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MONITORING OF WATER ABSORPTION AND ITS EFFECTS ON MECHANICAL PERFORMANCE OF THICK GFRP STRUCTURES BY INTEGRATED SMART SENSORS

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ABSTRACT

In many applications, such as offshore, marine, or wind energy industry, the aging of composites is an important issue, as the structures are exposed to severe environmental conditions. Typically, moisture gradients evolve from the surfaces in contact with moisture or water into the material. The underlying diffusion process depends on the ambient temperature and the specific material selection (e.g. the chemical structure of the polymeric resins). In this context, fiber reinforced polymers (FRP) are often assumed to exhibit approximately Fickian diffusion behavior. Long term predictions are based on isothermal aging tests, which are usually accelerated by full immersion of coupons in water with higher temperatures than the service temperature [1]. Design parameters are derived from small-scale coupon tests with saturated specimens. However, for FRP structures of several millimeter thickness in real operating conditions, it takes years until the laminates are fully saturated. As it is well known that especially glass fiber reinforced polymers (GFRP) can experience significant reductions in mechanical properties due to moisture absorption, a reliable determination of the current moisture condition at various points in the structures is beneficial. Precise knowledge about the effects of moisture on the mechanical behavior of the composites can, furthermore, extend the service life and prevent failure. Consequently, a method for monitoring local moisture absorption in thick GFRP laminates is presented in this work. Therefore, an integrated sensor system based on single carbon fiber (CF) bundles and impedance measurements as developed by Buggisch et al. [2] was evolved. Additionally, the mechanical effects of single-sided moisture absorption (only through thickness) are evaluated using four-point bending (FPB) and interlaminar shear strength (ILSS) tests.

GFRP laminates with a $[\pm45_2/90_2/0_3/90_2/0_3/90_2/0_2]_s$ lay-up, a total thickness of 9.2 mm, and a fiber volume content of 46.6 % were manufactured in a resin transfer molding process using Hexion EPIKOTE™ Resin MGS™RIMR 135 and EPIKURE™ Curing Agent MGS™ RIMH 137 as epoxy system. In the laminates, simple CF bundles (FT300B 6000-50B, Toray Carbon Fibres Europe) serve as integrated sensors by replacing single GF bundles of the 90° layers. To perform impedance measurements during hygrothermal aging the laminates were contacted. Therefore, 1.2 mm holes were drilled in the GFRP laminates at the positions of the CF bundles, filled with Acheson 1415 silver conductive paint, and one-pin screw clamps were attached and fixed in place using epoxy resin. The one-sided hygrothermal aging process was realized by gluing a glass basin onto each laminate quarter using silicon seal (Knauf), filling it with distilled water, and sealing it with PE-foil. For environmental aging, a climate chamber CTC 256 (Memmert) was used at 50°C and 40% rel. humidity.

Impedance measurements during aging were performed using a measurement board consisting of an impedance measurement board Digilent PmodIATM, a Wemos D1 mini microcontroller (MC) for wireless transfer of measurement data, an 8-channel multiplexer Nexperia 74HC4051, and a resistance used for calibration. A constant voltage source 3234 (Statron) was supplying a constant voltage of 5 V. A frequency of 10 kHz was used for all measurements as the best sensitivity was achieved for this frequency. The test and measurement setup is shown in Figure 1. While the impedance measurement for the water absorption was running permanently, after 125 days FPB (DIN EN ISO 14125) and ILSS (ASTM D2344) test specimens were prepared from some laminates. In case of the FPB tests both options, the water-affected side on the top or the bottom, were tested.

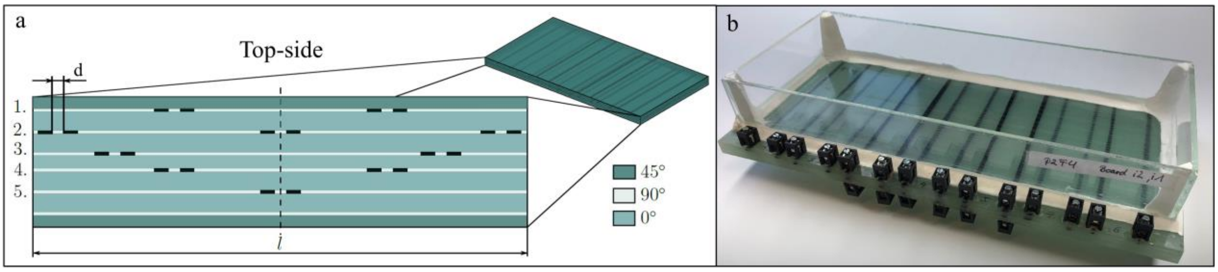

Figure 1: Schematic representation of sensor bundle and GFRP layout (a) and prepared laminate along with pin screw clamps and water bath allowing only diffusion in the thickness direction (b).

The water absorption leads to a change in the dielectric properties of the GFRP, which results in a clear increase of the phase angle and a simultaneous amplitude decrease of the electrical impedance. This is shown for the five sensor layers of a representative laminate in Figure 2. For the top-level sensor (0.7 mm below the water surface), a change in phase angle of more than 3 % and a reduction in amplitude of about 8 % can be seen. While the sensor in the second level just slightly started to change the measured impedance, the sensors in all other levels show almost no change in the same period. Thus, it can be assumed that the water penetrated the GFRP to a depth of about or less than 2.3 mm (position of the second sensor layer). The mechanical performance of the aged laminates reduced significantly, although the water penetrated less than a quarter deep into the material and was far from saturated even in the humid areas. The FPB-strength decreased by 6-8 % (compression resp. tension side) and the interlaminar shear strength (ILSS) by up to 12 %.

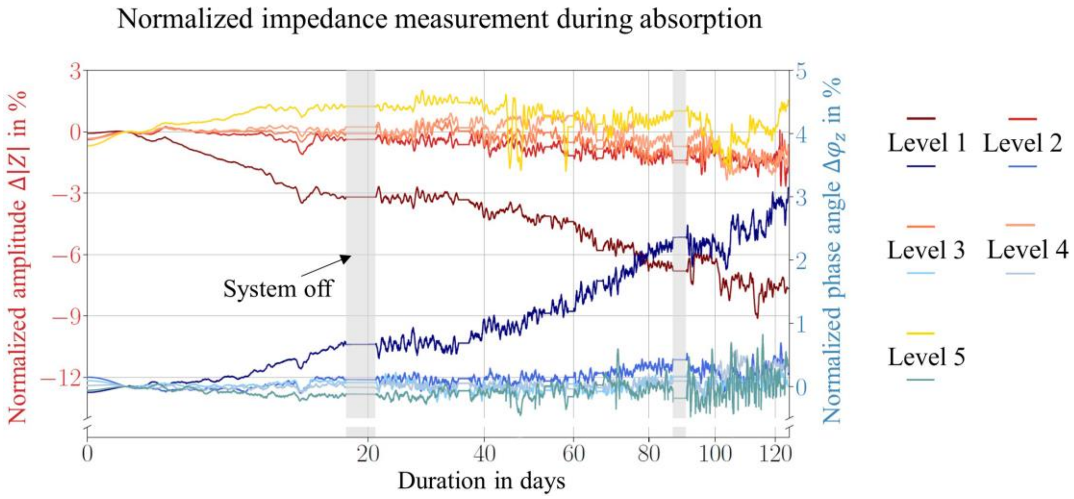

Figure 2: Normalized amplitude and phase angle developments during water absorption of 125 days.

The specimen failure was initiated by delaminations near the outer 90° layers (tension and compression side). For aged specimens, the delaminations started earlier and favored on the wet side compared to the dry reference. In summary, the work shows the high potential of the developed sensor system for in-situ measurement of moisture distribution in thick composite structures and illustrates how dramatically even local moisture impact can affect mechanical properties.

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