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A statistical approach for the fabrication of adaptive pleated fiber reinforced plastics

Moniruddoza Ashir*, Jan Hindahl, Andreas Nocke, Chokri Cherif

Institute of Textile Machinery and High Performance Material Technology, Faculty of Mechanical Science and Engineering, Technische Universität Dresden, 01069 Dresden, Germany

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ABSTRACT

The increasing demand for fiber reinforced plastics for different high-tech lightweight applications requires their continuous development, for example, by means of high functional density. Among various smart materials, fiber reinforced plastics can be functionalized by actuator materials, in particular shape memory alloys. This paper presents a statistical approach to the fabrication of adaptive pleated fiber reinforced plastics. Three geometrical factors – pleat thickness, pleat height and the spacing between two pleats were identified by the half-normal probability plot that affect the deformation of adaptive pleated fiber reinforced plastics during the activation of shape memory alloys. Overall, four responses were evaluated by means of the design of experiment. Significant statistical models were found for the deformation, level loss per cycle, heating and cooling speed of adaptive pleated fiber reinforced plastics. These statistical models were validated through experimental data by the goodness of fit function. The results of the statistical model tended to fit experimental results.

1. Introduction

The increasing global environmental pollution caused particularly by carbon dioxide emissions has put great emphasis on the development of sustainable materials. Consequently, material scientists have drawn more attention to the development of sustainable low-density materials using high-performance textile fibers and matrixes, so called fiber reinforced plastics (FRPs), in contrast to typical construction materials. Besides low density, FRPs exhibit higher tensile strength, in addition to high corrosion and fatigue resistance [1]. By these virtues, FRPs are employed for various novel applications in the automotive [2], aerospace [3] or marine industries [4], which reduce weight and thus carbon dioxide emissions, leading to enhanced environmental sustainability.

Reinforced fabrics for the fabrication of FRPs are produced by weaving, warp or weft knitting, braiding and non-woven technologies. Due to their high production rate and the possibility for producing a diverse range of fabric architectures, particularly for 3D fabric structures, weaving is the favored process for the manufacture of these reinforced fabrics [5].

By integrating functional materials – particularly active functional materials – into reinforcing fabrics, FRPs can be utilized more efficiently. Consequently, the market value of FRPs can be further increased. Active functional materials can convert one form of energy to another. Thermal, mechanical, magnetic and electrical energy are the basic forms of energy, whose form can be interchanged facilitated by active functional materials [6]. Piezoelectric [7], electrostrictive [8] and magnetostrictive materials [9] as well as shape memory polymers [10] and shape memory alloys (SMAs) [11–13] are some examples of active functional materials that can improve the response to external stimuli. Moreover, SMAs have drawn significant attention from the composite community for the fabrication of adaptive FRPs due to their high energy density of $10^7\ \mathrm{J/m^3}$ compared to that of other active functional materials [14].

In recent years, several publications have documented the fabrication and analysis of adaptive FRPs with SMAs [15–20]. In previous works conducted by the authors, the development of adaptive 3D FRPs and adaptive hinged FRPs have been reported, where SMAs were textile technically integrated into the reinforced fabrics by the tailored fiber processing technology [11,21–23]. Other studies have presented the one-step manufacturing of adaptive reinforced structures for the development of adaptive FRPs [24–26]. However, no statistical modelling for the fabrication of adaptive FRPs has been shown in previous studies.

Hence, the aim of our research project was the statistical modelling and validation of adaptive FRPs. The achievement of this objective demanded the simulation-based identification of relevant factors for the statistical modelling of adaptive FRPs, the analysis of different responses by the design of experiment (DOE) and finally the validation of

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* Corresponding author.
E-mail address: moniruddoza.ashir@tu-dresden.de (M. Ashir).

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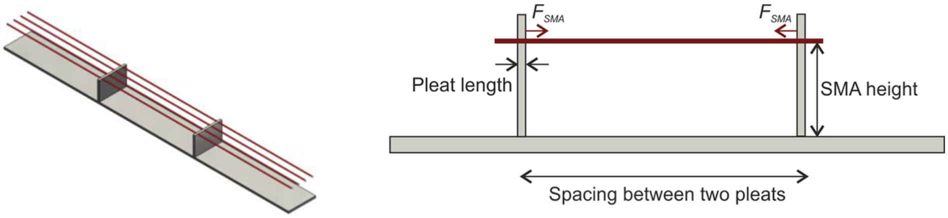

Fig. 1. Schematic diagram of APFRPs. SMAs are marked by red lines. F_{SMA} is the force, generated by SMAs during their activation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the statistical model by the goodness of work function of the responses.

2. Theoretical interpretation of APFRPs

2.1. Conception of APFRPs

In this research project, an example of adaptive FRPs, i.e. adaptive pleated FRPs (hereafter termed APFRPs), was chosen for statistical modelling and validation. The APFRP was a smart folded FRP, where SMAs were interlaced with the upper layer of reinforcing fabrics in the pleat positon during the single-stage manufacturing process. This type of pleated structure was developed for the realization of single-axis and intrinsic adaptive FRP. The schematic diagram of APFRPs is shown in Fig. 1. The APFRPs consisted of a narrow base plate and two pleats as an integral component produced in a single stage of weaving, where two pleats were stated perpendicular to the narrow base plate. Within APFRP structures, SMAs were interlaced to the pleat of APFRPs at regular intervals. Fig. 2

2.2. Simulation-based identification of relevant factors

By the Finite Element Method (FEM) software Altair HyperWorks Suite, a series of experiments with different configurations of APFRPs were simulated to identify the significant factors for their deformation. SMAs were interlaced in APFRPs as rod element. During the thermal induced activation of SMAs, they generate the force to deform the APFRPs. The maximum recovery strain of SMA during the thermal induced activation was specified as 8% [27]. During the thermal induced activaiton, SMAs changed their state from martensite to austenite. During the phase transition of SMAs, the martensite and austenite imposed stiffness was neglected, as described in [28]. The mechanical values of the austenite phase were used for the simulation. The mechanical values for carbon fiber reinforced plastics (CFRPs) and glass fiber reinforced plastics (GFRPs) were employed for the simulation; they are listed in Table 1. The size of APFRPs for simulation was defined as 300 mm × 100 mm × 0.155 mm^3.

The influence of the spacing between two pleats (a_s), pleat height (D_h), number of pleats (n_s), pleat thickness (t_s) and material type (CFRPs, GFRPs) was evaluated by simulation (see Fig. 2). The pleat thickness was varied by inserting no core or an additional core of 4 mm in between two layers of each pleat. The additional core was made from Rohacell-Foam.

Table 1
Mechanical values of SMA, CFRPs and GFRPs for simulation.

	SMA	CFRPs	GFRPs
E-Modulus E|| in MPa	70,000	140,000	44,500
E-Modulus E⊥ in MPa		7656	13,000
Poisson's ratio, η	0.33	0.263	0.25
Density, ρ in g/cm^3	6.5	1.4	2.0
Diameter, d in mm	0.305		
Fictional coefficient of thermal expansion in the austenite phase, α_{Fik} in °C	0.0008		

All factors were varied in two levels, so that the number of runs of $2^5 = 32$ resulted in a full factorial experimental design. An experimental overview of the simulation conception is provided in Table 2. Similarly to the actual test situation, one end of the APFRP was clamped orthogonally to the SMA direction, while the other end remained free. The deformation of the sample at the free end in the z-direction and the axial tension of SMAs were plotted in order to evaluate the goodness of fit of the APFRPs.

3. Materials and methods

3.1. Materials

Among different SMA actuators, a NiTi-based SMA was selected for this research project because of its maximum shape memory effect, corrosion resistance and high stability [29]. Alloy H ox. sa. (Memry GmbH, Germany), a class of NiTi-based SMAs, was chosen due to its favorable actuator quality [19]. The diameter, transition temperature, tensile strength and elongation at break of the employed SMAs were 0.305 mm, 82–90 °C, 1164.08 MPa and 12.16%, respectively [19,30]. The reinforced

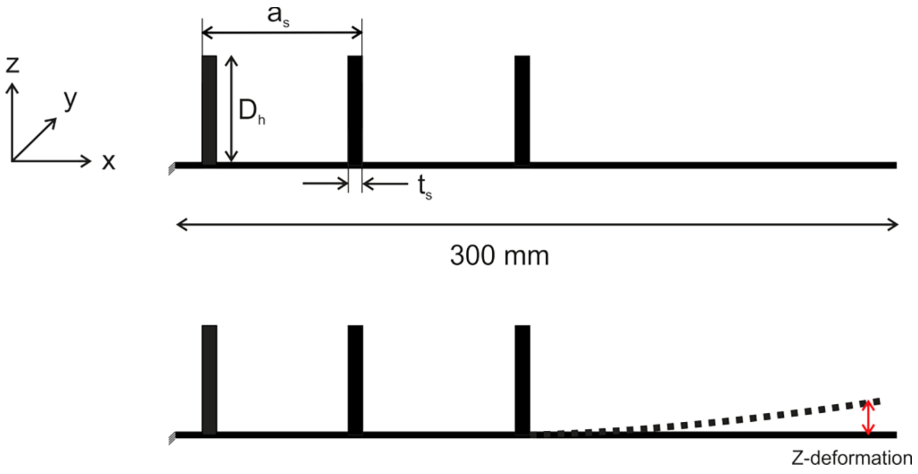

Fig. 2. Geometric factors of the simulation for the conceptual design and, deformation during the thermal induced activation of SMAs.