# STRUCTURALLY INTEGRATED SHAPE MEMORY ALLOYS FOR SHAPE-VARIABLE ADAPTIVE FIBER-REINFORCED PLASTICS

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## Abstract

Fiber-reinforced plastic (FRP) components with integrated textile-based actuators for lightweight kinematics represent innovative smart lightweight products. In contrast to conventional, in particular metal-based kinematics and such kinematics equipped with separate drives and actuators, adaptive FRPs provide an enormous saving potential in terms of moving dead weight and the number of necessary parts and joints of the moving machine parts. Hence, this research project presents the development of adaptive FRPs with shape memory alloys (SMAs) that are structurally integrated into textile-reinforced fabrics by means of weaving technology. In order to create a barrier layer between the SMA and the matrix material, the SMA is converted into SMA hybrid yarn prior to weaving. The adaptive FRP produced by the Seeman Composites Resin Infusion Moulding Process is electromechanically characterized by varying the SMA length. Results reveal that the deformation behaviour of adaptive FRP is increased by increasing the SMA length.

## 1. Introduction

To ensure the necessary movements and degrees of freedom, separate drives, gears and joints are required for conventional kinematics, which is inevitably associated with higher stationary and moving masses. The reduction of moving mass is essential to guarantee the required movements and degrees of freedom. However, simultaneously, the degree of freedom needs to be increased. This issue can be overcome by the functionalization of fiber-reinforced plastics (FRPs) with shape memory alloys (SMAs).

SMAs have the special property of "remembering" their original shape after permanent plastic deformation below a certain critical temperature by heating them above this temperature [1]. The advantages of SMAs for the functionalization of FRPs include: they have very high usable specific energy densities of $2 \cdot 10^3$ J/kg, reproducible deformation patterns for motion cycles far above $10^5$ and are commercially available in wire form. Therefore, they are in principle textile processable [2]. Areas of application for these adaptive FRPs are robotic-like kinematic and gripper mechanisms in confined spaces, flexibly adaptable orthoses to stabilize and support the skeletal and locomotor apparatus in medical technology and different components for aviation industries [3-4].

Through the development of textile-based novel adaptive FRPs with tailored fabric structures and integrated additional functions, the current application range of adaptive FRP-based kinematics can be further broadened compared to conventional drives based on metallic materials. In recent works carried out by the authors, the textile-technical integration of SMAs into reinforcing fabrics for the development of adaptive FRPs was described [5-8]. In order to improve the force transmission capability from SMAs to FRPs and to reduce their delamination during the thermal induced activation of SMAs, the weaving-technical implementation for the production of adaptive FRPs was also investigated by authors [9-11]. However, the influence of the SMA length on the deformation behavior of adaptive FRPs has not yet been evaluated.

Hence, this paper presents the influence of SMA length on the deformation behavior of adaptive FRPs, whereby the shape memory alloys were structurally integrated into the reinforcing fabrics using weaving technology.

## 2. Materials and methods

### 2.1. Materials

For this research project, nickel (Ni) and titanium (Ti) based SMA - Alloy H ox. Sa. from Memry GmbH, Germany was used for the development of adaptive FRPs. Taking into consideration textile processability as well as a high force generation capability, the diameter (Ø) of the chosen SMA wire was 0.305 mm. The other parameters of the used wire are stated in Table 1.

**Table 1.** Properties of the used SMA.

| Properties | Values |
|---|---|
| Mass proportion of Ni and Ti (%) | 54.8/45.2 |
| Austenite start and finish temperature (°C) | 82/90 |
| Martensite start and finish temperature (°C) | 65/55 |
| Tensile strength (MPa) | 1164.08 |
| Elongation at break (%) | 12.16 |
| Force generation capability (N) | 50 (for Ø = 0.305 mm) |

This SMA wire was wrapped by glass fiber rovings and polypropylene fiber rovings of 2000 and 4000 tex for the formation of the SMA-hybrid yarn (SMA-HY). To facilitate processing, a long glass fiber roving with a fineness of 300 tex was added as core material during the formation of the SMA-HY. The fibre material for the functionalized preform consisted of glass fiber rovings of type Glas EC17-1200-350. The mechanical parameters of the rovings were tested by the authors using already existing machine technology. The mechanical parameters are stated in Table 2.

**Table 2.** Mechanical parameters of the glass rovings (SD…Standard deviation).

| | 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 |

An epoxy matrix system was utilized for the infusion of the functionalized preform. The resin MGS® RIMR 135 and the hardener MGS® RIMH 137 (Hexion a. s., Sokolov, Czech Republic) were used for the infusion process. The properties of the matrix material can be found in ref. [12].

### 2.2. Shape memory alloy hybrid yarn (SMA-HY)

In order to protect the matrix from direct contact with SMA, to ensure free and even mobility of SMA in FRPs, and to fully exploit the deformation capability of SMA and therefore the adaption potential of the entire FRP structure, the wire-shaped SMA was converted into textile-based actuators in a core-sheath structure by the friction spinning technology - DREF 2000. During this process, SMA was wrapped with glass and polypropylene fibres to form SMA-HY. However, SMA was form-fitted to the reinforced fabrics in order to transmit the force from SMA to FRP. Details of this process stage are described in ref. [13]. A longitudinal and a cross-sectional view of the developed SMA-HY are shown in Figure 1.

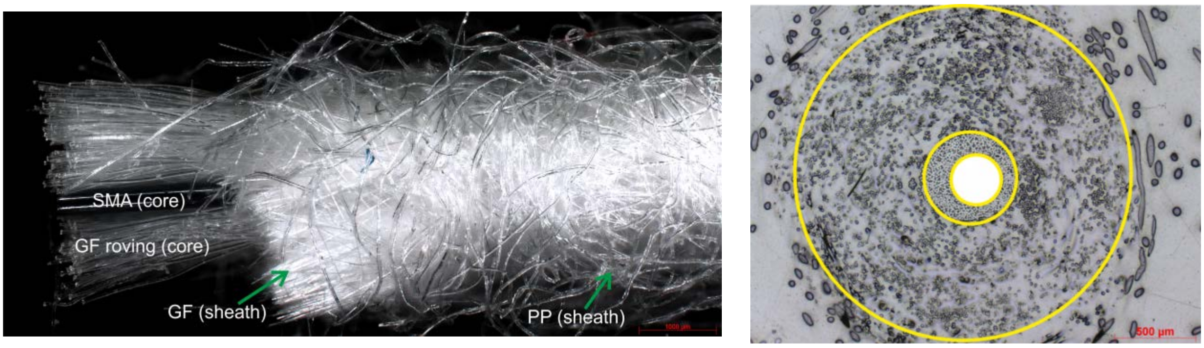

**Figure 1.** Longitudinal view (left) and cross-sectional view (right) of SMA-HY.

### 2.3. Development of the functionalized preform

The development of the functionalized preform was carried out on a rapier weaving machine of type P1 (Lindauer Dornier GmbH, Germany) with two warp beams containing glass rovings. The SMA-HYs were delivered from a separate creel. In order to increase the deformation potential of the adaptive FRP, a hinged structure was generated by means of the interlacement of the fibers (plain and multilayer) and the variation of the warp and weft yarn density. The plain and multilayer fabrics were produced with 1 and 3 weft yarns, respectively. There was no interlacement between the warp yarn from the lower warp beam and the weft yarn under the area of the plain fabric for the generation of floating warp yarns (see Figure 2-right). The floating warp yarns were cut by means of a scissor on the back side of the functionalized preform in order to form the hinged structure. The length of the hinged width was 100 mm. The distance between two SMA-HYs was 10 mm. The warp and weft yarn density in the thin area was 4 yarns/cm and 2.4 yarns/cm, respectively. The yarn density of the thick area was double that of the thin area. The functionalized preform, i.e. its top and bottom side, is shown in Figure 2. By means of two varying SMA lengths of 240 mm and 170 mm, two samples were produced in total.

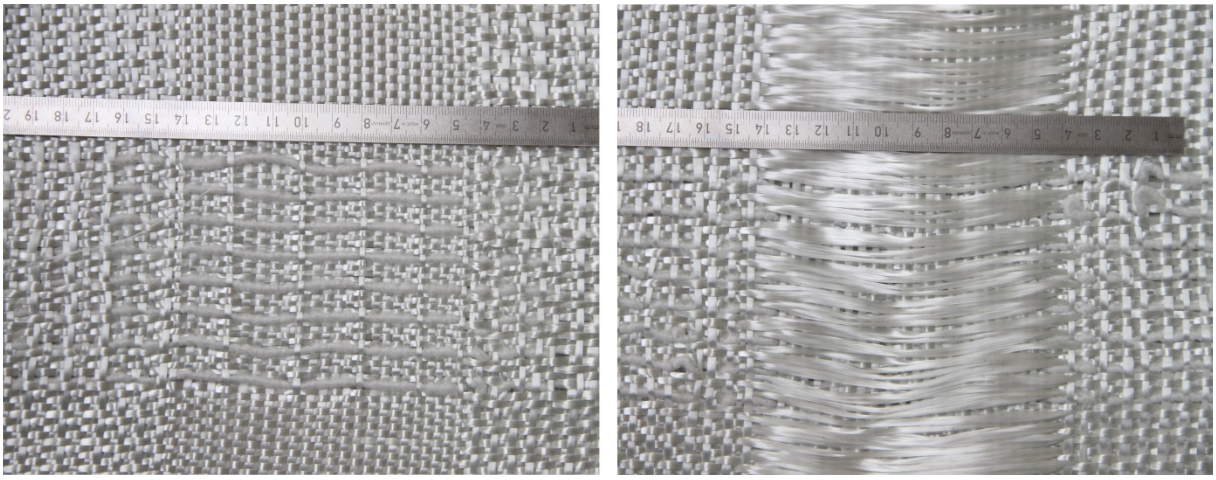

**Figure 2.** Functionalized preform: top (right) and bottom (right) side.

Since the SMAs in adaptive FRP were activated by Joule heating, the contacting of two adjacent SMAs was necessary. The contacting was executed by soldering in a meander form.

### 2.4. Infusion

The infusion for the fabrication of adaptive FRPs was carried out using the Seeman Composites Resin Infusion Moulding Process (SCRIMP). Prior to the infiltration process, the resin and the hardener were mixed at a mass-ratio of 10:3. In order to exploit their full deformation potential, SMAs should be straight during the infusion process. The straight position of SMAs was ensured by means of screws and wire. After the infusion and curing process, the adaptive FRPs were tailored by a laboratory wet saw to a size of 240 mm x 42 mm. An adaptive FRP after the infusion process is shown in Figure 3.

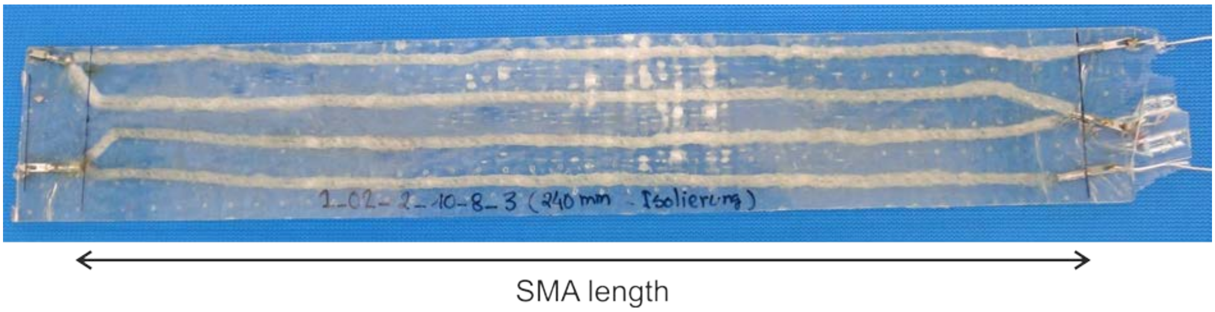

**Figure 3.** Adaptive FRP with the indication of SMA length.

### 2.5. Electromechanical characterization

The SMAs in the adaptive FRPs were activated electrothermally by a laboratory power supply unit with a current flow controlling unit. On- and off-times of the power supply were set to 60 s and 90 s, respectively. The off-time was selected to be longer than the on-time in order to increase the cooling time since the heating was executed actively and the cooling was executed by means of room temperature. During on-time, the applied current flow was 1.9 A. No current was applied during off-time, causing a passive cooling of the adaptive FRPs. During the periodic heating and cooling cycles, the resulting deformation of the adaptive FRPs was measured simultaneously.

## 3. Result and discussion

The deformation behaviour of adaptive FRPs over the entire measurement period is shown in Figure 4. After 500 s, the deformation curves become relatively homogeneous for both types of samples. It can be concluded that the deformation behaviour of adaptive FRPs varies depending on the SMA length.

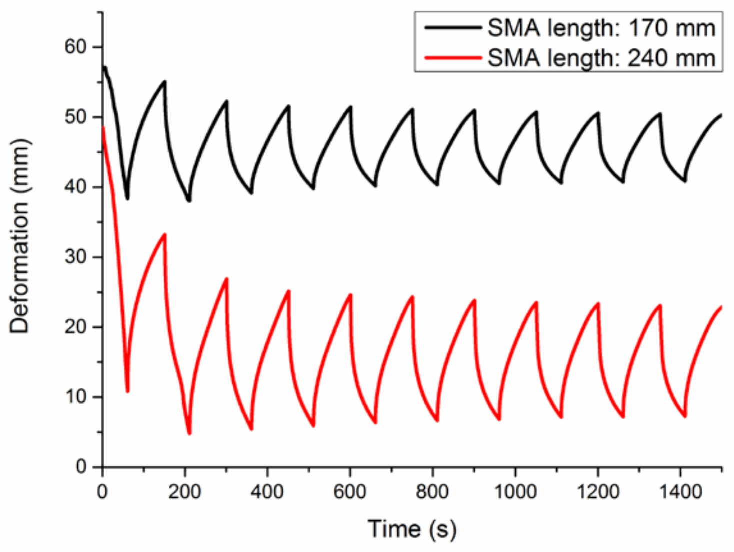

**Figure 2.** Deformation curve of adaptive FRP based on SMA length.

Figure 4 reveals that, by increasing the SMA length, the deformation of adaptive FRPs is increased. This phenomenon can be explained by the recovery length of SMA. The maximum recovery length of SMA is 8%. By increasing the length, the absolute recovery length of SMA is increased as well, which in turn increases the deformation of the adaptive FRPs. However, in this particular scenario, by increasing the SMA length from 170 mm to 240 mm, the maximum deformation of adaptive FRP is increased from 11 mm to 18 mm. Another reason behind this phenomenon is the distance of the force transmission point form the hinged width. For a constant generated force of each SMA during the thermal induced activation, the bending moment increases by increasing the distance of force transmission point from the hinged width.

## 4. Conclusions

Textile-based novel adaptive fiber-reinforced plastics (FRPs) with hinged fabric structures based on shape memory alloys hybrid yarns (SMA-HYs) were successfully developed in this study. Their electromechanical characterization showed that the maximum deformation of the adaptive FRPs was increased by increasing the SMA length. These lightweight adaptive FRPs can be used for various application scenarios, as robotic arms, aerodynamically efficient flaps/rudders, and medical applications (e.g. orthotics and prosthetics).

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