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Effective properties of composites utilising fibres with a piezoelectric coating

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Abstract

Composites with piezoelectric fibres are promising new materials, combining the beneficial properties of very different constituents. Recently hybrid fibres with an inactive core and a piezoelectric coating have been developed. For conventional two-phase systems the correlation between component properties and effective composite behaviour is well approximated using effective field or self-consistent models. Since the latter approaches are commonly based on solutions for homogeneous inclusions, they cannot be directly employed for heterogeneous particles as coated fibres. Different methods are employed to estimate the relevant effective electromechanical parameters of composites continuously reinforced with coated piezoelectric fibres: (a) a unit cell finite element model, (b) an effective field approach built on a rigorous solution for a coated fibre in an infinite matrix and (c) a simple homogeneous field approximation. The results of the approaches are compared and discussed.

Keywords: Composites; Fibres; Modelling; Piezoelectric properties

1. Introduction

Smart materials, that integrate sensor and actuator functionality directly into the structure, have been a subject of materials science for several years. Composite materials reinforced with piezoelectric fibres are a more recent development. They combine the superior piezoelectric properties of ceramic materials with the toughness and flexibility of a polymer matrix and are highly compatible to advanced composite materials as common basis for smart structures. Another aspect is that due to their piezoelectric anisotropy they allow decoupled deformations in different directions, which represent a problem for conventional film actuators based on the '31'-effect.

One route to piezoelectric composites utilises fibres made from the bulk piezoelectric material, for instance by a sol–gel spinning process.[1] An alternate concept is the hybrid fibre (Fig. 1). It consists of a core fibre coated with a high performance piezoelectric material.[2] The piezoelectric inactive core provides the mechanical support. An electrical potential difference between an inner and an outer electrode layer gives rise to an electrical polarisation and field in the radial direction of the coating. A corresponding axial deformation of the fibre is induced by the '31'-coupling of the piezomaterial, representing the preferred deformation mode for practical use.

Advantages that may be expected are improved mechanical stability, low control voltage and a comfortable voltage supply at a central electroding point sufficient for the whole fibre length.

An arrangement of fibres, as illustrated in Fig. 2, builds up a unidirectional composite material, which is investigated in the following.

Though modelling is the focus of this paper, the hybrid fibre is not merely a theoretical concept. A reactive sputtering technique for the piezoelectric coating based on a PZT material (SonoxP53) has been developed and prototypes based on various core fibres (glass, SiC, steel) are available.[3] The piezoelectric activity of the fibres could be verified, for which polarisation levels of about 30 μC/cm^2 have been obtained (Fig. 3). An optimisation of the whole process is under way in order to achieve material output rates that make production efficient from an industrial point of view.

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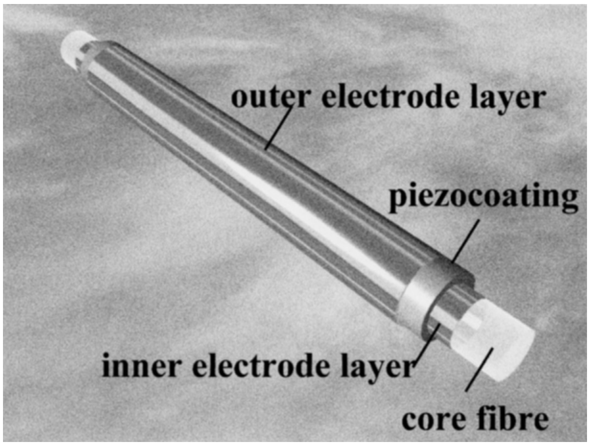

Fig. 1. Scheme of the hybrid fibre design with core fibre (diameter 2 r_{cf}), piezocoating (thickness h_{pie}), inner and outer electrode between which the control voltage ΔU is applied.

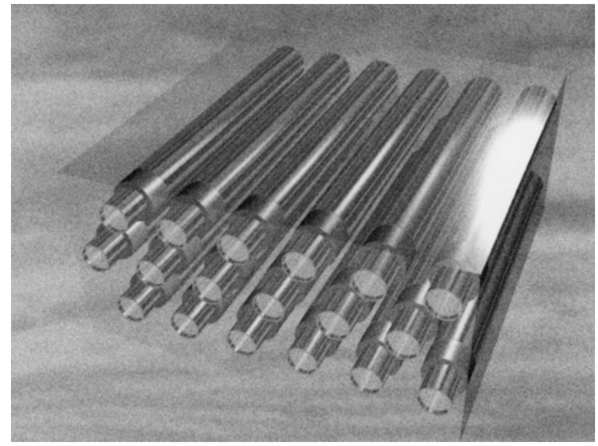

Fig. 2. Possible arrangement of hybrid fibres, embedded in a matrix, to an unidirectional composite (fibre volume ratio v_{p}).

2. Model

2.1. General

The effective material properties represent the correlation between the homogenised physical quantities affected, that are mechanical deformation, γ_α, mechanical stress, σ_α, electrical charge density (charge Q relative to composite xy-cross-section A_{xy}), $D^* = Q/A_{xy}$, and mean electric field strength in the piezocoating, $E^* = -\Delta U/h_{\mathrm{pie}}$ (as explained in the legend for Fig. 1).

The linear material equations for a transversal isotropic, piezoelectric material with hybrid fibres oriented in z-direction may be formulated as follows:

$$\begin{pmatrix} \gamma_{xx} \\ \gamma_{yy} \\ \gamma_{zz} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \\ D^* \end{pmatrix} = \begin{bmatrix} s_{11}^{\mathrm{E}} & s_{12}^{\mathrm{E}} & s_{13}^{\mathrm{E}} & 0 & 0 & 0 & d_{31} \\ s_{12}^{\mathrm{E}} & s_{11}^{\mathrm{E}} & s_{13}^{\mathrm{E}} & 0 & 0 & 0 & d_{31} \\ s_{13}^{\mathrm{E}} & s_{13}^{\mathrm{E}} & s_{33}^{\mathrm{E}} & 0 & 0 & 0 & d_{33} \\ 0 & 0 & 0 & s_{44}^{\mathrm{E}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{44}^{\mathrm{E}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^{\mathrm{E}} & 0 \\ d_{31}^* & d_{31}^* & d_{33}^* & 0 & 0 & 0 & \varepsilon^{*\sigma} \end{bmatrix} \cdot \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \\ E^* \end{pmatrix} \quad (1)$$

Due to the individual electroding of the fibres, the interpretation of the homogenised electrical quantities is different from conventional piezoelectric materials. One consequence is that the piezoelectric constants are not symmetric and will be distinguished by d_{ij} and d_{ij}^*. Three different approaches have been used and compared to estimate the effective parameters in this work.

2.2. Finite element approach

A two-dimensional, linear piezoelectric finite element analysis (FEA) was carried out, using the commercial code ANSYS. If a regular, hexagonal arrangement of fibres is assumed, a unit cell approach reflects the composite microstructure (Fig. 4). A complete set of effective

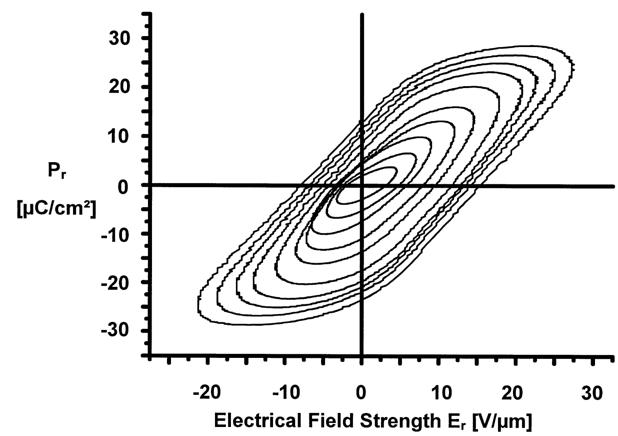

Fig. 3. P(E) hysteresis measurements for a prototype hybrid fibre (steel-fibre, PZT SonoxP53 coating).

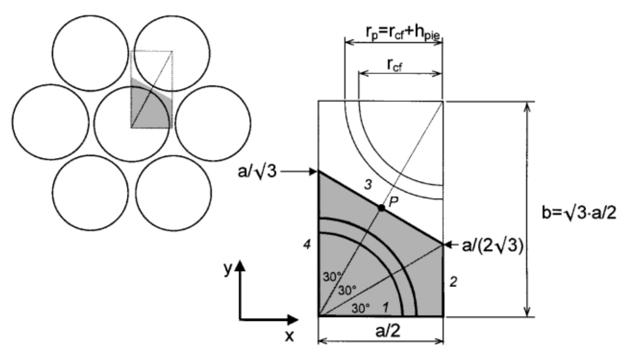

Fig. 4. Unit cell analysed in the FEA.

constants (except s_{44}^{E}) is obtained from the analysis of three different load cases:

a. $\Delta U = 0; \quad \sigma_{xx} = \sigma_{yy} = 0; \quad \gamma_{zz} = \gamma_{zz}^{(1)}$

b. $\Delta U = \Delta U^{(2)}; \quad \sigma_{xx} = \sigma_{yy} = \sigma_{zz} = 0$

c. $\Delta U = 0; \quad \sigma_{xx} = \sigma_{zz} = 0; \quad \gamma_{yy} = \gamma_{yy}^{(3)}$

2.3. Effective field approach

The effective field approach (EFA) is a common method of stochastic micromechanics (see, for instance, Ref. 4). Homogenisation of the heterogeneous microstructure is performed by averaging the physical quantities over the component phases involved. The effective properties characterise the correlation between these averages.

$$\langle\gamma_\alpha\rangle = s_{\alpha\beta}\cdot\langle\sigma_\beta\rangle + d_{3\alpha}\cdot\langle E\rangle \tag{2a}$$

$$\langle D^*\rangle = d^*_{3\alpha}\cdot\langle\sigma_\alpha\rangle + \varepsilon^*\cdot\langle E\rangle \tag{2b}$$

The EFA relies on the hypothesis that the average field values in the components may be estimated from a substitute model (providing field concentration factors $A_{\alpha\beta}$, $A_{\alpha U}$, $C_{\alpha\beta}$, $e_{3\alpha}$), which regards particles in an infinite matrix under an remote load of $\gamma^{(0)}_\beta$:

$$\langle\gamma_\alpha\rangle_p = A_{\alpha\beta}\cdot\gamma^{(0)}_\beta - A_{\alpha U}\cdot E^* \tag{3a}$$

$$\langle\sigma_\alpha\rangle_p = C_{\alpha\beta}\cdot\gamma^{(0)}_\beta - e_{3\alpha}\cdot E^* \tag{3b}$$

The interaction of the particles for higher volume fractions v_p is taken into account by a self-consistent correction of the assumed external load $\gamma^{(0)}_\beta$:

$$\langle\gamma_\alpha\rangle = \left[(1-v_p)\cdot\delta_{\alpha\beta} + v_p\cdot A_{\alpha\beta}\right]\cdot\gamma^{(0)}_\beta - v_p\cdot A_{\alpha U}\cdot E^* \tag{4}$$

Eshelby-type solutions for homogeneous ellipsoid inclusions are the common basis for the EFA,[5] but cannot be employed for the hybrid fibre due to its heterogeneous nature. Alternatively, an exact solution for a long coated fibre in an infinite matrix under axisymmetric load could be derived from the basic field equations. The application of the formalism of EFA provides values for the effective properties. Due to the axisymmetric character of the basic solution, only transverse isotropic loading states of the composite material can be analysed. As consequence, a complete set of effective material constants is not available. In particular values for s^E_{11} and s^E_{12} cannot be obtained separately apart from the combination $s^E_{11} + s^E_{12}$.

2.4. Homogeneous field approach (HFA)

In this approach the composite microstructure is replaced by an equivalent parallel (axial direction)/series (transverse direction) arrangement of component regions with homogeneous field distributions inside (Fig. 5). The material equations for the components, the overall field quantities as the weighted (by phase volume fractions) sum of the component values and the coupling relations between the different regions and directions provide a system of linear equations which must be solved to obtain the effective constants.

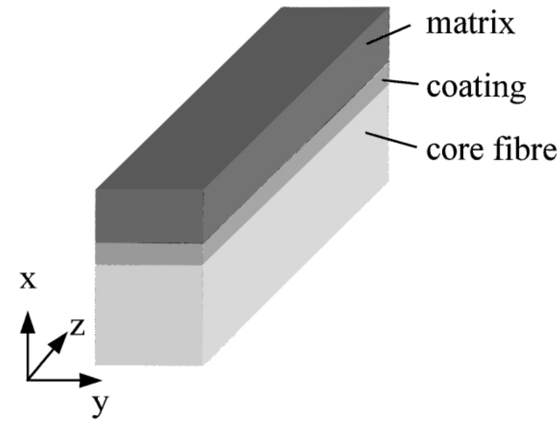

Fig. 5. Scheme of the parallel-series model of the composite.

In spite of the approximate character of the model, a two-phase version has proved to be successful in the case of piezoelectric bulk fibre composites.[6] The extension to a piezoelectric coating phase considerably increases the model's size, making an explicit formulation of the solution impractical. A numerical solution of the system of linear equations can be achieved, however. The HFA allows the computation of a reduced set of effective constants, since the transverse constant s^E_{12} is not available.

3. Discussion

Computations have been performed for a model system with a glass core fibre and a PZT-coating. The hybrid fibre volume ratio was varied between $0.1 \leqslant v_p \leqslant 0.7$ (Table 1).

The comparison of the results for the effective material constants obtained from the different approaches (mechanical: Fig. 6, piezoelectric: Fig. 7) reveals a nearly perfect coincidence between EFA and FEA for all parameters over the whole range investigated. The HFA provides a reasonable agreement with the more accurate models for the longitudinal properties (s^E_{11}, s^E_{13}, d_{33}, d^*_{33}), whereas the transverse properties (s^E_{33}, d_{31}, d^*_{31})

Table 1
Model parameters

Glass fibre		
	Diameter: $2\cdot r_{cf} = 20\ \mu m$	
$E^{(cf)} = 70\ GPa$,	$\nu^{(cf)} = 0.3$,	
PZT coating		
	Thickness: $h_{pie} = 1-5\ \mu m$	
$s^{E,(pie)}_{11} = 0.0158\ GPa^{-1}$,	$s^{E,(pie)}_{12} = -0.0056\ GPa^{-1}$,	
$s^{E,(pie)}_{13} = -0.0029\ GPa^{-1}$,	$s^{E,(pie)}_{33} = 0.0229\ GPa^{-1}$,	
$d^{(pie)}_{31} = -0.28\ 10^{-9}\cdot m/V$,	$d^{(pie)}_{33} = 0.68\ 10^{-9} m/V$,	
$\varepsilon^{\sigma,(pie)}_1 = 3580\cdot\varepsilon_0$,	$\varepsilon^{\sigma,(pie)}_3 = 3800\cdot\varepsilon_0$,	(ε_0, free space permittivity)
Polymer matrix		
	$E^{(m)} = 3\ GPa$,	$\nu^{(p)} = 0.3$

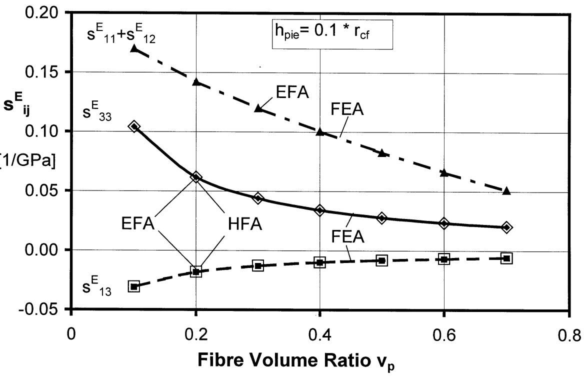

Fig. 6. Comparison of the results of the FEA (lines), EFA (filled dots) and HFA (hollow dots) for different effective mechanical parameters for a piezo coating thickness $h_{pie} = 1$ µm.

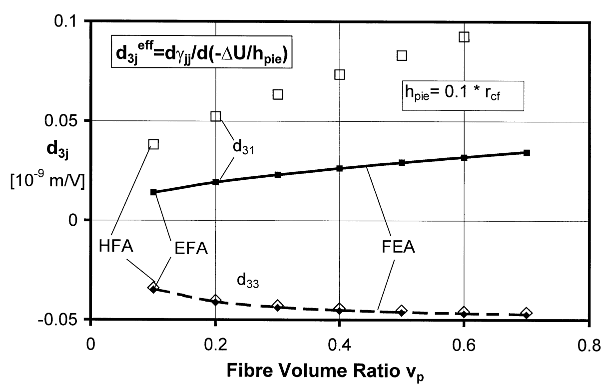

Fig. 7. Comparison of the results (analogous to Fig. 5) for the effective piezoelectric coefficients.

are poorly reproduced. For higher relative piezo coating thickness values ($h_{pie}/2r_{cf} > 0.5$) the quality of the HFA approach further decreases, since the radial variation of the field distributions becomes significant.

Finally, the effective piezoelectric longitudinal parameter $|d_{33}|$ from the EFA analysis of the hybrid fibre composite is compared to that of an equivalent composite of bulk fibres (Fig. 8).[7] The application of a comparable

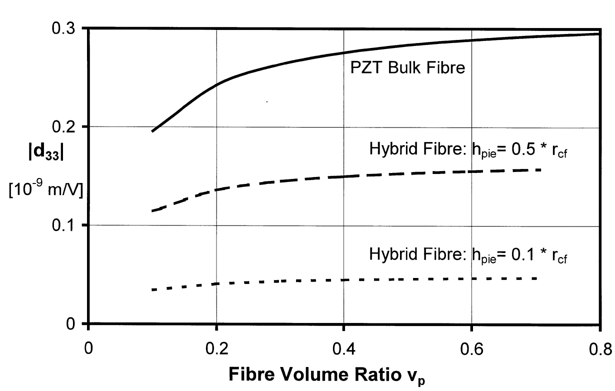

Fig. 8. Comparison of the absolute value of the longitudinal piezoelectric coefficient $|d_{33}|$ between the hybrid fibre composite (piezo coating thickness values $h_{pie} = 1$ µm and $h_{pie} = 5$ µm) and a piezo bulk fibre composite with identical PZT properties.

mean electric field in both composites causes a much higher longitudinal deformation in a bulk fibre composite with the same fibre volume content v_p, especially due to the decrease in volume of active material.

The efficiency of the hybrid fibre may be improved, to some extent, by a higher thickness of the piezocoating.

4. Conclusions

The analytical procedures EFA and HFA (restricted to longitudinal properties) provide a adequate approximation of the effective properties for hybrid fibre composites. A promising prospect is the formulation of equivalent methods for similar problems with coated fibres.

The piezoconstant for hybrid fibres is reduced, compared to bulk fibres. However, the practical actuator performance is the product of piezoelectric coefficient and the electric field that can be applied. Since the coating of the piezolayer is very thin (1–10 µm), an improved dielectric strength of the material may be expected, compared to the bulk material. This could compensate the shortcomings and make the hybrid fibre competitive even for actuator applications.

For sensor applications, the performance of the hybrid fibres is good. The moderate voltage level and the high output of electrical charge provide special advantages since they are well adapted to conventional electronic equipment.

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