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Individual functionalization of fiber-reinforced profiles via pultrusion

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Abstract

Profile-based design is widely used because of its flexibility. A good possibility to increase the lightweight aspect can be the use of fiber reinforced profiles. These can be produced in a series suitable process - pultrusion. In this paper, the integration of functions in pultrusion profiles is focused. In one project, potential sensor concepts for robust condition monitoring of fiber reinforced plastic (FRP) profiles were developed to expand the range of applications significantly. One application could be the substitution of complex aluminum profiles by fiber reinforced profiles with the advantage like high lightweight potential and low thermal expansion. Another objective was the integration of sensors and light-emitting diodes (LED) directly into the pultrusion profile.

The objective of a second research project was the integration, wiring and test of sensors into a curved roller ski profile to detect loads during training. Several types of sensors were investigated to evaluate the parameters accuracy, positioning, and wiring at the best economic efficiency.

The focus of the research and development of both projects was the integration of functions into pultruded profiles made of FRP. Successfully integrated functionalizing elements include sensors for strain, lighting elements, and touch sensors as well as temperature and humidity modules.

1 Introduction

Smart components are key technologies for lightweight design, Industry 4.0 as well as the Internet of Things (IoT). Areas of application include systems for sustainable production, the automotive industry, smart agriculture, and the smart home [1].

For the production of fiber-reinforced profiles, the pultrusion process established itself as one of the few economical processes [2]. These profiles are used in countless industrial sectors and applications [3]. In lightweight design in particular, a key objective is to reduce the number of components and manufacturing steps by integrating additional functions into FRP structures to reduce the mass of the whole component and to save resources. To make these profiles smart, the state of the art shows various studies. As pultruded FRP profiles have a high content of fibers, it seems obvious to use these fibers to achieve additional properties in the profile. Glass fibers, for example, can be used as fiber optic sensors [4–6] to transmit information. Another approach to functionalizing pultrusion profiles is the use of hybrid design methods. For example, metal fibers or even sheet metal can be integrated into the profile to achieve better mechanical properties [7, 8]. This approach might be used to create joining points for other parts.

One option for adding more functionality to FRP profiles is the integration of sensors, actuators, or display elements, which are subsequently applied or inserted in the state of the art. The pultrusion process allows additional sensory fibers like Shape Memory Alloy (SMA) wires [9] or Fiber Bragg Grating (FBG) [10] to be added directly in the process. These additional elements can be used for structural health monitoring. The integration of a tracer element is also possible [11]. This element is used to

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ensure that a part of the reinforcing fibers is located at the predefined position in the cross-section of the profile. Therefore, the profiles are cut at the tracer position.

This paper describes two different projects focusing on the integration of additional elements into pultrusion profiles to functionalize them.

In the first project, the objective was the integration of a stitched strain sensor into a straight pultrusion profile with the width of 300 mm and a thickness of 4 mm. With this sensor, bending loads could be detected. Furthermore, a curved profile with a radius of 1,700 mm and a cross section of 25 x 25 mm² with integrated lighting elements was manufactured. With these two profiles, a bridge was built up as a project demonstrator.

The objective of the second research project was the manufacturing of a sensorized curved hollow profile in the pultrusion process that could be used as a roller ski. Because of the radius of 1,700 mm, the roller ski provides increased ground clearance which results in a much more realistic ski feeling. The integrated piezo sensor detects loads during the training an gives the athlete a feedback for his or her training by sending information wireless to a mobile app [12].

2 Materials and processes

In the following, the examined materials are described, which are used in the projects. Furthermore, the methods and processes used to manufacture smart structures are presented.

2.1 Materials

For the trials, materials are used as they are usually applied in the pultrusion process – fibers and semi-finished fiber products as well as a thermoset plastic system. Sensors and lighting elements are used for the process-integrated components.

2.1.1 Components of the fiber-reinforced plastics

The fiber materials for the bridge demonstrator (straight and curved profile) are glass fiber rovings of the type PulStrand 4100 with 4,800 tex from the manufacturer Owens Corning and glass fiber nonwovens with a grammage of 30 g/m².

For the roller ski, semi-finished glass fiber products with fiber orientations of 0°, 90° and ± 45° from the manufacturer Gustav Gerster were used. Additional carbon fibers of the type PX35 with 3,750 tex from the manufacturer Zoltek were used to absorb high tensile loads.

For all demonstrators, unsaturated polyester resin was used as matrix component. Table 1 shows the components of the polymer system.

Table 1: Resin system

Component	Component name	Supplier
Resin 1	Synthopan 781-60	Synthopol
Resin 2	Synthopan 134-61	Synthopol
Curing agent 1	Peroxan MI-60 KX	Pergan
Curing Agent 2	Peroxan BEC	Pergan
Monostyrene	Monostyrene	BÜFA
Internal Mold Release	PAT-667	Würtz
Inhibitor	Pergaslow PK-30S	Pergan

2.1.2 Functional elements

In pretests, the integration of different functionalizing elements into the pultrusion profiles was analyzed:

- Temperature, humidity, touch sensors
  → standard purchased parts, which can be evaluated by a microcontroller system like Arduino
- Piezo sensors
- Lighting elements like LED or optical fibers
- Strain gauges (standard purchasing part / stitched / straight, constantan / SMA wires / FBG)

In this paper, the focus is on the elements used in the two demonstrator parts. As strain gauges for the bridge demonstrator, textile sensors from the manufacturer Modespitze Plauen GmbH were chosen. The properties are shown in Table 2.

Table 2: Properties of the stitched sensor

Property	Unit	Value
Electrical Resistance	Ω	120 ± 2 %
Sensor wire material	-	Constantan
Diameter sensor wire	µm	50
k-factor	-	1.9 ± 2 % [k-factor determination according to VDI/VDE/GESA 2635 (stitched strain sensors in FRP composite integrated)]
Elongation range	%	Up to ± 3
Sensor layup size	mm²	22 x 19

For the roller ski, piezo sensors of the type M2814-P2 from the manufacturer Smart Material GmbH were selected [13]. The properties of the sensor are described in Table 3.

Table 3: Properties of the piezo sensor [13]

Property	Unit	Value
Active length	mm	28
Active width	mm	14
Overall length	mm	37
Overall width	mm	18
Capacitance	nF	43 ± 20 %
Free strain	ppm	-630 ± 10 %
Blocking force	N	-76 ± 10 %

Figure 1 shows the LED stripe from the manufacturer V-TAC. It has an operating voltage of 12 V and 60 LEDs per meter with a degree of protection of IP20.

Figure 1: LED stripe before (left) and after integration (right)

2.2 Process

In the pultrusion process, profiles with complex cross section can be produced very economically. The standard process for manufacturing straight profiles with thermoset matrix is shown in Figure 2: Semi-finished fiber products (1) are pulled from bobbins by alternately moving pulling devices (4) and pass through a resin bath (2). Afterwards, the impregnated fibers are pulled through a heated die (3), in which the liquid thermoset plastic cures completely within seconds to a solid plastic. A saw (5) cuts the profiles to the desired length [2].

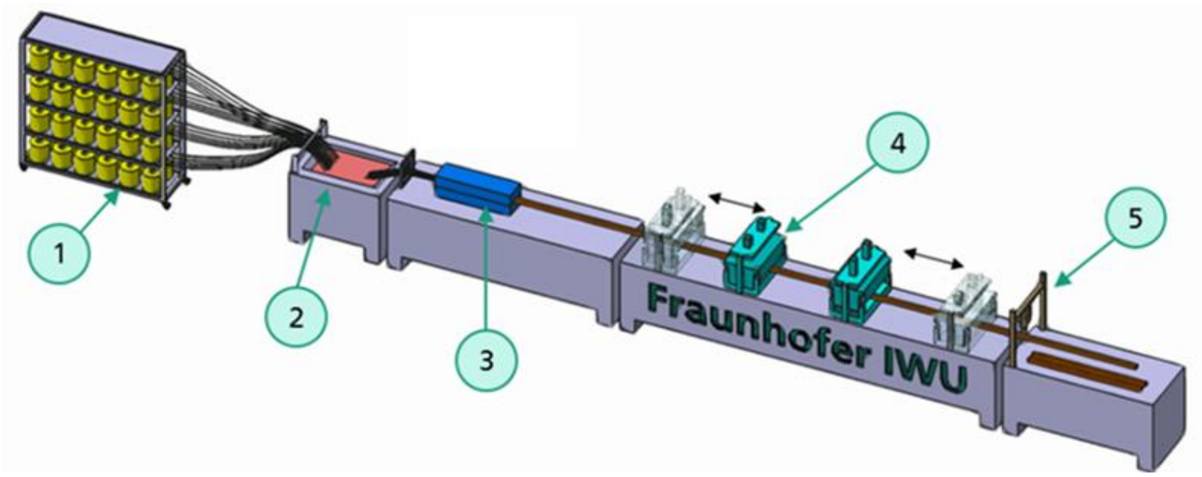

Figure 2: Pultrusion line (straight process)

It is already state of the art to produce complex reinforced pultrusion profiles by using semi-finished fiber products (rovings, mats, scrims, nonwovens, fabrics, etc.) with thermoplastic and thermoset matrix systems. In a modification of the process (radius pultrusion), constant curved profiles can also be produced [14]. The principle of this process is shown in Figure 3: In start position (1), the puller is opened. Then, the puller closes and grips the profile, while the heated die is moving on a circular path above the wet fibers. At this point, the gel zone moves in the opposite direction near to the end of the die – the cured profile leaves the die (2). After the die reaches the end position (3), the puller opens and the die moves quickly to the start position, while the cured profile is moving through the opened puller (4).

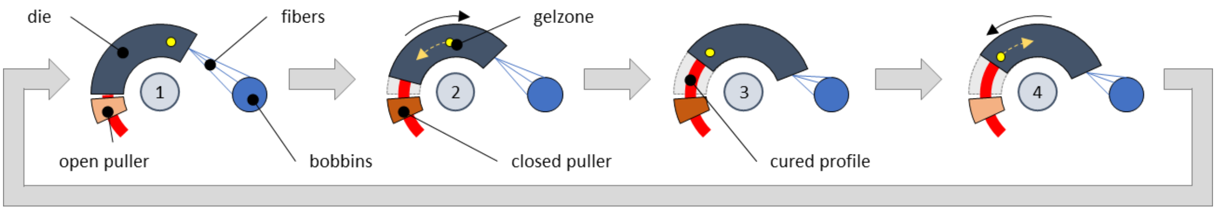

Figure 3: Radius pultrusion [15]

3 Results

The following describes how the 2 demonstrators were manufactured, the boundary conditions that applied, and how the demonstrators operate.

3.1 Experimental

For the profiles made by pultrusion a lay-up can be designed. It is possible to use different matrix systems (e.g. unsaturated polyester resin, epoxy resin, vinyl ester resin, etc.), different fiber materials (e.g. glass, carbon, basalt, etc.), different types of semi-finished fiber products (e.g. rovings or more complex semi-finished products like woven or non-woven fabrics, etc.).

3.1.1 Bridge demonstrator

In the pretest, 3 different LED-stripes were examined. Therefore, the cross-section of the stripe was determined because the fiber volume of the FRP has to be reduced to avoid a too high fiber fraction in the profile and therefore problems in the pultrusion process like too high pull-off forces. The fiber content that can be realized in the pultrusion process depends on the matrix system. Unsaturated polyester resin as matrix system has a high tolerance in the fiber fraction in comparison to other systems. A fiber content of about 60 to 70 % is suitable for the pultrusion of high quality.

For the lighting arches only glass fiber rovings and the LED-stripe itself were used. The bridges driveway was defined as a layup of glass fiber rovings, 4 glass fiber nonwovens, cut into the width of the profile, and again a layer of rovings (bottom to top, Figure 4).

Figure 4: Assembly of the semi-finished product feeder

The sensor was stitched on a thin nonwoven which was placed between two more nonwovens. To enable an easy contacting of the sensor, wires were soldered and already integrated into the profile (Figure 5). The driveway was manufactured with the straight pultrusion process while the lightning arches are manufactured with the radius pultrusion process.

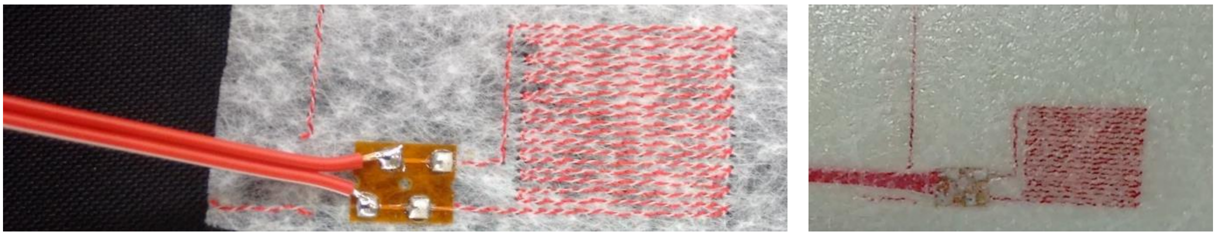

Figure 5: Contacted stitched sensor on a nonwoven fabric (left), profile with integrated sensor (right)

3.1.2 Roller ski

The roller ski demonstrator is a hollow curved profile. As shown in Figure 6 (left), finite element analysis derived a complex design of the lay-up to fulfill the mechanical requirements. The structure consists of various semi-finished products, such as scrims with fiber orientation at 0°, 90° and ± 45°. To withstand the traction forces while skiing, additional carbon fibers are placed on the bottom whereas the cheaper glass fibers and scrims are placed all around. The piezo sensor with soldered copper contacting elements was place on a nonwoven (Figure 6 right). After cutting the profile to the right length, these soldered wires allow easy contacting.

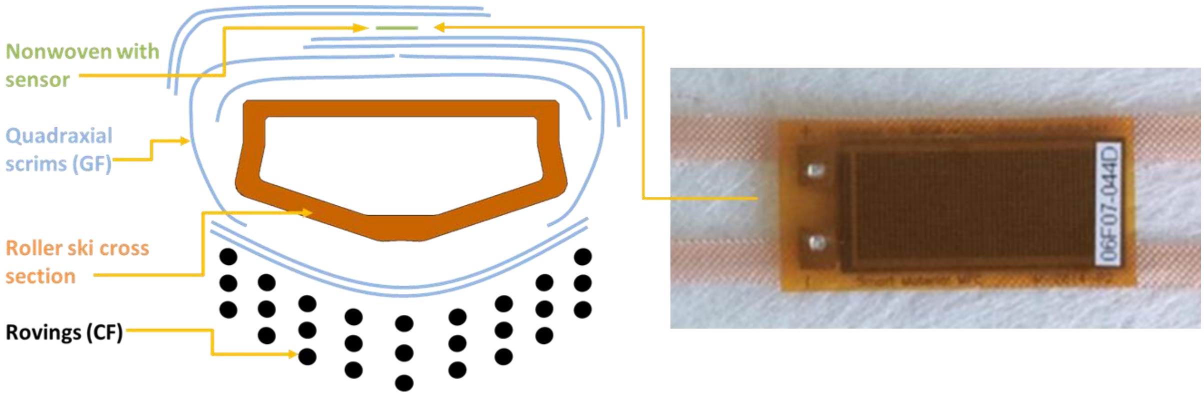

Figure 6: Layer set-up and sensor for roller ski (left), piezo sensor with contact tape (right)

The roller ski was manufactured in the radius pultrusion process. To manufacture a hollow profile, it is necessary to use a core, which is supported in the panels and floats in the die. To protect the sensitive carbon fiber rovings, an innovative direct impregnation process was used (Figure 7 left). In this modification of the pultrusion process, the impregnation of the reinforcing fibers and semi-finished products (Figure 7 right) is not carried out in an impregnation bath, but in a cooled injection box placed directly before the heated die. In this way, less deflections of the fibers are required.

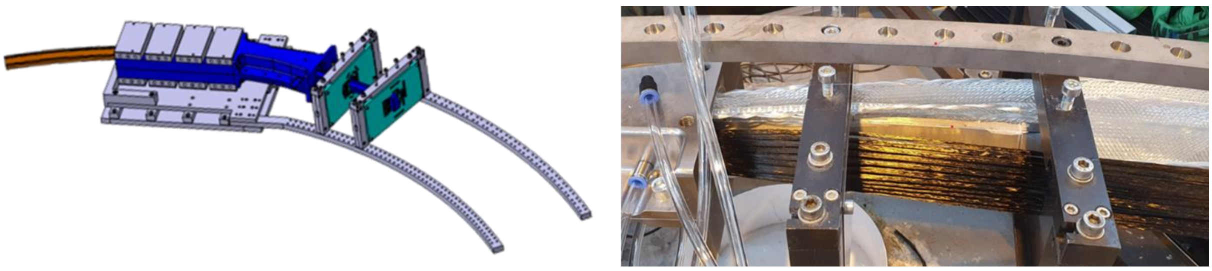

Figure 7: Manufacturing of the roller ski via radius pultrusion process in CAD (left) and trial (right)

3.2 Functionalized demonstrators

In the following the completed demonstrator parts are shown and their functions are described.

3.2.1 Bridge demonstrator

Figure 8 shows the bridge demonstrator with its pultruded arches and driveway. It was completed by 3D-printed parts as connections of the profiles.

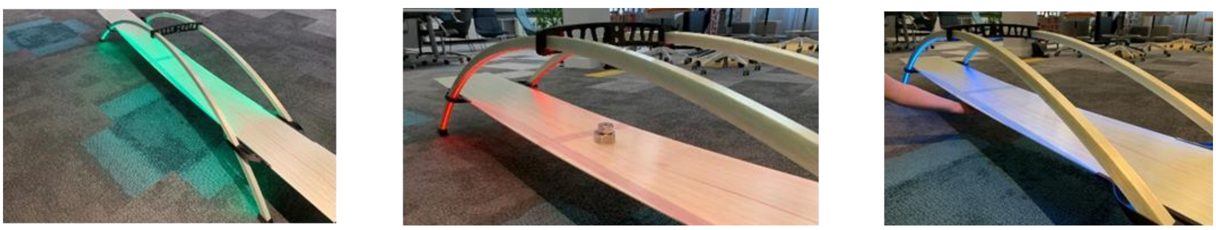

Figure 8: Bridge in three different loading states: unloaded (left), loaded (middle), pushed up (right)

Loading of the bridge, for example by vehicles or pedestrians, leads to a bending stress in driveway and to an elongation of the integrated stitched sensor. This elongation leads to a change in the resistance in the sensor wire, which is analyzed by an evaluation unit. For an optical feedback about the type of the occurring stress, the integrated LEDs in the arches are accessed to light up in the colors green (unloaded resp. noncritical load), red (overloaded) or blue (loaded from the bottom e.g. by wind load).

3.2.2 Roller ski

By realizing the roller ski as a curved profile with the ability to bend under load (Figure 9) a more similar feeling in comparison to real skiing can be achieved. The athlete gets the realistic feeling in comparison to the state of the art roller ski made of an aluminum profile. The integrated piezo sensor allows the training to be analyzed and adapted to the athlete's needs according to his or her deficits. The data can be read out wireless and displayed by smart phone application.

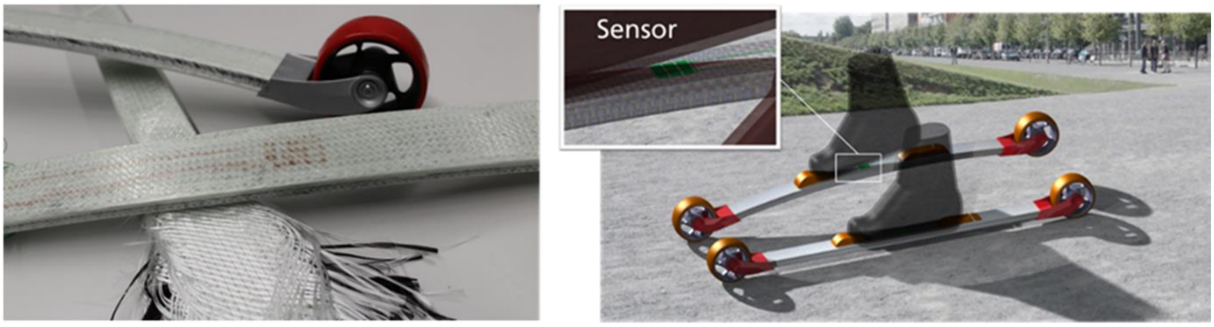

Figure 9: Roller ski with integrated sensor (left), use case (right)

4 Discussion and conclusion

The demonstrators with three different profiles (straight runway, curved arches, and curved roller ski) were successfully manufactured. For the realization of the complex lay-up of the roller ski, an iterative process was needed. The integration of the different functions into the profiles was also successfully proven. The contacting is possible, but easier ways for the realization are already in the investigation to enable a better practicability for serial production. The contacting has to be adapted for every application in a different way, because of the different functionalizing elements, varying profile cross sections, usage of different semi-finished products and design of the lay-up.

The bridge's runway is realized with only one stitched strain sensor. This causes that the measured value of the resistance is sensitive also to a change in temperature. For different applications, a compensation might be needed. To reduce the influence of temperature effects, for example, a measuring bridge can be realized by integrating two sensors rotated by 90° to each other into the profile. Further investigations should include the influence of the integrated functionalizing elements on the mechanical properties, especially regarding their use-cases.

The piezo sensor in the roller ski is ideal for the detection of the momentum which affects the roller under stress. However, this special type of sensor is quite expensive compared to other sensors. In further studies, the aim is to produce the roller ski with the same functionality using less expensive sensors. Such sensors could be piezoelectric disks or wire-shaped sensors (e.g. SMA).

4.1 Acknowledgements

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