MULTIFUNCTIONAL FIBER-REINFORCED PLASTICS WITH INTEGRATED TEXTILE-BASED SENSOR AND ACTUATOR NETWORKS

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Abstract

The structural health monitoring of endless fiber-reinforced plastics (FRPs), as well as the monitoring of textile membranes for civil engineering applications, plays a crucial role for the advancement of lightweight design approaches. It is only through structurally integrated condition monitoring systems, that damages can be detected early on, thus enabling local repairs before complete structural failure occurs. The performance can furthermore be considerably extended or increased by an additional functionalization, e. g. textile-processible and structurally integrated sensors and actuators in the same FRP component.

1. Introduction

For the continuous and non-destructive structural health monitoring of conventional FRPs and for the kinematics monitoring of actuatory FRPs realized by integrated shape memory alloy (SMA) metal wires, a one-step integration of one- or two-dimensional sensor - based on piezo-resistive PAN carbon filament yarns (CFY) or different legated metal wires respectively - in textile reinforced structures can be realized by different textile-technological manufacturing processes. For both applications, the approach consists of the textile integration of electro-conductive CFY or SMA wires using textile techniques such as multi-axial weaving with Open Reed Weave Technology (ORW) and multi-axial warp knitting. A two-dimensional alignment of the sensor and/or actuator pattern is realized by special process-specific manipulation devices such as stitch-weaving or warp yarn shogging devices respectively.

Through the integration of CFY-based sensors and sensor networks in-situ monitoring of mechanical loading conditions as well as structural degradation processes in inaccessible areas within immediate distance of the load-bearing layers of the further composite material component can be realized. In the framework of the current research, the focus is directed toward the achievable sensor characteristics especially with regard to the sensitivity and the long-term stability as well as to the qualitative and especially quantitative detection of mechanic loads. The sensor characteristics can be adapted by way of structural embedding of the CFY and their tensioning during textile processing for alignment purposes. The objectives of previous investigations at the ITM in the context of the basic research project CH174/17-2 are the adaption of machines and procedures for the integration of textile-based CFY sensors into textile reinforcements for FRP applications. Thereby, the potential and the reachable characteristic values of CFY-based strain sensors integrated in glass fiber reinforced polypropylene FRPs in comparison to conventional metal foil strain gauges have been shown in [1, 2]. Within the context of the research project IGF 17529BR/1, the technological integration feasibilities of CFY-based sensor networks in textile reinforcements using ORW weaving or multi-axial warp knitting machines are shown by means of two functional FRP models: a rotor blade for small wind energy plant and a gas collector membrane cover for a fermentation plant respectively.

In the framework of the research project CH174/23-1 on FRPs with actuatory capabilities, new adaptive thermoset FRPs are being developed based on reinforced semi-finished products with structurally integrated SMA wires. The adhesion behavior between actuator and surrounding matrix material can be tailored by special yarn constructions and the weave construction of the reinforcement fabric using the investigated textile processes. A strong adhesion of the SMA actuator is required only in the load transmission areas of the reinforcement structure, whereas a weak bonding between actuator and matrix is essential in the deformation zones reducing risks of delamination processes and therefore ensure the long-term stability and the high adaption potential of the FRP. The evaluation of the deformation properties and the in-situ monitoring capability underlines the innovative potential of the developed multifunctional FRP [3, 4].

2. Novel approaches for integral sensor manufacturing during the production of textile reinforcements for FRP and membrane applications

2.1 Multi-axial warp knitting technology combined with multiple warp yarn shogging

During the fabric formation of the textile reinforcement structure of a rotor blade for a small wind energy plant, the two-dimensionally and load-adaptedly placed sensor layouts are knitted with the structure of the multi-axial non-crimp fabric on a MALIMO 14024 multi-axial warp-knitting machine with a weft insertion system for progressively adjustable storage angles between -45° and +45° and 90° as well as a patented warp yarn shogging device (Figure 01, 02). The sensor layouts realizable with this technology are shown in Figure 03. Using the two installed warp yarn shogging devices, two yarn sheets of eight CF yarn systems each can be stored on the basic non-crimp fabric independently and at freely adjustable angles between -90° and +90° to the production direction. Due to the specific crossing of CF weft and warp yarn systems, two-dimensional sensor structures which can also be adapted to the directional alignment and orientation of the reinforcement yarn system, become feasible. This allows an application-oriented and load-adapted single-step production of textile reinforcement semi-finished products with integrated sensors. Additional personnel expenditures, as in the superficial application of adequate conventional strain gages, can be omitted. Only a finalizing contacting of the sensor elements in the textile fabric is required, which is relatively effortless given thoughtful tracking of the leads made from electrically conductive yarn products to the edges of the contour of the later FRP component.

Apart from elongation and bending sensor arrays for mechanical load monitoring inside the rotor blade (cf. Figure 04), sensor layouts are also realized particularly in the areas of the rotor blade front and back edges, which will allow monitoring of bond seams between top and bottom shells of the blade as well as an early measuring detection of delaminations or detachments, based on capacitive measuring approaches.

Figure 01. MALIMO® 14024 multi-axial warp-knitting machine with warp yarn shogging device (Pat.-No. DD 256882 A1)

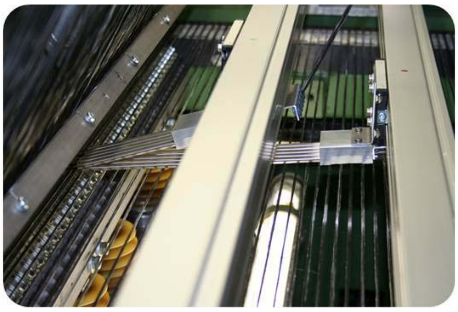

Figure 02. Side view warp yarn shogging device for selective manipulation of the warp yarn course

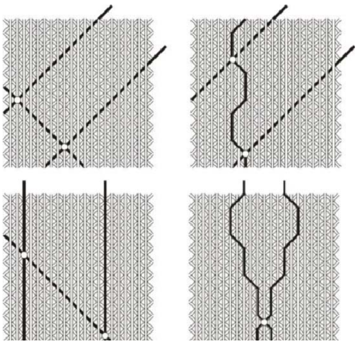

Figure 03. Selection of available placement patterns for the realization of planar sensor layouts

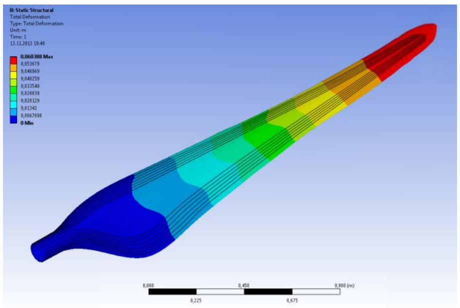

Figure 04. Simulated model of a rotor blade under wind loads with integrated sensor network for structural health and load monitoring task

2.2 Stitch-woven CFY sensors using ORW® technology

For the first time, a rapier weaving machine Dornier P1 ORW with open reed (Figure 05) is used for the production of the (CFY-based structural monitoring sensor-equipped) textile reinforcement of membrane semi-finished products for pneumatic constructions such as floating dome roofs or the silo covers of fermenter plants. A special heald frame, fitted with two independently acting warp yarn shogging devices, allows the selective-translational displacement of two additional warp yarn sheets with up to 24 yarns each, which can be joined to the basic woven fabric at any desired angle between -90° and +90° and under suitable binding, similar to multi-axial warp-knitting technology. Thus, innovative two-dimensional sensor layouts can be produced simultaneously with the fabric manufacture. Figure 06 shows in detail principally realizable 2D sensor form examples realized with stitch-weaving technique (ORW® technology).

To evaluate the sensory characteristics and the imaging performance of mechanical biaxial loads on the electrical carrier signal, GF-based woven fabrics are equipped with two-dimensional CFY sensor layouts. Utilizing the [$90°_{CF}$, 90°, 0°] layering of two woven fabric structures produced in this manner and the subsequent laminating with 2-component silicone rubber, membrane specimens (Figure 07) were produced and then exposed to equi-biaxial load profiles in a shear stress testing frame. The shear angle-dependent measurable sensor signal is shown in Figure 08. It displays a good correlation between the extent of the mechanical load and the signal amplitude.

Figure 05. P1 weaving machine with open reed (ORW) and warp yarn shogging device

Figure 06. Detail of exemplary CFY sensor forms realized with warp yarn shogging device on Dornier P1 ORW weaving machine

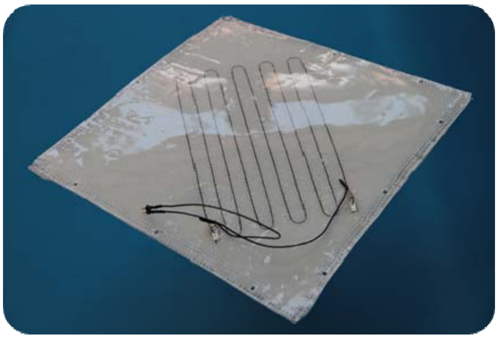

Figure 07. Silicone rubber membrane with GF woven fabric reinforcement and CFY sensor structure added by ORW machine

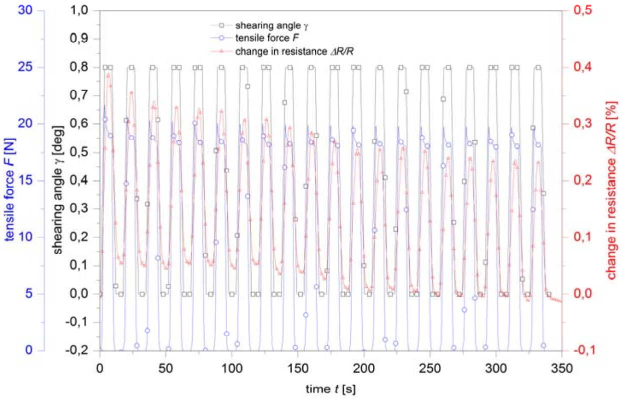

Figure 08. Measurable CFY sensor signal (blue curve), depending on the shear of the membrane structure (red curve)

3. FRPs with adaptive characteristics using integrated SMA kinematics

For the realization of FRPs with adaptive characteristics, which can be used for active component deformation, vibration damping or for the specific and local generation of forces, shape-memory alloys (SMA) are the primary actuating functional materials in the form of customized actuator networks. In the context of substantial basic research, adaptive FRPs were developed, realized and characterized.

Friction spinning hybrid yarns (HY) based on the DREF2000 friction spinning technology [3] are the foundation of the adaptive FRPs presented herein. Textile-processable SMA wires were used as core component. Glass reinforcement fibers and polypropylene (PP) fibers are used for the sheath component. This yarn structure aims to decouple the SMA wires from the composite structure, exempting the points of force introduction at the margin of the FRP. Not only does this optimally utilize the actuating potential of the actuator network. It also avoids mechanical strains in the region of the boundary layer between SMA wire and composite structure, which can cause irreversible damages in the form of matrix cracks or delaminations. The characterization of the actuating potential of the developed textile-based actuators and actuator networks in the consolidated composite is another focus. A contact-free and therefore mechanically reactionless measuring method by laser triangulation is used for this purpose. The thermally induced shape-memory effect (SME) is activated by electrical current. Using a defined current-time plot, the dynamic deformation behavior is examined. The dynamic deformation behavior of adaptive FRPs can be influenced specifically by current strength and switching frequency, as shown exemplarily in Figure 09.

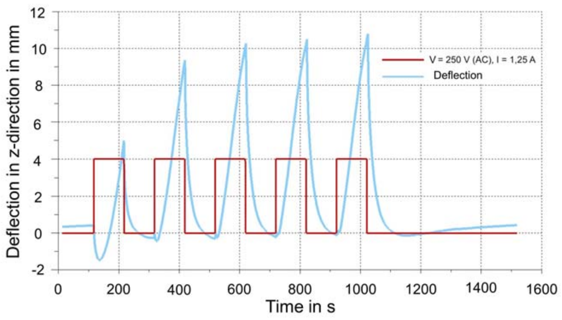

Figure 09. Comparison of currency-time plot with shifting of the plate center of an adaptive FRP in z-direction

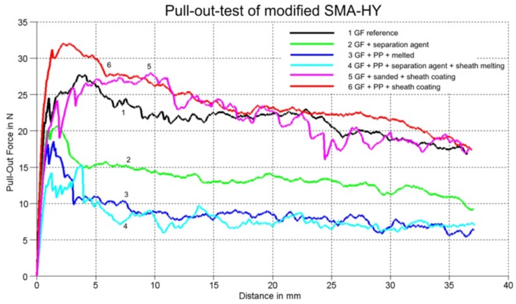

Figure 10. Force plots achieved from the pull-out tests of SMA wires from embedded SMA HY with varying mechanical and chemical finishings

Another focus of the research works is on the possible yarn constructions and yarn finishings, aiming at a targeted influence on the friction and adhesion relations between the SMA wire and the FRP. For this reason, a variety of different yarn structures made from GF and PP, the finishing of the SMA wire with a chemical abherent, the sanding of the SMA wire, and the coating of the SMA HY with a polymer coating were examined. The characterization is based on pull-out tests, in which the specimens were fixed in the test setup by positive locking [4]. The SMA HY variations characterized by pull-out tests show significant differences regarding the friction between the SMA wires and the matrix material (Figure 10).

The yarn variations with additional fiber sheath made from PP displays the smallest friction values. Thus, it can be shown that the HY construction has considerable influence on the internal friction relations, and thus on the utilizable actuating deformation potential of adaptive FRPs with structurally integrated actuator networks.

4. Summary

The textile-technically integration of CFY sensors into non-crimp GF warp knitted reinforcements (for composite applications) as well as into woven structures (for architectural membrane applications) has been realized successfully. For the integration of the sensors, two novel manufacturing processes are used: the integration into multi-axial non-crimp warp knitted fabrics is done through a warp shogging system, which offers the possibility to move individual CFY warp threads over the fabric's width. For the superficial embedding of two-dimensional sensor layouts onto woven structures, a stitch weaving machine with ORW technology is used, thus allowing the manufacture of textile sensors with custom layouts during the weaving process.

Preliminary investigations on silicone rubber membranes with double-layered reinforcement made of woven GF fabric with applied sensor network consisting of CFY meander in ±45° orientation, the functionality for usage of such structures acting as shearing sensor has been validated. During cyclical and stepwise increasing biaxial shearing of a membrane specimen equipped with such a sensor network, the inner stressing condition of the membrane has been mapped reliably to the CFY senor's electrical carrier signal. In the next step, two-dimensional sensor structures shall be applied on woven reinforcement fabrics using the stitch weaving technique.

Preliminary investigations of sensor manufacturing using the warp yarn shogging device for multi-axial warp knitting machines are used for determination of the reachable geometrical restrictions for deposition and shogging of functional warp yarns and their knitted link to the non-crimp fabric during the continuous manufacturing process. Sensor networks with different spatial resolutions for local or global structural health monitoring can be realized by local interconnections of electrical-conductive yarn systems for weft or warp insertion by selective application of inert coatings. The goal here is the integration of sensor structures and their interconnection by a textile-based electro-conductive aligning into functional FRP components acting as technology and functional model, e.g. holm bar, holm belt or shell of a small wind turbine rotor blade, made of non-crimp warp knitted fabrics.

The actuator potential of such functional elements in a composite was proven by FRPs with integrated SMA wires. To prevent damages to the FRP structure, the textile-based actuators have to be decoupled from the matrix, which was realized with sheathings made from GF/PP fibers in a friction spinning process. Pull-out tests on the SMA wires from sheathings of various mechanical and chemical functionalizations were performed to evaluate the fiber-matrix bond, aiming to reduce friction between the fiber sheath and the SMA core. Powering an FRP integrated SMA actuator with a current of 1.25 A and a supply voltage of 250 VDC, a nominal deflection of the plate's center point in a range of (4.0 – 5.0) % related to the FRP component's length has been achieved. In additional tests, the SMA actuator and the CFY sensor structure will be integrated simultaneously into the FRP to realize initial simple control circuits consisting of an SMA actuator and in-situ deformation/load monitoring by means of a CFY sensor, and to be able to evaluate their interaction.

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