Electro-bending characterization of adaptive 3D fiber reinforced plastics based on shape memory alloys

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Abstract

The industrial importance of fiber reinforced plastics (FRPs) is growing steadily in recent years, which are mostly used in different niche products, has been growing steadily in recent years. The integration of sensors and actuators in FRP is potentially valuable for creating innovative applications and therefore the market acceptance of adaptive FRP is increasing. In particular, in the field of highly stressed FRP, structural integrated systems for continuous component parts monitoring play an important role. This presented work focuses on the electro-mechanical characterization of adaptive three-dimensional (3D) FRP with integrated textile-based actuators. Here, the friction spun hybrid yarn, consisting of shape memory alloy (SMA) in wire form as core, serves as an actuator. Because of the shape memory effect, the SMA-hybrid yarn returns to its original shape upon heating that also causes the deformation of adaptive 3D FRP. In order to investigate the influences of the deformation behavior of the adaptive 3D FRP, investigations in this research are varied according to the structural parameters such as radius of curvature of the adaptive 3D FRP, fabric types and number of layers of the fabric in the composite. Results show that reproducible deformations can be realized with adaptive 3D FRP and that structural parameters have a significant impact on the deformation capability.

Keywords: shape memory alloy, adaptive structure, fiber reinforced plastics, hybrid yarn, electro-mechanical properties

(Some figures may appear in colour only in the online journal)

1. Introduction

Fiber reinforced plastics (FRP) offer high lightweight potential due to their high mechanical properties along the fiber direction combined with a low material density and are being increasingly used for the production of different novel products [1, 2]. For example, the automobile manufacturing company Bayerische Motoren Werke (BMW) used FRP for the first time for passenger cells in larger unit numbers. A total of 130 vehicle components of the electric driven vehicle the BMW i3 are manufactured from carbon FRP [3].

FRP are currently facing a challenge in comparison to the conventional construction materials due to their higher production cost leading to a higher component price [4–6]. Besides the research and development effort towards a cost-effective manufacturing of FRP, the function integration into FRP is also of high research and industrial interest for the composite community. As a functional material for adaptive FRP electroactive materials, magnetic materials, piezo electric bimetals, thermo-pneumatic materials or shape memory alloy (SMA) are investigated.
SMA can be an ideal variant for the actuation of FRP because of their higher energy density \(10^{3} \text{ J m}^{-3}\) compared to other actuator materials such as electrostatic materials \(10^{5} \text{ J m}^{-3}\), magnetic materials \(10^{4} \text{ J m}^{-3}\), piezo electric bimetalas \(10^{6} \text{ J m}^{-3}\) and thermo-pneumatic materials \(10^{6} \text{ J m}^{-3}\) [7, 8]. From the practical application point of view, this higher energy density of the SMA is of great interest because it allows generating high forces with a small amount of SMA and therefore being entirely consistent with the targeted lightweight concept [9]. Additionally, the SMA is commercially available in a wire form enabling compatibility with textile processes. The integration of SMA into the composite material shows a great potential in the high-tech market as it is used mainly in automobile, aerospace, robotic and biomedical sectors [10, 11].

SMA is a material which remembers its original shape after heating over its phase transformation temperature [10, 12–14]. Further, SMA has two solid phases: the martensite phase, at low-temperature and the austenite phase, at high-temperature [10, 15, 16]. The shape change effect or the shape memory effect (SME) is categorized as: one-way SME and two-way SME and superelasticity [17, 18]. One-way SMA does not retain its original position after changing its state. For a cyclic pattern of movement, one-way SMA has to be brought through an external force to return its original shape. Two-way SMA returns to its original shape after removing the heat induced activation. As it is favorable for experiments in this work in terms of the recovery action of the FRP, two-way SMA has been used.

To transfer the force of the SMA into the composite materials efficiently, the friction between the FRP-matrix and the SMA has to be as little as possible. The friction between the FRP-matrix and the SMA hinders the free movement of the SMA in the composite and the interface matrix of the SMA is damaged due to its thermally induced activation.

Nevertheless, there must be some positions, where the force transmission from the SMA to the FRP takes place. This can be executed by embroiderying the SMA in the form of a loop at the edge of the textile semi-finished products by tailor fiber placement method, insertion of continuous SMA as well during weaving or by making a direct adhesive contact between the FRP and the SMA wire at the edge of the FRP.

Kluge et al [19] have shown a method to minimize the fixation of the SMA with the matrix by producing a core–sheath hybrid yarn, where the core consists of the SMA. The sheath acts as a barrier for the infiltration of the matrix into the hybrid yarn, ensuring the maximum SME of the SMA into the FRP and less damage of the interface matrix.

A novel concept for the functionalization of FRP is the integration of the SMA wire into FRP during the textile-technical process itself. In previous works the design and actuation properties of the FRP are described [20]. Here, the adaptive FRP are actuated by a current flow of up to 2 A, where the deformation properties of the adaptive FRP are proportional to the current flow. These experiments are executed over a planar two-dimensional structure. However, practice-relevant components have mostly three-dimensional (3D) geometries. Therefore, for the future industrial application of adaptive FRP with a structurally integrated textile-based actuator, specifically knowledge of the spatial deformation behavior of 3D FRP is of great importance.

In order to disclose the structure property relationship between the 3D FRP and the SMA as actuator material investigations have been performed, which are presented in this paper.

## 2. Materials and methods

### 2.1. Materials

For this study glass woven fabric as reinforcing structure has been taken because of its significant importance in different fields of lightweight applications. 95% of total FRP are made from glass fibers (GF) [5]. 2/2 twill and 1/1 plain woven fabrics are the weave mostly used for automotive applications [21]. For this reason, 1/1 plain, 2/2 twill and unidirectional (UD) warp yarn reinforced plain woven fabrics have been used as a substrate for the adaptive 3D FRP production in order to explore the effect of weave on the actuating properties of 3D FRP. The UD warp yarn reinforced plain woven fabrics have been used for the easy deformation of the composite in terms of a lower number of filaments in wefts during the activation of the SMA. In order to ensure the comparison of the test result, the textile physical parameters of the base materials are kept almost the same. An overview of the base materials used in this work is shown in table 1.

The nickel (Ni) and titanium (Ti) based SMA wire—alloy H ox. Sa. (Menry GmbH, Germany) is used for the production of the shape memory alloy hybrid yarn (SMA-HY). The NiTi based SMA is preferable for most applications because maximum recovery stress and normal working stress are higher than other SMA wire compositions such as copper–zinc–aluminum or copper–aluminum–nickel [11, 22].

This SMA wire along with a glass roving (type EC 300-352, P-D Glassseiden GmbH, Oschatz, Germany) serves as the
core of the SMA-HY. Polypropylene (PP) and the glass staple fibers with 16 μm diameter (UniTex 2000, John Manville, Canada) of both 4 ktex and 2 ktex are taken for the manufacturing of the hybrid yarn. GF are used as a mechanical barrier between the SMA wire as well as the matrix. PP fibers are used for the production of compact hybrid yarn.

2.2. Hybrid yarn production

A friction spinning machine DREF2000 (Fehrer AG, Linz, Austria) is used for the production of the friction spun hybrid yarn (SMA-HY), which is demonstrated in figure 1.

The SMA-HY production is realized in three stages. In the first stage, the SMA along with the glass roving as the core and four glass staple fibers roving as sheath are fed in the spinning drum. The core material for the second and the third stage are the output material of the first and the second stage. The sheath fineness of the second and the third stage are 600 and 400 tex, respectively.

The feeding and the delivery speed of the SMA-HY are 2.5 m min$^{-1}$ and 50 m min$^{-1}$, respectively. The speed of the spinning drum, opening roller and the suction drum are 4500 revolution per minute separately.

2.3. Embroidering of the hybrid yarn on the substrate

The hybrid yarn is embroidered on the substrate by an embroidery machine (ZSK Stickmaschinen GmbH, Germany) based on tailored fiber placement (TFP) method. The TFP process is a further development of the embroidery process, which mainly aims at producing load-adapted textile semifinished products in the stress direction. Apart from the load adapted reinforcing, the TFP is also capable of functionalizing the textile semi-finished products. Figure 2 is an illustration of the TFP process [4].

The textile semi-finished product is fixed on a tenter frame, which is referred to as pantograph. The textile semifinished product moves in X and Y direction to the embroidery head. The embroidery head moves only in the Z direction and rotates around its own axes. The yarn guide is mounted on the embroidery head, which carries out a predetermined oscillating movement. The functional material is placed adjacent to the embroidery needle. Thus, piercing and damage of the functional material is prevented. In addition, yarn guides and embroidery head are pivoted in order to enable flexible yarn deposition. In this experiment, SMA-HY are laid at a distance of 10 mm from one another. The sample is produced according to the predetermined image or vector file on the machine. The SMA-HY is fixed on the substrate by a lock-stitch seam.
2.4. Parameters of adaptive FRP-samples

Adaptive 3D FRP samples vary according to the radius of the curvature, fabric layer and the woven fabric type. Here, a total of four radii of curvature of the adaptive 3D FRP are selected: 5, 15, 25 and 50 mm. These radii of curvature are named as $R_1$, $R_2$, $R_3$ and $R_4$, where the first two radii (5 and 15 mm) are convex radii (negative radii) and another two radii (25 and 50 mm) are concave radii (positive radii). During the activation of the SME, the samples should reduce the curvature. For this reason the SMA-HY are laid in the front side of sample radii $R_1$ and $R_2$ and the back side of sample radii $R_3$ and $R_4$. Each sample is produced in three numbers to reduce production caused deviations. The number of layers for each woven fabric type is varied between two and three layers. The overview of the material parameters are given in Table 2.

The radius of curvature of the adaptive 3D FRP is produced during infiltration according to the shape of the mold. The dimension of the mold accompanied with the textile semi-finished product is shown in Figure 3.

2.5. Production of adaptive 3D FRP

From vacuum infusion resin infusion derived Seeman composites resin infusion moulding process (SCRIMP) is used for the infiltration of the adaptive 3D FRP. SCRIMP contains a flow aid, helping the even infiltration of samples. During the infiltration MGS™ RIMR 135 as the thermoset matrix and MGS™ RIMH 134-RIMH 137 as the hardener by the company of Momentive, USA are used. The mixing ratio of the matrix and hardener is 10.3 by weight.

During the infiltration of the adaptive textile semi-finished products a unicameral system is used in order to reduce the workload. In the unicameral system all textile semi-finished products are infiltrated at the same time. The positive and the negative radii are draped during the stacking of the embroidered substrate on the mold. A graphic representation of the sequence of the infiltration is shown in Figure 4. Prior to infiltration the sheath of the projecting SMA-HY is removed and then the exposed SMA wires are wrapped with sealing tape. Thus, after curing of the samples the sealing tapes can easily be removed and the SMA wire is ready for contact with the electrical circuit. In order to support the draping of the textile semi-finished products to each radius of the mold, special draping tools are used. The draping tools contain a modular structure and are adapted to the inserted shape.

After infiltration, adaptive 3D FRP are tempered at 50 $^\circ$C for 15 h. Through the tempering a full crosslinking between the molecules of the resin takes place. At this temperature the used SMA wire does not activate. A deformed, infiltrated textile semi-finished product is shown in Figure 5. Three identical samples of the adaptive structure are produced together, which are separated from one another by a wet saw.

2.6. Testing

A test set up for measuring of the deformation behavior of the adaptive 3D FRP is shown in Figure 6. A laser triangulator and the sample are maintained on the test stand. A laboratory power supply unit with controlling system is used for the cyclic heating of the adaptive FRP (active process). Here, samples are cooled through the environment (passive process). The maximum deformation point of the adaptive FRP in this work has been defined as mid-point in width direction and 25 mm upward from the free end of the specimen, which is shown in Figure 6 by a hole in a red marking area.

In Figure 6 the operation of laser triangulator is also shown. For the experiment an ILD optoNCDT 1401-20 with a
measuring range of 20 mm and a resolution of 5–10 μm is used. The programming of microcontroller controlled switch is performed by the Arduino development environment.

To define the total number of cycles, various long-term measurements of the test specimens are performed. From the total number of cycles has been derived, which is based on whole samples to be measured and the setting time of the specimen.

Setting time refers to the time duration, in which the amplitude of the deformation curve with increasing number of cycles does not make any significant changes. An exemplary curve of the two layered glass woven fabrics with 50 mm radius of curvature is shown in figure 7. This sample has been chosen because it requires the longest setting time. From this experiment total duration of each sample testing of 15 min is selected, which corresponds to eight heating cycles.

The heating and the cooling cycle of 60 s is determined for this work, and the current flow during the heating and the cooling are set as 1.5 A and 0 A, respectively according to the pretest. The current flow can be set as arbitrary as long as no damage to the SMA wire and the matrix occurs. Here, by this set current flow the generated force of the SMA lies in the elastic zone of the thermoset matrix, therefore no damage of the adaptive 3D FRP occurs.

3. Result and discussion

3.1. Evaluation of the external structural properties of test specimens

The optical evaluation of the side surfaces of the adaptive 3D FRP determines that the resin accumulation decreases in the bending region with the increasing radius of curvature (see figure 8).

Representative details of figure 8 show that used draping aids only conditionally contribute to an optimal draping of the woven fabrics. The relationship between resin enhancement and radius applies to almost all tested samples except the substrate made from UD fabric. Here, all four radii of the UD fabric show very good draping properties in textile semi-finished products, which results in minimum resin enhancement in the bending region. The cause of this effect is the low rigidity of the UD woven fabric in the weft direction. Thereby, a very good drapability around the mold is possible. Samples with lower resin concentration than specimens with higher resin concentration in the bending region allow a better deforming by the SMA-HY because with low resin concentration the bending strength of adaptive FRP is reduced.

The geometry of the radius of curvature (positive or negative) has a significant influence on the position of the SMA-HY in FRP. This effect is shown in figure 9 with
exemplified specimens of radii $R_1$ (negative radius) and $R_4$ (positive radius).

From figure 9 it can be concluded that the back side surfaces of samples containing negative radii are rougher than those of samples with positive radii. This effect is caused through the vacuuming in the infiltration process. The smooth surface occurs because after vacuuming the textile semi-finished product remains in the same position. On rough surfaces, due to the vacuum pressure the carrier material displaces partially.

### 3.2. Comparison of the deformation behavior

In order to compare the deformation behavior, test specimens are heated and cooled by 1.5 A current flow and by the environment (room temperature), respectively.

This behavior is measured from the cycle shown in figure 7, from which the heating and the cooling cycles are

![Figure 8. Exemplary representation of the influence of the radius on the resin enrichment in the bending region. The black lines on the fabrics of the specimens are the positioning aid during the SCRIMP process.](image)

![Figure 9. Exemplary comparison of negative and positive radius represented by the samples $R_1$ and $R_4$ with plain woven fabric.](image)

![Figure 10. Response characteristics of adaptive FRP in context of heating and cooling cycle of maximum and minimum current flow of 1.5 A and 0 A.](image)
Figure 11. Comparison of the deformation rate during the heating cycle at maximum current flow of 1.5 A.

Figure 12. Comparison of the deformation rate during the cooling cycle, without applied current.
resemble to each other. The displacement of samples, generating from the heating and the cooling cycle, with radii from \( R_1 \) to \( R_4 \) are shown in figure 10.

Figure 10 shows the heating and cooling cycle of all four radii (\( R_1 – R_4 \)) over a time from 0 to 120 s. It is seen that with enlarging radius, the deformation behavior of the adaptive FRP is increased. From figure 10, it is seen that the deformation of radii \( R_1 \) and \( R_2 \) is very low in comparison with radii \( R_3 \) and \( R_4 \). This is due to the effective curvature length of the SMA-HY in the adaptive FRP. Due to different radii of samples, the effective curvature length of samples is also varying. Here, the effective curvature length of samples with radii of curvature \( R_1 \) is minimum and \( R_4 \) is maximum. For this reason, samples with radius \( R_4 \) show higher deflection than others.

Additionally, from figure 10 it can be concluded that the deformation of the adaptive composites in heating and the cooling cycle take place differently. This is due to the active heating by a current flow of 1.5 A and a passive cooling of adaptive samples by the environment.

From the measured deformation of adaptive FRP in figure 10, the deformation rate can be calculated since the deformation is measured over time. The stated values of figures 11 and 12 represent the mean values of the respective three identical test specimens.

In addition, the influence of the material parameter, i.e. woven fabric type and number of layers, on the deflection behavior of the adaptive 3D FRP has been investigated. The influence of material parameters increases with the increased radius of curvature of the 3D FRP because the bending strength is lower with the increasing radius of curvature of samples. Therefore, the curves for the radii of \( R_3 \) and \( R_4 \) are especially different. P3L and P2L are the most rigid among other samples. The maximum heating and cooling speed difference between these two samples is very low.

The tendency of deformation for all samples with an arrangement of P3L, P2L, T3L, T2L, UD3L and UD2L are gradually increasing, which are clearly shown in samples with radius \( R_4 \). This deformation tendency of the above mentioned samples is due to the bending strength of adaptive FRP, and is valid for both the heating and the cooling cycle.

3.3. Comparison of the setting time

For the application of 3D FRP with integrated SMA-HY, the setting time is significant because after this time the analogous heating and cycles take place, which enables test specimens to perform approximately reproducible and uniform deformation.

As there is no standard for the evaluation of this parameter, a qualitative analysis of the setting time is taken. Figure 13 demonstrates the deformation of adaptive 3D FRP in the time range from 0 to 360 s.

From figure 13, it can be derived that the sample with the radius of curvature \( R_1 \) and \( R_2 \) shows a predominant displacement above the zero line for the first heating cycle, i.e. 0–60 s, which is probably caused by conventional thermal expansion of the sample, i.e. the dimension of the sample expands by the application of heat. This can be recognized by the extent of the test specimen above the zero line. Samples of the radius of curvature \( R_3 \) and \( R_4 \) also show the same deformation behavior, which is also recognized by the graph above the zero line. From the second heating cycle (120–180 s) of
the adaptive 3D FRP, all samples show the typical deformation behavior due to the SME i.e. samples contract due to the thermally induced activation of the SMA in samples.

In the next section the exact analysis of the amplitude has been executed, where the additional information of the setting time is being expected.

3.4. Comparing the amplitude gradient as a function of the cycle

The attainment of the deformation behavior over the measuring time is shown in figure 14. From this figure a comparison between the amplitudes of the individual cycles are carried out. This evaluation is performed exemplarily from the average measuring values of three specimens of the sample UD3L $R_3$. From the graph of figure 14, it can be seen that with the increasing number of cycles the deformation paths deviate more from the zero line.

The difference between cycles with respect to the deformation path decreases with the increasing number of cycles. From the sixth cycle an approximately constant deformation over the cycle time can be expected. Thus, these values are specified in the comparison of the setting time (previous section).

Furthermore, it can be clearly seen from figure 14 that only the first heating cycle at the beginning of the heating phase contains a conventional thermal expansion of the SMA wire. After the first heating cycle the expected deformation patterns of the UD3L $R_3$ are available.

4. Conclusion

Electro-bending properties of the adaptive 3D FRPs are investigated in this work. 3D FRP containing hybrid yarn with SMA are produced successfully, which included producing the SMA hybrid yarn, laying this hybrid yarn on the glass woven fabrics by TFP method and finally making the composites by a thermoset resin. Besides woven fabrics, the SMA can also be applied on the other reinforcement fabrics, such as warp or weft knitted, braided and non-woven fabrics, by TFP. The developed adaptive 3D FRP in this research can be used as vibration damping elements, translational or rotational moving elements or as a gripper in robotics. The produced samples are varied according to the structural parameters such as different radius of curvature of the adaptive 3D FRP and the layer of the textile semi-finished product. As textile semi-finished product, woven fabrics of different woven type are selected.

The electro-mechanical testing is executed through the actuating properties of the adaptive 3D FRP by measuring the deformation speed, setting time for the deformation and the amplitude gradient of the 3D FRP. These parameters are tested with respect to different woven fabric type, different number of fabric layers and different radius of curvature of the produced adaptive 3D FRP. The size of the radius has a significant influence on the deformation rate of the adaptive 3D FRP. The actuation properties are proportional to the radius of curvature of the adaptive 3D FRP. The actuation of the adaptive 3D FRP also depends on the drapability of the used fabrics, which results from the interlacement between warp and weft yarns. By reducing the number of layers of the used fabric more actuation can be realized since the bending strength of FRP is reduced. Regarding the deformation rate, it can be said that the deformation during the heating cycle occurred slightly faster than in the cooling cycle. However, the actuating properties of the SMA are realized in the adaptive 3D FRP and the actuation property of adaptive 3D FRP are dependent on different material parameters.

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