bundle within the composites, I used an E-glass reinforcing glass fabric which had a refractive index of 1.56, a density of 2.54–2.60 g/cm^3. It was [0,90] plain weave (weft direction 400 tex; warp direction 300 tex). Its areal density was 320 g/m^2±6% (STR 014-320-125, Krosglass, Poland). The matrix was MR3012 epoxy resin (Ipox Chemicals, Germany) and the curing agent was MH3122 (Ipox Chemicals, Germany) in weight ratios of 100:25 (refractive index 1.505) and 100:40 (refractive index 1.520).

In order to detect any factors that may influence the results, I also tested the individual fiber bundle built into resin. My goal was to produce a multifunctional composite specimen in which an arbitrarily chosen fiber bundle of the continuous reinforcing glass fabric is used as sensor, therefore the selected fiber bundle is an organic part of the reinforcing structure, not an additional, separate element. For this reason, I guided two ends of an arbitrarily chosen fiber bundle of a layer of [0,90] weave reinforcing fabric out of the fabric, leaving the tested length of the bundle within the fabric. Then I connected the two ends to the optical coupler I developed. I then soaked the prepared fabric and optical coupler with resin by hand layup and cured it in a drying chamber at 70 °C for 4 hours. I added clamping tabs to the specimen or glued it to a composite sheet with AcraLock SA 10-05 BLK (USA) adhesive, depending on the type of test. I always polished the fiber bundle in the cord-end terminal (with polishing paper of 30 μm, 6 μm, 3 μm, 1 μm, and 0.2 μm fineness), to make the surface of the fibers smooth enough for the test.

4. Summary

The reinforcement in 95% of fiber-reinforced composites is glass fiber. Since 2010, production has been increasing continuously. A third of the amount is used by the vehicle industry. The use of composites in the vehicle industry requires the health monitoring of composite structural elements. In my literature review, I presented current health-monitoring methods and classified them as direct, indirect, built-in and built-in optical methods. My goal was to examine the health of composite structures with optical methods, therefore I presented built-in optical methods in more detail. These methods can measure microdeformations but are costly.

Thanks to the widespread use of optical fibers in telecommunication, they, and their accompanying equipment have become cost-effective and easily accessible. I managed to prove my assumption that the changed attenuation of a monomodal optical fiber built into polymer composite can indicate the elongation of the structure compared to its original, unloaded state, and this elongation can be classified into categories before the optical fiber breaks. I also proved that the location of deformations in polymer composite structures can be found with ODTR equipment (used for checking the coupling of optical fibers).

Building in optical fibers has a disadvantage: when the optical fiber is built in, a resin-rich area forms near the optical fiber, which disturbs the homogeneity of the composite part, impairs its mechanical properties and can be the starting point of failure. Although reinforcing glass fibers in a composite part are different from optical fibers in several respects, including material and manufacturing technology, they can be made capable of transmitting light in properly selected general-purpose matrix material, even without special preparation, as I proved with tests. I also proved with measurements that the optical properties of the fiber bundle can be characterized with attenuation. I proved that if an arbitrarily selected fiber bundle of a reinforcing glass fabric is illuminated and the emitted light power is measured, it provides information about the direction of the load, and elongation as a result of the load can be measured as well. I proved with tests that an illuminated fiber bundle can also indicate damage in the composite structure (fiber breaking, fiber-matrix delamination). I showed that the reinforcing glass fiber bundle can be used as an *in-situ* sensor, resulting in a multifunctional, self-sensing composite, and this way it is not necessary to build in an external health-monitoring sensor, which would affect the integrity of the structure.

5. Theses

Now I will present and summarize the results of the tests and their background. Based on these, I formulated my theses concisely.

I showed that the attenuation of a telecommunications glass optical fiber built into a composite is affected by the deformation of the composite. As the elongation of the composite increases, the attenuation of the optical fiber also increases. Using this phenomenon, and with a loss test set, I worked out a new method for the health monitoring of glass fiber-reinforced composite structures with a matrix of unsaturated polyester and with a built-in optical fiber. I showed that based on the change of attenuation of the glass optical fiber built into the composite, the deformation state of the elongated structure can be categorized: (1) good, (2) requires additional testing and (3) critical. I proved with tests that in the case of an optical fiber of given length, the maximum attenuation change corresponding to no more than 1% strain can be determined. In the case of higher attenuation, the composite structure needs additional testing for strain. Over 1 dB of attenuation change, the deformation of the composite structure is to be considered critical. The cause of attenuation change is that there is good adhesion between the optical fiber and the matrix, therefore when the composite part is stretched, the optical fiber is stretched, too, which reduces its light transmitting ability and therefore increases its attenuation. I proved my claim using G.652.D monomodal glass optical fiber embedded in a matrix of unsaturated polyester, and an optical loss test set. I formulated the following thesis:

Thesis 1

The deformation state of composites can be classified as adequate, requires additional testing or critical, with the use of a built-in monomodal glass optical fiber and an optical loss test set, used in telecommunications [2, 7, 11].

I showed that in a composite of epoxy resin (with a refractive index lower than that of glass fiber) and general reinforcing glass fiber bundles, the fiber bundle can transmit light. Similarly to optical fibers, a glass fiber bundle can be characterized with its attenuation at a given temperature, wavelength of light and in a given resin system. Attenuation is independent of the length of the fiber bundle or the quality of coupling the light. It can be calculated with the following formula:

$$\alpha_{(\lambda, T)} = 10/L * \log_{10} (P_2/P_1)$$

where $\alpha_{(\lambda, T)}$ [dB/m] is attenuation (at a given wavelength λ and temperature T), P_2 [W] is the light power exiting the fiber bundle, measured along the whole length of the bundle, P_1 [W] is the emitted light power measured on the fiber bundle cut shorter and L [m] is the difference between the whole length of the bundle and the length of the bundle that was cut shorter.

I showed that the attenuation of the fiber bundle is considerably different at different wavelengths. As opposed to optical fibers, the attenuation of fiber bundles is lowest (~0.14 dB/mm) when the wavelength of illumination is 542 nm (green light). In the infrared range attenuation is so high that equipment used to test optical networks (operating in the IR range) cannot be used.

I proved my claim tests by testing an E-CR glass fiber bundle embedded in MR3012:MH3122 epoxy resin systems. The resin systems were 100:40 wt% with a refractive index of 1.520, and 100:25 wt% with a refractive index of 1.560. I performed measurements in the wavelength range of 450–720 nm, and at 1310 nm, 1490 nm, 1550 nm and 1625 nm. Based on the tests, I formulated the following thesis:

Thesis 2

A glass fiber bundle used for reinforcing polymer composites can be made capable of transmitting light if embedded in a general-purpose resin of lower refractive index, even without special preparation (without removing its sizing). This property can be characterized at a given wavelength and temperature with the attenuation of the fiber bundle [1, 4, 6].

I developed a procedure and the necessary equipment with which the ends of an arbitrarily chosen fiber bundle of a reinforcing glass fabric can be clamped in an optical connector and polished to optical quality. With the optical connectors, the ends of the fiber bundle can be connected directly or through an optical fiber the light source, or the signal processing unit. This way, the elementary fibers of the fiber bundle can be illuminated and the power of light emitted by the elementary fibers can be measured. For this, monochrome illumination around 542 nm is recommended, as well as a polymer optical cable of 1.5 mm outer diameter and an optical power meter. I proved with tests that with this procedure, the interfering effect of direct light coming from the light source can be eliminated and the power of emitted light is only influenced by the light transmitted by the illuminated elementary fibers. This procedure enables the illumination of an arbitrarily chosen fiber bundle of the reinforcing fabric of the composite, thus making the fiber bundle a sensor, and the composite becomes a multifunctional, self-sensing composite. I proved my claim by testing an arbitrarily chosen fiber bundle of a glass fabric embedded in a MR3012:MH3122 100:40 wt% epoxy resin system, and formulated the following technology thesis:

Thesis 3

Light can be coupled to an arbitrarily chosen fiber bundle of a reinforcing glass fabric of polymer composites, and the power of light emitted by the elementary fibers can be measured with the following method:

- **the two ends of the selected continuous fiber bundle have to be guided out of the glass fabric in such a way that the section to be tested remains in the fabric,**
- **the two ends have to be positioned within an optical connector of given diameter for coupling the light from the source and to the signal processing unit in such a way that the axis of the fiber bundle is at an angle (a cord-end terminal can also be used as an optical connector),**
- **the resin-soaked end of the fiber bundle within the connector has to be polished to optical quality,**
- **the two polymer optical fibers have to be fastened to the light source and the connector of the fiber bundle, and the power meter and the connector securely; the polymer optical fibers have to have a larger core diameter than that of the inner diameter of the connector, and their ends also need to be polished [1, 3-5, 12, 13].**

Publications report that when an illuminated roving in a matrix is loaded, the power of light emitted by the fiber bundle decreased permanently. Researchers explained this with damage to the fiber bundle and defects appearing in its vicinity. I proved with measurements that the power of light emitted by an arbitrarily chosen illuminated fiber bundle of the reinforcing glass fabric changes even when the load does not cause damage to the composite, and after the load ceases, the power of emitted light is restored to its original level, before loading. In this case, the change in emitted light power is not caused by damage to the elementary fibers and their environment (breaking, delamination), but because loading causes intact fibers to change the amount of light they transmit to the end of the fiber bundle. This is because much light can be coupled out of the illuminated fiber bundle where other fiber bundles cross it. If the compressive force between the crossing fiber bundles increases (e.g. tensile force or compression perpendicular to the axes of the fibers), and so their distance decreases, the power of light coupled out at the crossing bundles increases, which leads to a decrease in the light power at the end of the fiber bundle. On the other hand, if the crossing fiber bundles get further from each other (in the case of compression parallel to the axis of the bundles), less light can be coupled out and transmitted light power increases.

I proved my claim by testing an arbitrarily chosen fiber bundle of a reinforcing glass fabric embedded in a MR3012:MH3122 100:40 wt% epoxy resin system, and formulated the following thesis:

Thesis 4

Measuring the power of light emitted by an arbitrarily chosen and illuminated fiber bundle of a reinforcing glass fabric of a composite can indicate deformation in a composite that does not damage the composite. This is because the distance of crossing fiber bundles in the reinforcing fabric changes, which changes the amount of light coupled out at the fiber bundle junctions, and therefore the power of light emitted by the fiber bundle at its end [3, 4].

I proved with measurements that an arbitrarily chosen fiber bundle of the glass fabric can not only indicate deformation but can also be used for the analysis of damage to the composite. If the illuminated fiber bundle of the composite structure breaks and light exits the elementary fibers at that location, the power of light emitted at the end of the fiber bundle decreases to zero. When the illuminated fiber bundle only partly breaks, the power of emitted light decreases permanently (although in the case of load causing failure, the elementary fibers of the fiber bundle break in a fraction of a second). In the case of partial break, the microscopy images of the end of the fiber bundle clearly show elementary fiber ends that have stopped shining as the fiber broke.

I showed that a load causing delamination causes the power of light emitted at the end of the fiber bundle to decrease permanently. This is because micro-level and macro-level damage as a result of the load cause the amount of light coupled out of the illuminated fiber bundle to increase; this, in turn, decreases the power of light emitted at the end of the fiber bundle to decrease permanently. As a result of fiber-matrix delamination, the elementary fibers do not stop shining but the intensity of light is lower than in the case of the original, homogeneous composite. Some fibers shine with more intensity and some with less intensity, which indicates that the matrix was torn off the fiber bundle or the layers separated. I proved my claim by testing an arbitrarily chosen fiber bundle of a single-layer reinforcing glass fabric embedded in a MR3012:MH3122 100:40 wt% epoxy resin system, and formulated the following thesis:

Thesis 5

An arbitrarily chosen fiber bundle of the reinforcing glass fabric of a polymer composite structure can be used for damage analysis, as the micro-level and macro-level defects caused by loading decrease the power of light emitted at the end of the illuminated fiber bundle irreversibly. This phenomenon can be used to indicate fiber breaking and fiber-matrix delamination if the ends of illuminated fibers are also examined with a microscope [5, 6, 13].

6. My own publications

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