Adaptive fiber-reinforced plastics based on open reed weaving functionalization

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Abstract. It is aimed at realizing adaptive, and thus mechanically adjustable fiber-reinforced plastic (FRP) components with complex 2D layouts so that complex 3D deformation of adaptive FRPs can be achieved. Therefore, the textile-technical integration of shape memory alloys into reinforcing fabrics is required. Hence, this paper presents the development of adaptive FRPs, where nickel-titanium-based shape memory alloy was structurally integrated into textile-reinforced semi-finished products by means of open reed weaving technology to generate adaptive FRP components. After manufacturing of the functionalized preform, it was infused by both a thermosetting resin system and a thermosetting system modified by means of plasticizer. Results of thermo-mechanical characterization revealed that the deformation of adaptive FRPs increased fourfold by adding the plasticizer to the reference thermosetting resin system.

1. Introduction

The innovation potential of fiber-reinforced plastics (FRPs) is based on the design of load-bearing lightweight constructions in accordance with the end product. These load-bearing structures for FRPs can be implemented by the specific arrangement of high-performance fibers in the load direction. The enormous potential of FRPs can furthermore be increased by means of functionalization. By developing FRPs with adaptive characteristics, smart lightweight structures with a high application potential can be realized. These structures possess highly tailored energy absorption capabilities and their mechanical characteristics, such as geometry and stiffness, can be adjusted to external influences.

The adaptive characteristics of FRP can be generated integrating shape memory alloys (SMAs) into reinforcing fabrics during the production process [1-3]. After plastic deformation at low temperature, SMAs return to their original shape during the thermal induced activation. The textile-technical integration of SMAs into reinforcing fabrics is mainly executed by means of the weaving technology because weaving has the advantage of high manufacturing flexibility and productivity compared to other textile techniques such as knitting, braiding or stitching. Furthermore, woven structures have a notable lightweight strength and long-term durability. By utilizing appropriate weave patterns and parameters, a wide variety of structures can be achieved using the weaving technique without requiring complex constructive modifications.

In previous works, the authors presented the integration of SMAs into reinforcing fabrics by weaving technology, whereby the SMAs were parallel to warp or weft yarns [4-6]. However, it is aimed at realizing adaptive, and thus mechanically adjustable fiber-reinforced plastic (FRP) components with
complex 2D layouts so that complex 3D deformation of adaptive FRPs can be achieved. Therefore, the textile-technical integration of shape memory alloys into reinforcing fabrics by means of open reed weaving technology (ORW) is required. Technically, the ORW technology is developed on the basis of a conventional weaving machine. Besides essential working elements, such as warp let-off device, conventional shafts or heald frames, weft feeder and fabric take-off system, an ORW weaving machine is equipped with an open reed and a so-called special shaft that is mounted between the open reed and other conventional shafts (Figure 1). In the special shaft, flat needles are used as thread guides and coupled with a linear motor to form a sideward movable system. In combination with the open reed, offset of warp yarns that are guided in the special shaft during weaving is possible. In this way, woven fabrics with diagonally integrated yarns can be achieved in a one-stage process [7].

![Figure 1. Schematic and actual representation of an ORW weaving machine [8].](image)

There is a diversity of potential applications for ORW products. One example is decorative fabrics with various embroidery patterns [9]. In the field of composites, multiaxial fabrics, locally reinforced fabrics, grid-like non-crimp woven reinforcing fabrics and 2D net shape fabrics for different end uses can be manufactured [9-11]. Another very promising approach is to employ ORW technology for the fabrication of functionalized textiles. Known products are woven structures with integrated CF-strain sensors for on-line controlling of composite components [12]. However, the use of ORW technology for the development of functionalized preforms with SMA for the fabrication of adaptive FRP has not yet been reported. Hence, in the framework of this research project, adaptive FRPs were developed, where SMA was structurally integrated into textile-reinforced semi-finished products by means of ORW technology. Next, the functionalized preforms were infiltrated by two different resin systems, and finally, the thermomechanical characterization of both types of adaptive FRP was executed.

## 2. Materials and methods

### 2.1. Materials

In this research project, a SMA (Alloy H ox. sa., Memry GmbH, Germany) in the form of a wire was selected for the development of adaptive FRP. The transition temperature, diameter, tensile strength and the elongation at break of the selected SMA were 95-110°C, 0.305 mm, 1152.7 MPa and 11.1%, respectively. In order to ensure free and even mobility of SMA within FRPs, which is necessary to fully exploit the deformation capability of SMA and therefore the adaption potential of the entire FRP
structure, the wire-shaped SMA was coated by a separating agent – Dexcoat 8 (Tag chemicals, Germany). This separating agent is suitable for all thermoset resins.

Subsequently, the coated SMA was integrated into the reinforcing fabric that consisted of glass rovings (Glas EC17-1200-350, Glasseiden GmbH Oschatz, Germany). The parameter of glass rovings for the realization of adaptive FRPs, which were tested by the authors at the research institute, is stated in Table 1. These glass rovings were chosen due to their price-performance of 1-2€/Kg, high applicability in FRP applications of around 98%, electrical insulation and high elongation at break of up to 5.4%.

| Table 1. Mechanical parameters of the glass rovings (SD...Standard deviation). |
|---------------------------------------------------------------|
| Parameter | Average | SD | Norm applied |
| Fineness (tex) | 1200 | 2.5 | DIN EN ISO 2060 |
| Tensile strength (N) | 540 | 34 | ISO 3341 |
| Elongation at break (%) | 1.96 | 0.08 | ISO 3341 |

In this research project, a cold-curing thermosetting matrix system was used. This system can withstand temperatures of up to 130°C or even 200°C, which is significantly higher compared to the transition temperature of SMA. In order to prevent the SME during the infusion process which is an exothermic reaction, a cold-curing system was used. In this case, the commercially available resin system MGS® RIMR 135 in combination with curing agent RIMH® 137 (Hexion, USA) were selected. The combination of materials displays an interconnection temperature of 70°C, which is significantly below the transition temperature of the selected SMA. In order to increase the flexibility of the matrix material, a plasticizer - Heloxy (Hexion, USA) was mixed with the resin system.

### 2.2 Development of functionalized preform by means of ORW technology

The rapier weaving machine PTS 4/SOD with ORW function from Lindauer Dornier GmbH, Lindau, Germany was employed for the development of functionalized preforms. To manufacture a functionalized reinforcing fabric with integrated SMAs, conventional shafts were used to form the base woven fabric, whereas needles of the special shaft interweave SMAs on its surface. Two sideward movable systems with independent horizontal movements are available in mentioned machine, hence woven structures with two sets of SMAs, each having a separate pathway, can be achieved. It is necessary to note that SMAs were preferably considered as weft yarns in the resulting fabric due to their offset movement. During the production of the functionalized preform, the offset of the SMA was 20 mm. Therefore, different fabric thicknesses had to be realized along the fabric width to enable the plastic deformation of the final FRP component. Technologically, varied fabric thickness can be achieved by alternately implementing single and multi-layer structures in different fabric areas. Based on the desired thickness ratio, an appropriate layer count with the corresponding warp and weft ratio in every single fabric area was determined. Subsequently, suitable weave patterns together with corresponding drafting and lifting plans were developed. For the weaving process, it was important to synchronize the needle movement with the shedding motions of other working elements, so that the desired structure could be attained. The machine used for the development of functionalized preforms is shown in Figure 2.
One challenge to the fabrication of reinforcing fabric with integrated SMAs was the specific material stiffness of the selected SMAs. This stiffness limits the material flexibility during the weaving process and may lead to yarn damage in case of extreme movements. To overcome this issue, technological solutions were implemented to enable the supply of SMAs at different rates and to compensate the difference in yarn length when the working elements move relatively to each other. Furthermore, experiments have been carried out to determine the maximal offset movement and yarn tension, at which the particular SMAs can be processed. The results were carefully considered when setting fabric and machine parameters to attain functionalized reinforcing fabrics with minimized damage. The functionalized preform with integrated SMA is shown in Figure 3.

2.3. Infusion
Considering its cost-effectiveness and suitability for the production of small composite parts, in this research project, the Seeman Composites Resin Infusion Molding Process (SCRIMP) was used for the infusion of the functionalized reform. An additional flow aid was used in order to ensure the proper
distribution of the resin throughout the reinforced fabrics and to avoid dry areas on the structure surface. Prior to the infusion process, resin and curing agent were mixed at a ratio of 10:3 for the formation of reference adaptive FRP. The plasticizer was mixed at a ratio of 7:3 with the matrix system for the fabrication of adaptive FRP with plasticizer. In this case, resin and curing agent were mixed at a ratio of 10:2.4.

After preparing the matrix material, the functionalized preform was prepared by cutting the floating weft yarns. The free ends of SMA were secured against slippage and to generate a local force transmission area during the thermal induced activation of SMA. This was executed by fixing the free ends of SMA with a screw, as shown in Figure 4 (Fixing of the free ends of SMA). Subsequently, the functionalized preform was laid onto the metal plate, and the free ends of SMA were isolated by means of tacky tape for their contacting during electrical characterization. Later, the perforated foil, distribution channel and non-permeable film were placed on top, and the resin was flown by means of the help of negative pressure. The whole infusion system is shown in Figure 4. In a next step, the whole sealed system was cured for 12 hours at room temperature and then tempered in a hot gas chamber at 50°C for 3 hours in order to reduce the residual stress of adaptive FRP. After the infusion process, the adaptive FRP was tailored by means of a laboratory wet say to a size of 210 mm x 110 mm.

2.4. Electromechanical characterization of adaptive FRP

The electromechanical characterization of both types of adaptive FRP was executed by means of the deformation measurement. The maximum deformation was measured by a laser triangulator of type LJ7200 (Kyence, America), featuring a contact-free and therefore mechanically reactionless measuring principle. The adaptive FRP and the laser triangulator were mounted on the test stand. The deformation was measured at a distance of 180 mm from the clamping distance.

The thermal induced activation of SMA was executed by a laboratory power supply unit (BT, Germany). Based on preliminary results considering the generated temperature of SMA, in this research, the SMA was activated by 14.5 V/1.6 A current flow. The periodic heating cycle was set to 60 s, and the periodic cooling cycle was set to 90 s. The periodic cooling was executed at room temperature. Both periodic heating and cooling were controlled by a LilyPad programmed by an Arduino environment unit due to the ease of use and flexibility. The adaptive FRP during the heating and the cooling cycle is shown in Figure 5.
3. Results and discussions
The deformation behavior of the adaptive FRP over the entire measurement period is demonstrated in Figure 6. This figure shows that during the thermal induced activation, the adaptive FRP deforms due to the phase change of integrated SMA from martensite to austenite state.

Figure 6 reveals as well that, by adding the plasticizer to the reference resin, the deformation of adaptive FRPs was increased fourfold. In order to evaluate this relationship, a three point bending testing of reference resin and resin with plasticizer was executed. Result reveal that bending modulus of reference resin with plasticizer was reduced significantly compared to reference resin as shown in Figure 7. The deformation potential of adaptive FRP was increased by creating locally soft bending areas, which was enabled by the mixing of plasticizer into the reference resin system.

Figure 5. Adaptive FRP (here, in two setting positions – deformed and original) during the heating and the cooling cycle.
4. Conclusions
The deformation characterization of adaptive FRP by a thermosetting resin system and another thermosetting resin system modified by means of plasticizer was executed in this work. For the optimum use of SMA in adaptive FRP, it was coated with a coating agent. Furthermore, to increase the deformation behavior, a variable thickness of the functionalized preform was realized. After manufacturing of the functionalized preform, it was infused by the thermosetting resin system as well as the thermosetting system modified with plasticizer and reference resin system at a mixing ratio of 7:3. The deformation of adaptive FRPs increased fourfold by adding the plasticizer to the reference resin because the plasticizer reduces the bending stiffness of the reference resin system.

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