Analysis of the deformation speed of adaptive fiber reinforced plastics with variable hinged width

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Abstract. The functionalization of the fibre reinforced plastics plays an important role for the progressive development of lightweight materials. Integrating functional material, Shape Memory Alloys for instance, in the reinforced structure an adaptive fibre reinforced plastics can be developed. Adaptive fibre reinforced plastics is deformed due to the shape memory effect of shape memory alloys. By varying the geometry of adaptive fibre reinforced plastics, such as cross-section variation, their deformation as well as the deformation speed can be changed. However, this paper presents the influence of hinge width on the deformation speed of fibre reinforced plastics with integrated shape memory alloys. In order to achieve this aim, friction spun hybrid yarn with shape memory alloys as core are produced and the produced yarn are embroidered by means of tailored fibre placement on the hinged reinforcing structure before impregnation. The deformation speed of adaptive hinged fibre reinforced plastics is found to be the proportional to the hinged width.

1. Introduction
The importance of fiber-reinforced plastics (FRP) for different novel products in automobile, aerospace or wind energy is growing steadily in recent years [1]. The integration of functional materials in the reinforcement fabrics of FRP is a breakthrough for developing different innovative products for lightweight applications. Electroactive materials, magnetic materials, piezo electric bimetals, thermo-pneumatic materials, shape memory polymers or shape memory alloys (SMA) are some examples of functional materials, which are some potential candidates to act as an actuator in the FRP. However, SMA shows their novelty than that of other functional materials due to their higher energy density (10³ J/m³) [2]. Moreover, SMA is commercially available in the wire form, which is one of the most important criteria for the textile technical integration of SMA in the reinforcing fabric.

SMA is a material which remembers its original shape after heating over its phase transformation temperature [3]. The thermally induced shape-memory effect (SME) is activated by Joule heating. Below the transformation temperature, the twinned martensite alloy is deformed plastically without damaging its crystalline structure. By thermal induced activating the detwinned SMA above its transformation temperature includes a phase change into an austenite state, which is accompanied by the regression of deformation. By cooling SMA to temperatures below the transformation temperature triggers the phase transition into martensite and thus into the initial state.

In previous work, the planar two-dimensional and three-dimensional adaptive FRP has been developed and extensively characterized [4-7], where the cross-section of adaptive FRP are constant. In order to increase deformation of adaptive FRP with regard to its length, the cross-section of FRP is varied by developing the adaptive hinged FRP (AHFRP) [8].

However, this work focuses on the deformation speed characterization of adaptive hinged FRP (AHFRP). The AHFRP is realized by integrated textile-based actuators, which is produced by the friction spun technology in the form of a core-sheath hybrid yarn (HY). The SMA-HY contracts during the thermal induced activation of SMA by SME. In order to investigate the influence on the
deformation speed of AHFRP, investigations in this work are varied according to the geometry of AHFRP by varying the hinged width.

2. Materials and methods

2.1. Materials

As a SMA-actuator, Alloy H ox. sa. (Memry GmbH, Germany) is used in this research for the development of AHFRP. The transition temperature, diameter, tensile strength and the elongation at break of the used SMA are 95-110°C, 0.305 mm, 1152.7 MPa and 11.1%, respectively. The parameter of reinforced fabrics for the realization of AHFRP is stated in Table 1.

Table 1: Parameter for the reinforcing structure

| Parameter                  | Value   |
|----------------------------|---------|
| Material                   | Carbon  |
| Interlacement              | Plain   |
| Areal weight (g/m²)        | 245     |
| Roving fineness (tex)      | 200     |
| Warp rovings density (rovings/cm) | 6       |
| Weft rovings density (rovings/cm) | 6       |

As a matrix material, resin and hardener (MGS RIMR 135 and MGS RIMH 134 – RIMH 137, Hexion, Inc. USA) in a mixing ratio of 10:3 by weight are utilized.

2.2. Production of SMA-HY

For the free and even mobility of SMA in AHFRP during its thermal induced activation, a barrier between SMA and the matrix of AHFRP is necessary. This barrier aims at not only to proper utilize SME of SMA but also to avoid the delamination or cracks in the interface of SMA and matrix in AHFRP. For this purpose, a core-sheath hybrid yarn structure is developed, where SMA acts as the core [5]. The glass staple fibres of 2 ktex and the polypropylene staple fibres of 4 ktex forms the sheath. The SMA-HY is produced on the DREF2000 friction spinning machine (Fehrer AG, Linz, Austria). The feeding of the sheath material and the produced SMA-HY are shown in Figure 1. The SMA-HY is produced in three process stages in order to produce even and compact SMA-HY. The fineness of the sheath in the first, second and third stages are 500, 600 and 400 tex, respectively. Process parameters for the production of SMA-HY are listed in Table 2.

![Feeding of the sheath material for the production of SMA-HY (left) and the produced SMA-HY (right).](image)
Table 2: Process parameters for the three staged production of SMA-HY

| Process parameters            | Corresponding value |
|------------------------------|---------------------|
| Feeding speed                | 2.5 m/min           |
| Sheath feeding finesses       | 8 ktex              |
| Delivery speed                | 50 m/min            |
| Spinning drum speed           | 4500 rpm            |
| Opening roller speed          | 4500 rpm            |
| Central suction speed         | 4500 rpm            |

2.3. Concept for the Realization of adaptive hinged preform

The adaptive hinged preform can be realized by laying the patch fabrics with different length but identical width in a step wise manner between top and bottom fabric layers. In the first step, the bottom fabric layer can be laid. Then, three patch fabric layers can be positioned in a step-wise manner. In the last step, the top fabric layer can be positioned on patch fabrics. On the top fabric layer, SMA-HY can be integrated mechanically. A theoretical concept for the realization of adaptive hinged preform is demonstrated in Figure 2. In this research, three different hinge widths of 40 mm, 80 mm and 120 mm are realized in order to reveal the influence of the structural geometry (hinge width) on the deformation speed of AHFRP.

![Concept for the development of adaptive hinged preform.](image)

2.4. Integrating of SMA-HY on the hinged preform

The SMA-HY is mechanically integrated with the preform by the SGY 0200-650D embroidery machine (ZSK Stickmaschinen GmbH, Germany) using the tailored fibre placement (TFP) technology. The size of the embroidery frame is 600*300 mm², on which the reinforced fabrics are arranged in a step wise manner in order to develop a hinged preform. In the first step of fabric laying, the bottom fabric layer is laid and aligned in the embroidery frame. Then, three patch fabric layers are positioned in a step-wise manner. In the last step, the top fabric layer is positioned on patch fabrics and the entire structure is clamped by the magnetic tensioning device on the embroidery frame. The alignment of the bottom, patch and top fabrics layers is controlled by positioning aid, which are set parallel to the x-axis of the feed device on the embroidery machine. The integration of SMA-HY on the reinforcement fabrics are shown in Figure 3.

![Figure 2]
A reproducible meander distance for integrating SMA-HY on the preform is not possible if the distance between two adjacent SMA-HY’s is less than 10 mm [8]. Hence, adaptive hinged preform with the meander distance of 10 mm, 12.5 mm and 15 mm are produced.

2.5. Impregnation
Considering the cost-effectiveness and to produce high strength and high quality Resin Transfer Moulding process is used for the impregnation of adaptive pleated preform. In order to ensure the proper distribution of the resin in the reinforced fabrics and to avoid the dry state over the structure, an additional flow aid is used. The resin used for impregnation is thermosetting in nature. After laying the adaptive preform on the mould, it is evacuated by the vacuum pump along with a non-permeable film placed on it. The resin is entered into the system by the help of negative pressure. Then the whole sealed system is 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 FRP. The impregnated part is tailored by the laboratory wet saw in a size of 300*100 mm². For the electrical testing, AHFRP with the average meander distance of 12.5 mm is considered further. Adaptive hinged preform (before impregnation) and AHFRP (after impregnation) are shown in Figure 4.

Figure 3. Integrating of SMA-HY on adaptive hinged preform by means of tailored fiber placement technology.
2.6. Deformation speed characterization of adaptive hinged FRP
The SMA in AHFRP is activated electro-thermally by a laboratory power supply unit of type EA-PS 3032-10 B with a current flow controlling unit. Due to its ease of use and flexibility, a LilyPad Arduino is used for periodic switching of current flow. Here, on- and off-time of the current flow are programmed for 40 s, respectively. During on-time the applied current flow is 1.5 A. No current flows during the off-time causing a passive cooling of AHFRP by the ambient temperature. The deformation of AHFRP by the on- and off-time of the current flow is shown in Figure 5. During the periodic heating and cooling cycle, the resulting deformation of AHFRP is measured simultaneously by a laser triangulator of type optoNCDT 1401-20 (Micro-Epsilon GmbH, Germany), featuring a contact-free and therefore mechanically reactionless measuring principle. The deformation and current flow data are transmitted in real time to a measuring computer with a LabVIEW based data acquisition and processing software.

Figure 4. Adaptive hinged preform (left) and AHFRP (right).

Figure 5. Deformational speed behavior of AHFRP by the on (deformed position) and off of current flow (straight position).
3. Results and discussions
The deformation speed of AHFRP can be calculated using the difference quotient between two adjacent measurement points according to equation (1).

\[ V(k) = \frac{s(k+1)-s(k)}{t(k+1)-t(k)} \]  

Where, \( V(k) \) represents the speed in the data point \( k \). \( s(k+1) \) and \( s(k) \) represents the deformation of AHFRP in the data point \( k+1 \) and \( k \), respectively. \( t(k+1) \) and \( t(k) \) represent the time in the data point \( k+1 \) and \( k \), respectively.

The deformation speed curves of AHFRP based on structural parameter of hinged width variation by different heating and cooling cycle are presented in Figure 6.

![Figure 6. Deformation speed of AHFRP by different hinge width (left = deformation during heating cycle and right= deformation speed during cooling cycle).](image)

In general, the deformation speed of AHFRP during the cooling cycle is higher than during the heating cycle. The phase changing of integrated SMA from martensite to austenite is responsible for the deformation of AHFRP. During the heating cycle, the deformation speed of FRP is lower due to the ability of the sample to resist the distorting (deformation) influence. During the cooling cycle, the deformation stress is removed and since the sample is within the elastic limit, the cooling cycle is aided by this factor thereby making the sample to return faster to its original shape. In the first 2 s, the deformation speed of samples can easily be distinguished from one another. After the 2nd s of the deformation, the deformation speed is almost the same for all samples, which indicates that the internal stresses of the entire structure leads to equilibrium. The deformation speed of AHFRP tends to reduce from larger to smaller hinge width of 120 mm to 40 mm, which is also demonstrated in Figure 6. The AHFRP become stiffer by reducing the hinged width is the reason behind this phenomenon [7].

4. Conclusion
The deformation speed characterization of AHFRP by variable hinged width is executed in this work. For the optimum use of SMA in AHFRP, it is converted in core-sheath hybrid yarn. The adaptive hinged preform is realized by laying the patch fabrics of different length. On the adaptive hinged preform, SMA-HY is integrated by the tailored fiber placement technology. Results show that the
deformation speed of AHFRP during cooling cycle is higher than that of during heating cycle. The deformation speed of AHFRP is higher by increasing the hinge width.

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