SWITCHABLE FIBER REINFORCED STRUCTURES – FROM SMART MATERIALS TO COMPONENTS

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Abstract
In this contribution we present a new method as a "basic toolbox" for proper design of active composite structures. The characterization of the structure is described, including the properties of the hosting composite material, the proper choice and characterization of the active material which is to be integrated and the behavior of the complete integrated active component. The finite element model which was used to design the active component is presented. In order to improve prediction accuracy and functionality of this phenomeno-logical modeling approach the behavior of the integrated active material, namely SMA, is analyzed separately. An application-oriented finite element model able to predict the structure shape in hot and cold states enables more complex designs and demonstrates the potential of this new technology for various applications.

1 Introduction
Increasing functional integration shows promise for enabling substantial savings concerning material usage, exploitation of available space and cost of new products. Fiber reinforced composite materials allow for easy integration of sensors or actuators into structural components which turns these structural materials into active or nowadays so called smart materials [1]. In practical use energy efficiency, robustness and simple design are key requirements for these smart materials or smart structures. For many applications it is sufficient to integrate a bi-stable ("zero – one") switchable functionality into the component where energy is not required in the switched state but is for switching. Even though the necessary electrical power supply for driving additional actuators is already available in many products, it is obvious that future product development will be driven mainly by the need for energy- and cost efficiency. Therefore, low energy consumption will become more and more important, opening up many new application possibilities for this new technology of adaptive composite materials.
High performance composite materials are already used in a wide range of applications and their share is still increasing, as shown by the newest aircraft of the leading manufacturers with over 50% composite materials [2]. The main advantages of these materials are their high strength, stiffness and low density. In combination with many degrees of freedom in design high performance components can be developed [3].
Furthermore composite materials offer an astonishing simple solution to the challenge of switchable structures: bi-stable structures, made by a tailored unsymmetric architecture of the reinforcing fibers. These materials with special stacking sequences of unidirectional fiber

layers can be designed in order to generate two different stable geometric shapes. These bi-stable structures have been investigated by [4] [5] [6] concerning the effects of design parameters, the “snap-through” behavior, and the accuracy of simulation models. It is important to point out that there is a minimum area size requirement to archive the bi-stable state.

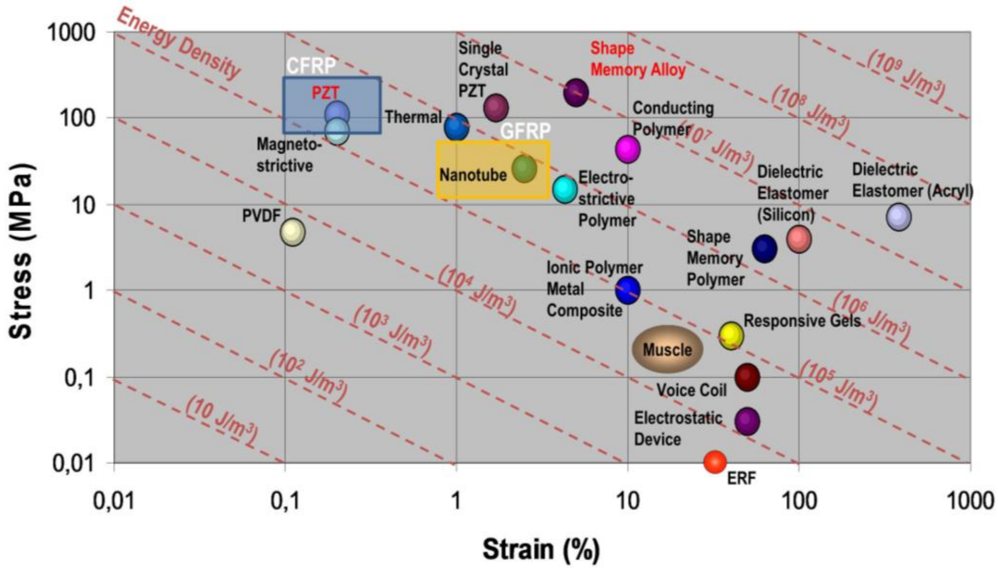

Figure 1. Active materials and their performance in comparison to CFRP and GFRP

Regarding the active materials to be used in smart structures there is a broad variety of different materials ranging from dielectric polymers over piezoceramics (like PZT) to shape memory metals. Popular ones to be integrated in FRP are PZT and shape memory alloys (SMA) because of the matching performance in terms of possible strains and stresses (see Fig. 1). Several investigations try to assume various functionalities with these active materials, e.g. energy harvesting, active or passive damping, shape morphing and many others. Compared to PZT the SMA is able to perform high strain, but is not as dynamic as the piezoceramic material [1]. Former investigations used these active materials to initiate the “snap through” and it was shown that both are suitable [7] [8] [9] [10]. If actuation at high frequencies is not required, the heat activated motion of the SMA is a good choice, instead of the PZT which mostly requires high voltage for actuation.

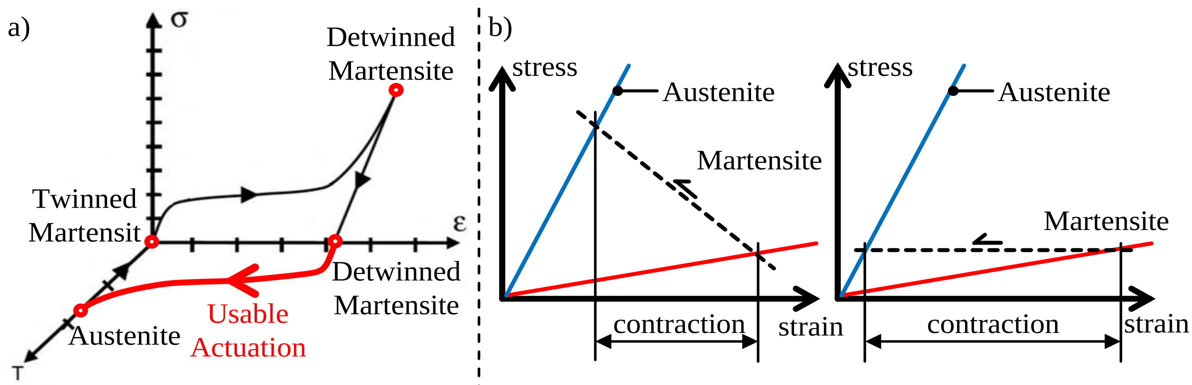

Figure 2. a) One-way effect according to [11]. b) Working against bias spring and static load according to [12].

The actuator effect of SMA is based on the phase transition between austenite and martensite. The effect show in Fig. 2 a) is the so called one-way-effect. The material only remembers the

geometry in the austenite phase. The other effects which can be obtained are the two-way-effect and pseudoelasticity. Even though there is a two-way effect seen in this investigation, it is necessary to differentiate between the above mentioned "trained" two-way effect and the later shown load initiated two-way effect. The "trained" two-way effect can only be obtained after a time consuming cycling of the material. By contrast the load initiated two-way effect offers a cheap way to gain this two-way functionality [11].
To describe the load-dependent material behavior, mostly thermal cycling at a constant load is presented [11], more application related is to describe stress vs. strain behavior with respect to the hot and cold states, shown in [12]. Fig. 2 b) shows the expected behavior in principle for two different load types: working against a bias spring or against a constant force.
Many simulation models have been developed such as [13] [14] [15]. Thermo-mechanical or multi-physics analysis is necessary for proper description of the actuating behavior of the material. For most cases such simulation effort is way too complicated for the design process of a whole composite-component. A complexity reduced design tool must be developed to enable systematic design of SMA actuators in the well-established development processes of FRP parts and structures. A validated phenomenological model should be suitable for potential applications like clamping or morphing/switching the shape, as they can be found in aeronautics, automotive and construction for example.
Fundamentals are presented in more detail in [16]. This paper concentrates on the load-initiated two-way effect in SMA-composite structures.

2 Experimental

2.1 Smart Structure

To demonstrate the performance of CFRP-SMA composites a planar CFRP sheet had to be bent by SMA wire actuators. Besides the high possible actuation strains and the easy way of activation by joule-heating, there are big advantages concerning the integration in FRP, if SMA material is used in wire form. Due to the high cost of thin SMA-filaments of about 20µm and difficulties in handling, SMA in wire form, consisting of Alloy M with oxide surface of manufacturer Memry GmbH was chosen. After delivery the material is heated up above the austenite finish temperature as preconditioning to ensure a uniform condition. To prepare the SMA wires for actuation they were stretched in order to introduce a remaining elongation of about 2%, not knowing exactly how much the strain has to be increased to reach the contraction of 2% actuating travel at projected 138MPa. In order to activate the wire via joule heating a laboratory power supply is used. As structural material unidirectional carbon fiber prepreg, namely CE 1007-150-38 from SGL epo GmbH with a thickness of 0.14mm was used. The material properties and the manufacturing process of the CFRP sheets are described in [16]. Due to the circumstance that the contraction of the SMA wire is temperature activated, a cold hardening adhesive was used to bond the wire to the laminate.

2.2 Wire Testing

The wires are tested in a tensile testing machine with some special clamps for electrical insulation to the testing machine, so the wire can be heated electrically during the test process. End of heating and cooling is controlled by temperature measurement using thermal imaging. To realize a constant load during actuation of the SMA, the control of the testing machine was used, accepting some deviation during fast changes. Working against stiffness was realized with different tensile springs connected in series, while the position of the tensile machine was fixed. For strain measurement the macro displacement transducers of the testing machine were used.

2.3 FE-Model

First objective of this finite element modeling approach is to identify a useful combination of CFRP structure and applied active material. This is the case if the working point of the

actuation (2% actuating travel/ 138MPa) and a noticeable deformation is realized within the first contraction, however without claiming to represent a realistic behavior of the structure, for all other stresses or strains. Furthermore this approach gives a first impression of how to predict the behavior of the structure in a wider range and how to include the load initiated two-way effect functionality into the structure.
In order to conduct simulations during the design process of active components, the underlying model of the SMA-material behavior has to be as simple as possible. As a first step in this direction we describe in this paper how a phenomenological model, with different levels of complexity, can be derived from characteristic features of measured stress-strain relations of SMA wires. For validation purpose this simplified material-model is integrated in a FE-simulation of the composite structure, wherein the SMA-wires were approximated with a layer of shell elements type S4, of course with variable cross section and center of area, so effects of different diameters and different numbers of wires can be analyzed. In order to approximate the behavior of several separated wires in a shell layer other properties are set zero or nearly zero to avoid numerical problems.

Property	E_1	E_2	ν	G	α_{11}	α_{others}
Value	$\mathbf{E_{SMA}}$	~ 0	0	~ 0	$\boldsymbol{\beta_{SMA}}$	0
Unit	[GPa]	[GPa]	[ ]	[GPa]	[1/K]	[1/K]

Table 1. Properties of SMA Shell

Furthermore to avoid the complexity of thermo-mechanical coupled simulation, the expansion of the SMA wire is applied homogeneously in direction of the wire to the SMA shell element. The added expansion term is similar to thermal expansion:

$$\varepsilon_{SMA} = \beta_{SMA} \cdot \chi_{SMA} \tag{1}$$

where χ_{SMA} is a control parameter and β_{SMA} is the expansion coefficient. The stiffness E defines a line were the contraction will stop, when the parameter reaches the desired value, representing the hot or cold state (see Fig. 3).

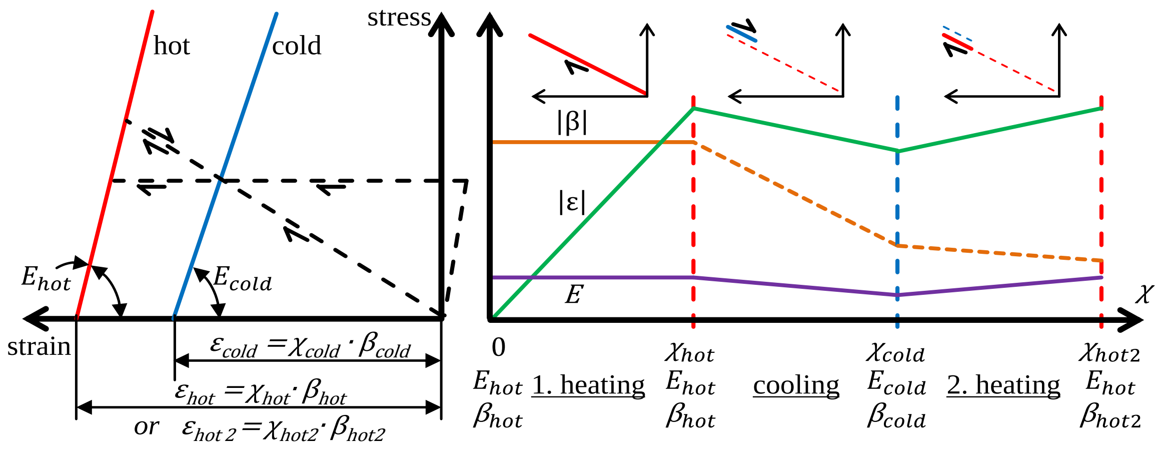

Figure 3. Simulation parameters and their variation for different values of χ during first and second heating cycle

To realize a contraction while χ is still rising, negative strain coefficient β_{SMA} must be applied. The control parameter χ can be increased from 0 to 300, for example, where value 0 defines the initial state; 100 describes the hot, contracted, state; 200 the cold, elongated, state and 300 again the hot state of a second heating cycle. The purpose is to give a precise prediction of these end-states but not to consider the changes over time or temperature in between. Of course no unrealistic behavior shall appear in between. Assumed that the motion limit can be described as a line, as already shown in Fig. 2 b), in Fig. 3 the situation is presented when both states, hot and cold, are approximated with a simple line. Therefore the intersection points with the abscissa and the gradients must be identified. The gradient is used as stiffness E_{SMA} and the coefficient β_{SMA} can be calculated with equation (1) and the intersection point ε_{SMA} and the specified value of χ_{SMA}.

The first contraction was simulated by increasing the parameter χ constantly until 100, β_{SMA} and E_{SMA} have their constant values β_{hot} and E_{hot}. During contraction the behavior between origin and the fully contracted state at the hot line is completely controlled by the surrounding structure or by applied loads. For the next step, parameter χ was increased constantly to 200, the cold state, while parameters β_{SMA} and E_{SMA} have to be modified to their cold values β_{cold} and E_{cold}. It is important to notice, that the change of β has to be inversely proportional to χ, otherwise no linear deformation behavior can be obtained between 100 and 200 and unrealistic deformation states can appear. In principle the values of β, E and ε over χ are shown in Fig. 3. Furthermore the expected values for a second heating are shown, provided the same hot line is reached again.

2.3.1 Smart Composite Design Studies

In order to find a smart structure design allowing for the desired working point at the hot state, it is not necessary to ensure that all other points of the hot state line represent realistic behavior. The objective was to identify a design where the known working point is realized.

The laminate and its layup are also represented by shell elements of type S4. In this analysis we modified the number and/or the orientation of plies. Concerning the active material the design space includes two different diameters (0.76 and 1.01mm) and two numbers of wires (10 and 15). The complete model has a surface area of 150 x 150mm², also large enough to obtain bi-stability, if the layup would be unsymmetric [9]. The wires are distributed equally over the CFRP sheet, with their 1-direction aligned in 0° direction of the layup, and the SMA shell is attached with an ideal stiff tie contact. During this state of the simulation effects connected to the bonding of the wires to the laminate are only considered by increasing the offset between laminate and SMA to include the geometrical changes caused by the bonding gap. For the simulations Abaqus/Standard was used.

The identified design, achieving the pre-calculated working point, consists of a layup (90/90/0/0/90/90) and 15 wires with a diameter of 1.01mm.

3 Results

3.1 Smart Composite Behavior

The combination of CFRP structure and actuating elements described above was predicted by simulation as the most suitable one, where a maximum displacement out of plane of about 42mm is reached after heating (see Fig. 4). Furthermore the appearing stresses and strains in the SMA elements meet the pre-calculated working point.

In the experiment a maximum deflection of nearly 20mm was reached after several heating cycles at 8A over 5s (see Fig. 4). In most cases an inhomogeneous bending could be observed in contrast to the simulation and after some cycles a failure of the bonding proceeds.

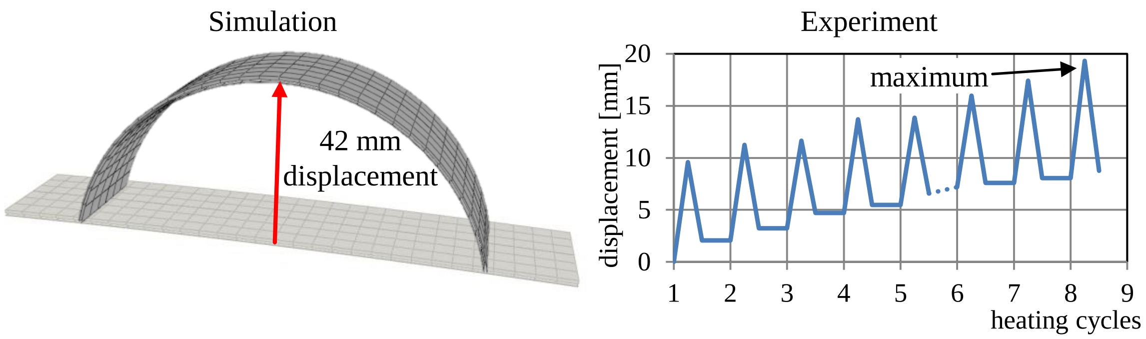

Figure 4. Comparison of simulation and experiment

Differences between simulation and experiment can be caused on simulation side, by assuming an ideal stiffness of the applied tie contact and a disregarded influence of the additional bending stiffness added by the adhesive. On experimental side several improvements are necessary, including an increased quality of the adhesive bonding and an increased heating current for a more homogeneous heating of the SMA-wires. To avoid an uncontrolled destruction of the test specimen, it is necessary to be able to control the temperature and contraction during the experiment.

Furthermore the introduced elongation of 2% in the SMA wires was insufficient to allow for the projected working point of 2% actuating travel at 138MPa stress. A maximum actuation of 2% will only be achieved, if the contraction is free of external stresses. How load level and load type will influence the contraction behavior of the SMA actuator is shown in the following section.

3.2 Wire Behavior

The measured actuation behavior of the wire is shown in Fig. 5. For both load cases the complete procedure is presented, starting with introduction of start strain, followed by first heating and then five subsequent heating and cooling cycles. For the heated state it was ensured that the temperature was well above 70 °C and the translation had stopped, for the cold state a temperature of 26 °C has been defined. In both load cases it is evident that the hot and the cold state are not varying within these cycles. This behavior could be observed in all other tests of this investigation.

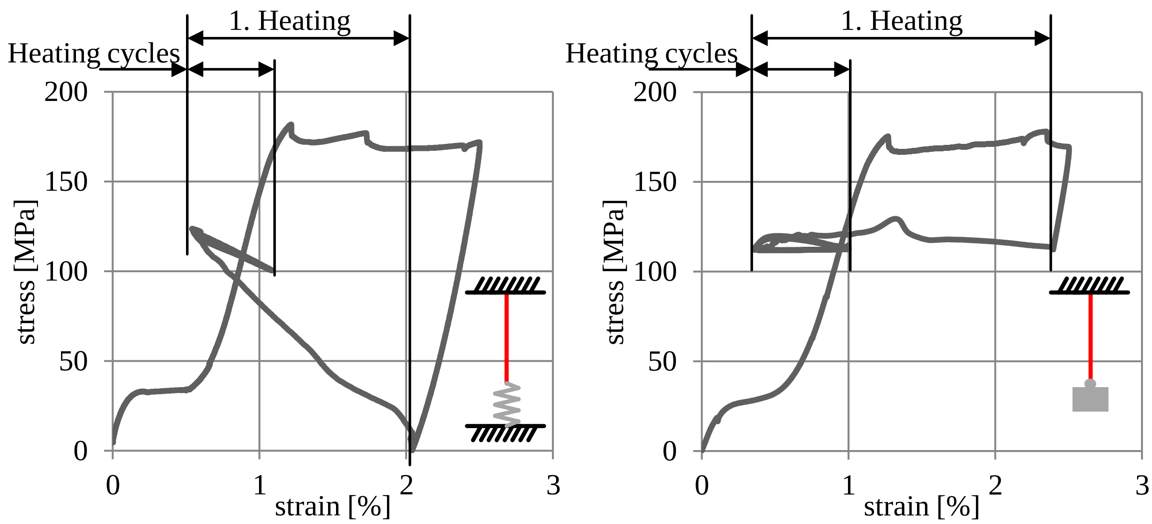

Figure 5. General actuation behavior of first heating and further heating cycles measured for two different load cases

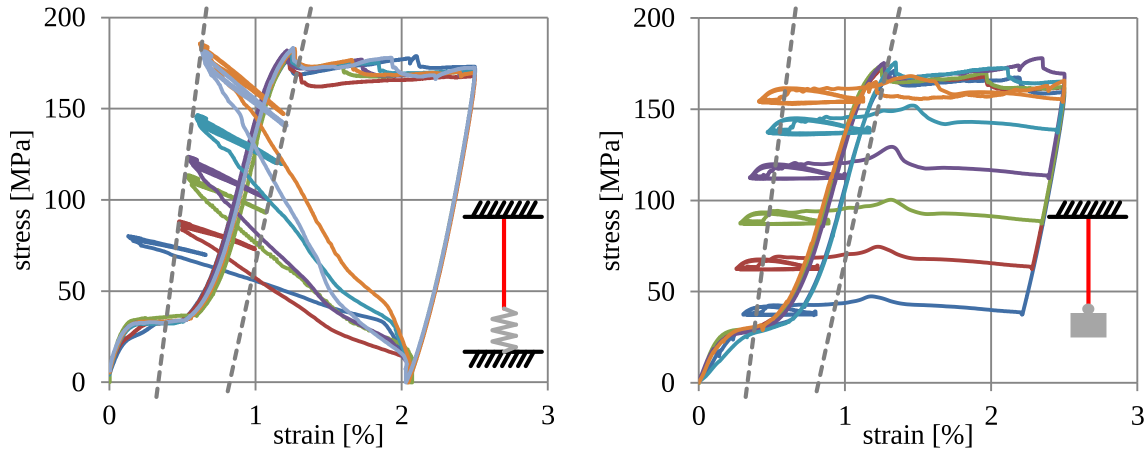

Figure 6. Measured actuation behavior depending on stiffness and load level.
The hot and cold lines for the actuation limits are shown as dashed lines.

To gain information on how load level and load type affect contraction and elongation, tests with different load levels and different spring stiffness were performed (Fig. 6). It is necessary to notice, that neither the static load nor the spring stiffness have an ideal behavior, so that the absolute values should not be considered, but influences can be analyzed. If the different load types regarding the first contraction are compared, it is surprising to gain more contraction against the static load, even though a higher amount of work is done by the wire from the beginning. The first contraction is nearly not affected by the load level, only in case of the spring stiffness a slight reduction can be obtained with increasing stiffness. Regarding the second contraction the load level has no influence during working against stiffness, while against static load the second contraction is increased a bit with higher stress level. In contrast to Fig. 1 b) the behavior depends partly on the load type, but within certain limits simple lines, defining the hot and cold state, can be found.

3.3 Simulation

Within the framework of the suggested modeling approach, the actuation limits at the hot or cold state are not affected by the load type, as highlighted in Fig. 7. The accuracy of the simulation depends strongly on the way these limits were identified by experiment, but for direct integration of SMA-wires in a component the stiffness case is more relevant.

For any simulation based on actuation against stiffness, limits for validity of the results need to be identified and integrated in the model. The experimental results of tests with low stiffness coefficient and highest stress level give a first idea where they can be found.

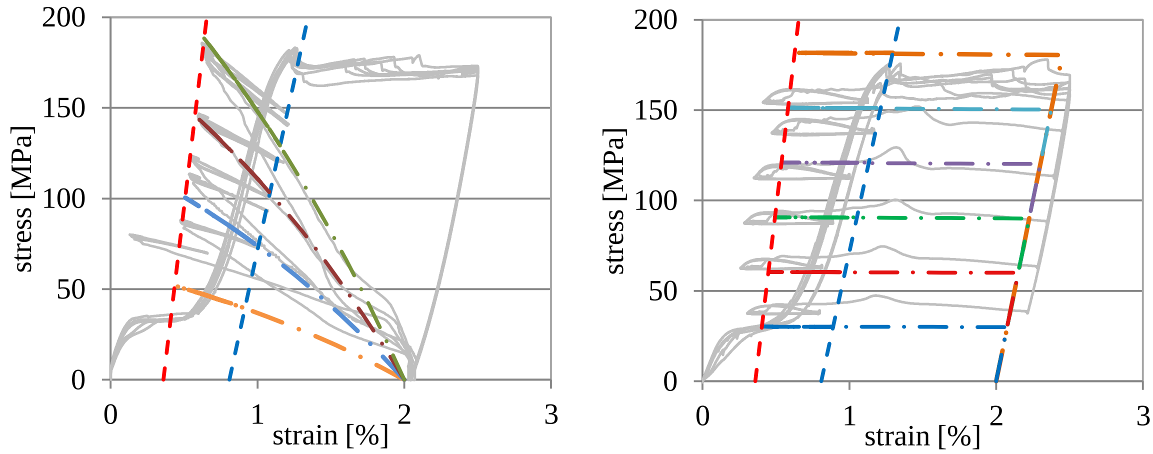

Figure 7. Comparison of measured actuation behavior (solid) and simulation results (dashed lines)

4 Conclusion

With the phenomenological model approach described in this paper it is possible to improve the design process of smart structure components. Structure stiffness and the load initiated two-way effect can be included in an easy way. For proper description of SMA-material properties it is essential to determine reliable hot- and cold- state limits depending on the load-case for actuation as well as to introduce reliable limits of validity into the model. For further investigation it would be interesting to evaluate the possibilities that different start strains of the SMA-material offer for design purpose. This additional degree of freedom could prove interesting for the design of more complex applications. The experimental validation of the simulation model revealed the necessity to take into account not only the material behavior of the actuating elements but also their integration into the composite structure. Especially the adhesive bonding between the wires and the structure has to be investigated.

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