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Analysis of the applicability of optical fibers as sensors for the structural health monitoring of polymer composites: the relationship between attenuation and the deformation of the fiber

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ABSTRACT

The goal of our research is to prove that the single-mode optical glass fiber used in telecommunications and the optical loss test set used for the characterization of telecommunication networks is suitable for the structural health monitoring of polymer composites. We built optical fibers into specimens and analyzed the relationship between attenuation of the fiber and the deformation of the specimen. Based on our results, we worked out the basics of a cost-effective measurement method. In the case of general-purpose polymer composite products, where the knowledge of structural health is important but not critical but the more complex embedded sensor systems would be too expensive, the method can show the strain state of the structure unambiguously (within categories). The method can be used in practice and evaluated easily and can show whether a thorough structural examination is necessary.

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1. Introduction

Nowadays optical fibers are widely used in telecommunications. Light cannot exit the optical fiber, it can transfer information even across continents. Due to the large amounts of optical fibers produced, they are easily available. The quality or state of couplings of optical networks in telecommunications are most often tested with the optical loss test set, since attenuation is the most commonly measured characteristic when optical systems are installed, operated and maintained. The optical loss test set consists of a fixed wavelength (most commonly 1310 or 1550 nm) light source, and an attenuation meter connected to the other end of the network. Attenuation (a) is the ratio in decibels of the input power (P_{in}) and the output power (P_{out}) [1] (1):

$$a = 10\ lg(P_{in}/P_{out}) \tag{1}$$

Attenuation shows a reduction in the light transfer ability of the optical network, in other words, its "quality". The attenuation of the fibers is in the range of a few tenth of a dB/km, depending on the wavelength (e.g.: fused silica glass –SiO_2– at 1310 nm ~0.30 dB/km, at 1550 nm ~0.16 dB/km [2]). Where fibers are joined by welding, attenuation is −0.01–0.02 dB (~2–5% reduction in power) depending on the quality of welding, while in the case of mechanical couplers, attenuation is ~0.50 dB (~10% reduction in power).

The diameter of generally used glass optical fibers is 125 μm, with a core of about 10 μm in diameter, which has a higher refractive index (it is optically denser) than the cladding around it. The glass fiber is protected mechanically by a layer of coating of ~60 μm thickness and another outer protective layer. The advantage of optical glass fibers is that radio frequency (RF) waves do not disturb their operation, therefore the fiber do not need radio frequency shielding, and glass fibers do not emit RF waves either, therefore they do not cause RFI (Radio Frequency Interference) [3–5]. They are highly resistant to corrosion and heat [6]. Their other advantages are their low diameter, low mass and high flexibility. These advantageous properties make glass fibers suitable to use as sensors. Optical fibers can be used as sensors in two ways: if the fiber only transfers the information between the sensing unit and the processing unit, it is called an extrinsic sensor, while if the fiber is both the sensor and the medium transferring the signal, it is called an intrinsic sensor. A characteristic of the light travelling in the optical fiber of optical sensors (e.g. intensity, spectrum) changes as a result of external influences (e.g. deformation) [7]. A common feature of different types of optical sensors [8,9] is that the signal

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processing device is a separate unit and can be detached from the optical fiber.

Optical fibers can be built into polymer matrix composites easily due to its advantageous properties, and it doesn't affect significantly the overall mechanical performance of the composites [10,11]. The development of polymer matrix composites has been uninterrupted to the present day [12], fiber-reinforced composites are used nearly everywhere (e.g.: sports equipment, medical implants, rotor blades of windmills, the body of airplanes, ships, cars, trucks and buses). As opposed to the far more homogeneous structure of metals, composites have a matrix and reinforcing fibers, which behave differently under loads [13,14]. For this reason information about the health of composite structures is very important, especially in the case of parts related to personal safety. The spread of composites brings new methods of checking structural health, and requires the development of simple, non-destructive, in-situ structural health monitoring methods. There are numerous methods for the analysis of the structural health of polymer matrix composite structures [15], of which optical sensor methods are attracting more and more attention from researchers. The price of optical structural health analysis systems makes the use of the technology uneconomical in the case of non-special, general use products. The cost of these systems is far greater, than simple devices, such as the optical loss test set and optical fiber used to test optical networks.

Several researchers have examined the applicability of optical fibers for the structural health monitoring of polymer matrix composite structures. Crane et al. [16] laminated optical glass fibers into glass fiber reinforced epoxy matrix composite specimens. Crossing each other, the fibers formed a square grid. Each fiber was illuminated with visible light separately, and the location of damage was identified with the help of the light exiting the fibers. The panel did not emit light if the magnitude of the damage was high enough to break the embedded optical fiber. This principle was used by Glossop et al. [17], and LeBlanc and Measures [18] in their research. The disadvantage of the system is that it only provides information about the damage if it was big enough to cause at least one optical fiber to break. In this case the method can locate the damage but does not provide information about its magnitude. Several researchers have examined how attenuation changes as a result of deformation. They showed that the micro-level and macro-level bending of optical fibers causes a change in attenuation, in the light power transferred by the optical fiber [19–21]. Takeda [22] analyzed how the change in attenuation can be applied to analyze the health of composite parts by analyzing the deformation of glass fiber reinforced bismaleimide matrix composites with the help of polymer optical fibers embedded into the composites. He used a LED light source of a wavelength of 660 nm and measured the transmitted light power with a photo detector. The power changed proportionally to the deformation under load. He found that ~1% deformation caused a change of 0.5–2% in the transmitted light power depending on the layer structure of the reinforcement (this means an attenuation change of ~0.02–0.09 dB). He found the method suitable to observe not only deformation but crack propagation as well.

Based on the literature, it can be stated that the transmission properties of the fiber largely depend on the material of the fiber (glass or polymer). Generally available polymer optical fibers absorb infrared radiation to a great degree, therefore the optical loss test set generally used in telecommunications cannot be used in the case of polymer fibers because it uses infrared light (1310 and 1550 nm).

We examined the applicability of optical glass fibers widely used in telecommunications for the structural health monitoring of general polymer composite materials. Our goal is to assess the deformation of the structure based on a changed characteristic of the light transmitted by the optical fiber embedded into the polymer composite, therefore we examined the change in the attenuation of the fiber while it was loaded. Our goal is to apply the optical loss test set generally used in telecommunications, to show large-scale deformation in critical points of the composite part before a critical state which causes failure, and develop a simple and cost-effective test method. We also wish to develop structural health monitoring system with which the health of structural elements can be classified into given categories over their whole life cycle (during operation, during maintenance, in the case of damage, in the case of breakdown).

2. Materials and methods

The experiments served to prove that the deformation of optical glass fibers causes a change in the attenuation of the optical fiber both when it is alone and when it is embedded into a composite specimen. From this change we can estimate the state of the environment of the fiber. The analysis of the changed attenuation of the fiber can be the basis of a new structural health monitoring procedure, therefore we conducted several measurement series to determine the best way to build the optical fiber into the composite and which factors influence the measured attenuation values.

2.1. Materials used, manufacturing the specimens

The type of optical fiber used in the experiments is G.652.D. It is a single-mode glass fiber with a diameter of 125 microns (Corning, USA). Its core has a diameter of 9 microns, it is sensitive to deformation and the fiber end is perpendicular. We examined the optical fiber alone, and embedded into a glass fiber reinforced composite specimen. When the optical fiber was examined alone, the coating, which protects it mechanically, was not removed because the fiber broke very easily as a result of the slightest force. When the fiber was embedded into a composite, the coating was removed because the surrounding matrix protected the fiber mechanically and we tried to preserve the continuity of the composite structure by making the embedded fiber as thin as possible. When making the specimens by hand lamination, we placed the optical fiber between two layers of [0/90] woven glass fiber fabrics (plain weave, $300 \pm 5\%$ g/m^2, RT 300 N, Kelteks, Croatia) equidistant from the longitudinal edges, and used unsaturated polyester resin as matrix (AROPOL M105 TB, Ashland S.p.A., Italy). We also added an initiator (PROMOX P200TX, PROMOX SRL, Italy) to the resin. The amount of the initiator was 1.5% of the mass of the resin. The thickness of the specimens were 1.6 ± 0.2 mm.

2.2. Equipment and measurement methods

We used a cleaver (Fujikura, CT-30, USA) and a fiber welder (Fujikura, FSM 12 S, USA) to connect fibers. At one end an infrared light source of 1550 nm provided light (AFL Telecommunications, OLS7 FTTH UCI, USA), and on the other hand an attenuation meter with a resolution of 0.01 dB (AFL Telecommunications, OPM5-4D, USA) measures the change of intensity of the emitted light. We deformed the optical fiber and the composite specimens in a tensile tester (Zwick, BZ050/TH3A, Germany). In the tensile tests crosshead speed was 0.4 mm/min, while in the compression tests, maximum force was 5000 N, loading speed was 10 N/s, and the compressed area was 10×25 mm.

3. Results and discussion

For each test, 6 specimens were made. The tests can be found in Table 1. The location where the fiber exits the specimen of

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