Determination of critical and minimum volume fraction for composite sensors and actuators

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Abstract

Composite actuators and sensors manufactured by combining a ferroelectric ceramic such as lead zirconate titanate (PZT) and a passive phase such as a polymer are used in a variety of applications including SONAR, vibration damping, change of structural shape (morphing) and structural health monitoring. The composite route provides specific advantages, including tailored piezoelectric response, high strain, a degree of flexibility and increased damage tolerance compared to conventional dense monolithic ceramic materials. For piezoelectric fibre composites, where fine scale brittle ceramic fibres of 40-800μm in diameter are introduced into a ductile polymer matrix, the composite strength and failure mechanism ultimately depends on the mechanical properties of each phase and their volume fraction. This paper examines the mechanical properties of piezoelectric fibres and the matrix phase and discusses the influence of fibre volume fraction on mechanical properties and failure mechanism of the composite. The 'critical' and 'minimum' volume fraction of fibre based piezocomposite sensors and actuators are also determined. The data is of particular use in determining the failure stress, failure strain and failure mechanism of composite actuators and sensors subjected to high levels of stress, for example in applications where these materials are embedded into structural elements for shape control and morphing.

Keywords: composite, sensors, actuators, piezoelectric

1. Introduction

Piezoelectric materials, which develop an electrical charge when subjected to a force and develop a strain when subjected to an electric field, are used in a variety of sensors and actuator applications. The most common piezoelectric ceramic is lead zirconate titanate, $Pb(Zr,Ti)O_3$ (PZT) and in the last few years a variety of micron scale PZT fibres (40-250μm in diameter) have been manufactured by various routes, including sol-gel, extrusion, viscous suspension spinning process; some of which are now commercially available [1-4]. The applications for these fine scale fibres include 1-3 composites, which are aligned fibres embedded in a polymer matrix for medical transducer and SONAR applications [5,6] and Active Fibre Composites (AFCs) which have a variety of potential benefits over conventional piezoelectric sensing and actuating devices [7,8]. AFCs were developed by the Active Materials and Structures Laboratory (AMSL) and patented in 1994 [8]. Since their initial development, advancement has been made in many areas including fibre manufacture, matrix materials, electrode design, manufacturing techniques, and composite modelling [9]. A typical AFC configuration is shown in Fig. 1 and comprises of a monolayer of uniaxially aligned piezoelectric fibres embedded in a polymer matrix between two interdigitated surface electrodes through which the driving voltage and associated electric field is supplied. The configuration combines interdigitated electrodes and a composite architecture to overcome the limitations associated with monolithic structural actuators. The advantages of the AFC configuration are that the electric field is applied in the direction of actuation and the fibre direction, which

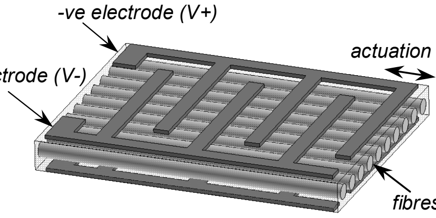

Figure 1. Active fibre composite construction using micron scale fibres and an interdigitated electrode pattern.

results in the larger d_{33} piezoelectric coefficient being utilised (the smaller d_{31} coefficient used in monolithic actuators is typically ~$0.5d_{33}$).

The introduction of fine scale fibres into a polymer matrix also provides the composite with a degree of flexibility and is able to conform to the shape of irregular structures [1-4,10]; a property which has attracted significant interest in research into embedded actuators for change of structural shape (morphing). It has also been proposed that the combination of interdigitated electrodes and ceramic fibres offers an enhanced toughness and damage tolerance since fracture of individual fibres does not lead to ultimate failure and loss of sensing or actuating capability of the AFC. The unidirectional nature of the fibres creates in-plane actuation anisotropy, allowing torsional actuation and sensing [11]. Multi-ply composites can also be developed which introduce bending or torsion. Applications for AFCs therefore include shape control, structural health monitoring and vibration control [12-14].

If active fibre composites are to be attached or embedded in engineering structures for shape control or structural health monitoring, knowledge of the mechanical properties of the configuration in Fig. 1 is essential to prevent failure and loss of strain or sensing capability. Failed or fractured AFCs may also act as a point of weakness in the engineering structure that it is embedded in. This paper determines the mechanical properties, in particular the tensile strength and failure strain, of piezoelectric fibre based composites as a function of fibre fraction. The change in failure mechanism (related to the 'minimum' volume fraction) and the 'critical' volume fraction (the volume fraction where any strengthening effect of the fibres is observed) is also determined and discussed.

2. Minimum and critical volume fraction

The influence of composite architecture on composite tensile strength is well known and has been studied extensively for structural composites consisting of brittle fibres in a ductile matrix [15, 16]. However, it is surprising the approach has not been applied to determine the important parameters for active fibre composites, since it is equally valid for brittle piezoelectric fibres in a ductile polymer matrix (see Fig. 2, which shows a cross section of an AFC). It is assumed that the fibres and matrix are well bonded and deform together (i.e. the strain in the fibres, matrix and composite are identical). Since the system consists of ceramic fibres in a polymer matrix, it is assumed that the failure strain of the matrix (ε^*_m) is greater than that of the fibres (ε^*_f). The influence of the mechanical properties of the electrode, which is orientated 90° to the fibre, is ignored.

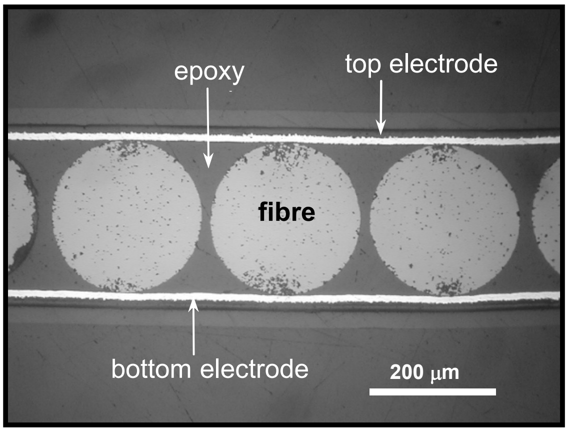

Figure 2. Cross-section of active fibre composite [18].

As the composite strain (ε^*_c) increases in response to a mechanical load, the piezoelectric fibres will be the first component to fail when the composite strain (ε_c) is ε^*_f. At this point two possible failure regimes exist depending on whether the piezoelectric fibre volume fraction (v_f) is above or below a minimum value (V_{min}).

2.1. Regime I ($v_f > V_{min}$)

If v_f is above V_{min}, brittle failure of the fibres at ε^*_f leads to failure of the whole composite, since the polymer matrix in unable to support the additional load which is transferred into the matrix from the fibres. The strength of the composite is described by Eq. 1 [15].

$$\sigma^*_C = v_f \sigma^*_f + (1 - v_f)\sigma'_m \qquad (1)$$

where σ^*_c is the composite failure stress, σ^*_f is the fibre failure stress and σ'_m is the stress carried by the polymer matrix at the fibre failure strain. In this regime, since failure of the fibres leads to composite failure, $\varepsilon^*_c = \varepsilon^*_f$.

2.2. Regime II ($v_f < V_{min}$)

If v_f is below V_{min} the polymer matrix is able to carry the applied load after fracture of the piezoelectric fibres. Failure of the piezoelectric fibres at ε^*_f does not lead to composite failure; it merely increases the stress in the matrix. The failed fibres, which now carry no load, can be regarded as holes in the polymer matrix. The tensile strength of the composite in this regime is described by Eq. 2 [15].

$$\sigma^*_C = (1 - v_f)\sigma^*_m \qquad (2)$$

where σ^*_m is the matrix failure stress. In this regime, composite failure occurs when $\varepsilon^*_c = \varepsilon^*_m$. Since, one advantage of the interdigitated electrode configuration is that AFCs can still actuate after fibre fracture, this is potentially the most appropriate regime for the actuators to operate in. The disadvantage of this regime is that, since the fractured fibres are regarded as holes when $\varepsilon^*_c > \varepsilon^*_f$, composite tensile strength decreases with increasing fibre volume fraction in the range $0 < v_f < V_{min}$.

2.3 Minimum (V_{min}) and critical (V_{crit}) volume fractions

The value of V_{min}, which is volume fraction that results in the lowest composite strength and determines the transition from each regime and failure mechanism is calculated from the intersection of Eqs. 1 and 2 and is given by Eq. 3 [15].

$$V_{\min} = \frac{\sigma^*_m - \sigma'_m}{\sigma^*_f + \sigma^*_m - \sigma'_m} \qquad (3)$$

The critical volume fraction (V_{crit}) for the composite system is the amount of fibres necessary to ensure the composite strength is at least greater than that of the matrix ($\sigma^*_c > \sigma^*_m$), assuming the fibres are stronger than the matrix. Rearranging Eq 1., with the condition that $v_f = V_{crit}$ when $\sigma^*_c = \sigma^*_m$, gives Eq. 4 [15].

$$V_{crit} = \frac{\sigma^*_m - \sigma'_m}{\sigma^*_f - \sigma'_m} \qquad (4)$$

3. Experimental

To determine the necessary composite mechanical properties as a function of fibre volume fraction, the relevant properties (ε^*_f, σ^*_f, σ^*_m and σ'_m) of the component phases were determined by tensile testing individual fibres and fabricating tensile test specimens of the epoxy polymer matrix. The fibres were an unpoled soft lead zirconate titante material (PZT-5H) from Smart-Materials produced by the Alecru method (a form of suspension spinning). Relatively large diameter fibres (800μm) were tested to minimise errors associated with specimen clamping and accurate measurement of failure loads. Errors due to variations in the cross-sectional area across the fibres were minimised by measuring the cross-sectional area directly at the fracture surface (Fig. 3). Although the samples were all cylindrical in shape, the analysis should be equally valid for other shapes, providing stress concentrations do not induce premature failure of the composite.

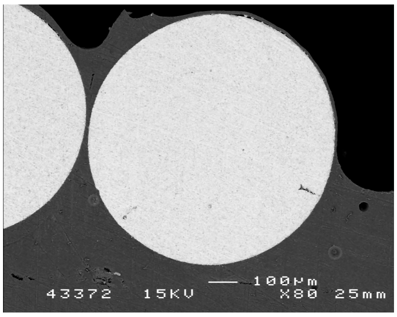

Figure 3. Scanning electron microscope image of fibre cross-section. Grey area is an epoxy mount.

Due to the statistical variation in the strength of brittle fibres, 38 fibres were tested in total and Weibull analysis undertaken to examine the statistical variation of fibre strength (according to BS 1007-4:1994). The matrix was a low viscosity epoxy resin (Specifix-40) that was cast into tensile specimens and tested in accordance with EN ISO 527-2:1996.

4. Results

4.1 Fibre properties (ε^*_f and σ^*_f)

Fig. 3 shows the strength distribution of the piezoelectric fibres, plotted as a Weibull plot, where P_f in Fig. 4 is the probability of failure at the applied stress. From the results the calculated Weibull modulus of the fibres, a measure of the variability of fibre strength, is 7.2; typical of many brittle ceramics.

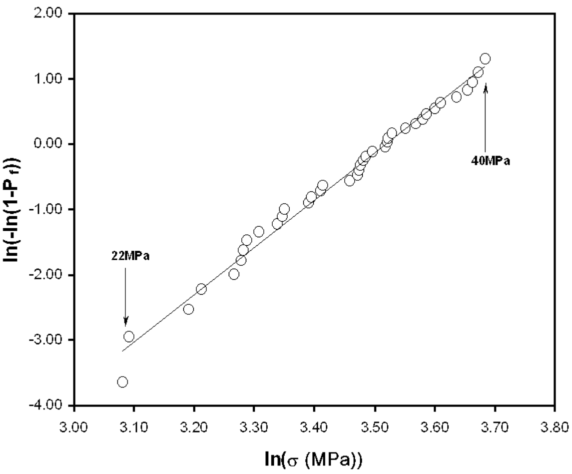

Figure 4. Weibull plot for the PZT-5H piezoelectric fibres. Weibull modulus is 7.2. The scale parameter, σ_0, is 34MPa.

The failure strength of the fibres (σ^*_f), determined as the scale parameter (σ_0) of the Weibull analysis, is 34MPa. There is a broad range of failure strengths with the weakest fibres failing at 21MPa and the strongest fibres failing at 39MPa. The elastic modulus for the unpoled PZT-5H material is 66GPa, estimated from the open and closed circuit stiffness of the poled material. Assuming linear elastic behaviour of the fibre up to the failure stress, the fibre failure strain (ε^*_f) is ~0.05%. This estimation of ε^*_f neglects any possible additional strain due to domain wall motion under the applied stress (ferroelastic behaviour).

Kornmann et al. [17] measured the mechanical properties of 250µm diameter piezoelectric fibres made from a PZT-5A material; with measured scale parameters ranging from 50-68MPa and failure strains of ~0.3%. These property values will also be considered in determining the V_{min} and V_{crit} parameter for active fibre composites in order to examine a range of potential composite strengths.

4.2 *Matrix properties* (σ^*_m and σ'_m)

The tensile strength (σ^*_m) of the epoxy was 46MPa. Based on an elastic modulus of 3GPa, the stress levels in the polymer at the fibre failure strains (σ'_m) of 0.05% (PZT-5H) and 0.3% (PZT-5A) were 1.5MPa and 9MPa respectively.

4.3 Composite strength versus volume fraction

Using the composite theory described in section 2, composite strength as a function of volume fraction was determined from Eqs. 1 and 2. The predicted composite strength versus fibre volume fraction for a PZT-5H/epoxy composite is shown in Fig. 5. The solid line is the predicted composite tensile strength at each volume fraction. The minimum volume fraction (V_{min}) is 0.56 and for fibre volume fractions in the range $0<v_f<0.56$ failure of the fibres does not lead to composite failure. As v_f increases in this fibre fraction range there is a gradual decrease in composite tensile strength from the matrix value (46MPa) to ~20MPa at $v_f=0.56$.

For fibre fractions greater than 0.56, fibre failure leads to failure of the composite. For a monolayer of cylindrical piezoelectric fibres in an epoxy matrix the maximum theoretical volume fraction is 0.78, although slightly lower fractions are desirable to minimise fibre contact (see Fig. 2). At the maximum volume fraction of 0.78 the tensile strength is ~27MPa. Higher volume fractions are achievable with rectangular specimens. Since the tensile strength of the fibres is lower than that of the matrix, no strengthening of the composite is expected and there is no critical volume fraction (V_{crit}).

The fibre property data of Kornmann et al. [17] was used to estimate the strength characteristics of active composites made from PZT-5A fibres. The results are shown in Fig. 6. The higher tensile strength and higher failure strain of the fibres results in a lower minimum volume fraction compared to PZT-5H, with V_{min} estimated to be 0.34. The composite strength gradually decreases with volume fraction in the range $0<v_f<0.34$, with a minimum strength of ~30MPa at V_{min}. For higher volume fractions ($v_f>0.34$), fibre failure results in composite failure and the strength increases with fibre fraction. The composite tensile strength is ~55MPa at the maximum packing density of 0.78. The critical volume fraction (V_{crit}), the point at which the fibres are contributing to strengthening the composite, is 0.62.

5. Conclusions

Piezoelectric fibre and matrix properties have been determined to evaluate the tensile strength and failure mechanisms of active fibre composites as a function of fibre volume fraction. Two different fibre types have been examined, PZT-5H (this work) and PZT-5A [17] with different failure strengths and strains. This therefore represents a range of the potentially available composite tensile strengths and typical minimum and critical volume fractions for active fibre composite materials.

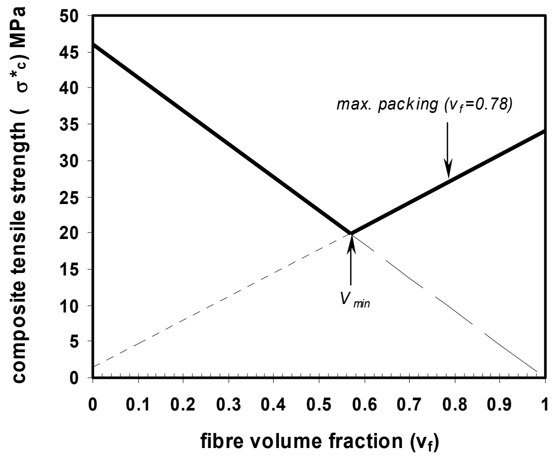

Figure 5. PZT-5H/epoxy composite tensile strength as a function fibre volume fraction. Parameters used: ε^*_f =0.05%, σ^*_f=34MPa σ^*_m =46MPa and σ'_m =1.5MPa.

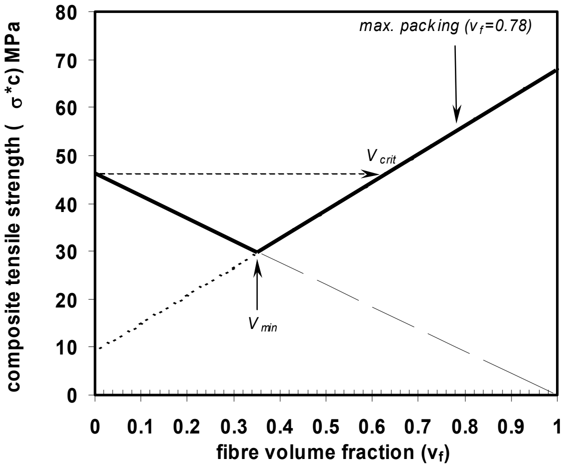

Figure 6. PZT-5A/epoxy composite tensile strength as a function fibre volume fraction. Parameters used: ε^*_f =0.3%, σ^*_f=68MPa σ^*_m =46MPa and σ'_m =9MPa.

For PZT-5H fibres in an epoxy matrix, the minimum volume fraction (V_{min}) is 0.56. For fibre volume fractions from 0 to 0.56, failure of the fibres does not lead to composite failure and composite failure occurs at the matrix failure strain. In this fibre fraction range the tensile strength decreases with increasing fibre fraction with a minimum strength of ~20MPa at V_{min}. At volume fractions greater than 0.56, fibre failure at ε^*_f leads to failure of the composite. Since the fibres are weaker than the matrix material no strengthening of the matrix is achieved.

For PZT-5A [17] fibres in an epoxy matrix, the minimum volume fraction (V_{min}) is 0.34 and for v_f<0.34 failure of the fibres does not lead to composite failure. In this range the tensile strength decreases with increasing fibre fraction with a minimum strength of ~30MPa at V_{min}. When v_f>0.34, fibre failure leads to failure of the composite. At the maximum packing density the tensile strength is ~55MPa.The critical volume fraction of the PZT-5A/epoxy composite system is 0.62, indicating that some strengthening of the matrix is achieved.

For both active composite systems examined the minimum and critical volume fractions obtained are high, particularly compared to engineering composites such as carbon fibre/epoxy. Critical and minimum volume fractions are typically less than 3% for these structural materials, due to the much higher tensile strength of the fibre (>2 GPa [15]) compared to matrix. The active fibre composites also have lower tensile strengths for the same reason. These predictions, and failure mechanisms, are to be verified by further experimental testing of composites of known fibre volume fraction.

A potential advantage of the high minimum volume fraction of active fibre composites is that the composite failure strain can be as large as the matrix failure strain (ε^*_c=ε^*_m). If active fibre composite are designed to fail in this regime, it is less likely to act as a point of weakness if it embedded in a composite structure experiencing a high level of stress. A lower volume fraction of fibres will, however, lead to reduced actuation and blocking force. This information is of particular interest for those considering embedding active fibre composites in engineering structures for structural health monitoring, vibration damping or shape control.

Acknowledgements

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