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Tensile Strength of Active Fibre Composites – Prediction and Measurement

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The Active Fibre Composite (AFC) has been the subject of much interest as a smart technology that can be embedded into host structures for adaptive shape control and structural health monitoring. The electromechanical performance of these devices has been extensively studied, although the structural properties have received little attention. Knowledge of the mechanical performance of the AFC is essential to prevent loss of performance and failure. Experimentally measured tensile strengths of PZT fibre—epoxy composites were found to contradict the behaviour predicted by simple composite theory. It has been shown that the selection of appropriate matrix material is an essential factor in controlling the failure mode of active composites.

Keywords Mechanical properties; piezoelectric; PZT; active fibre composite; strength

1. Introduction

The commercial availability of fine-scale PZT fibres has stimulated novel applications such as the Active Fibre Composite (AFC) [1–8]. The AFC comprises of aligned piezoelectric fibres embedded in a polymer matrix between interdigitated electrodes (IDEs). This composite architecture has been the subject of much research interest, due in part to the possibility of embedding this smart technology into host structures for adaptive shape control and structural health monitoring [8–11].

The electromechanical properties of these devices have been extensively studied [8, 12, 13], while the structural properties have received little attention [14, 15]. This has hindered adoption of active composites for critical applications such as aeronautical components and civil engineering. If such devices are to be attached or embedded in engineering structures, knowledge of the mechanical properties of the AFC is essential to prevent failure and loss of strain or sensing capability. More significantly the damaged AFC may weaken the host structure.

In this work, simple composite theory has been used to predict the tensile strength of PZT fibre based composites as a function of fibre fraction. The change in failure mechanism

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(related to the 'minimum' volume fraction) is also determined and discussed. To assess the effectiveness of this approach, representative PZT—epoxy composites were manufactured and tested. The experimental results were found to contradict the mechanical behaviour predicted. This paper identifies reasons for the discrepancy and suggests design parameters for active fibre composites with improved robustness.

2. Theory and Background

2.1. Failure of Active Composites

The introduction of fine-scale ceramic fibres into a polymer matrix provides the active composite with a degree of flexibility to conform to irregular shaped structures [5]. It has been suggested that unlike monolithic piezoceramics, good damage tolerance and robustness may be achieved, since fracture of individual fibres does not lead to ultimate failure of the device [5, 8]. The influence of composite architecture on tensile strength and fracture mechanism is well known for structural composites consisting of brittle fibres in a ductile matrix [16, 17]. Applying this simple composite theory to determine the behaviour of active composites was considered a valid initial approach for predicting AFC tensile strength.

It is assumed that the composite consists of long fibres, aligned in the loading direction. The fibres and matrix are considered to be perfectly bonded (iso-strain). The influence of the electrodes (IDE) is ignored. Since the system consists of relatively brittle ceramic fibres in a ductile polymer matrix, the failure strain of the matrix (ε_m^*) is considered greater than that of the fibres (ε_f^*). At a certain load, the composite strain will reach the failure strain (ε_f^*) of the brittle fibres, which will be the first component to fail (Fig. 1a). At this point two possible failure regimes exist (Regime I or Regime II), depending on whether the fibre volume fraction is above or below a minimum threshold value ($V_{\min}$).

If V_f is above $V_{\min}$ (Regime I), brittle failure of the fibres at ε_f^* leads to failure of the entire composite, since the polymer matrix in unable to support the additional load which is transferred to the matrix after fibre failure (Fig. 1b). Equation 1 [16] describes the strength of the composite in this range of fibre volume fractions.

$$\sigma_c^* = V_f \sigma_f^* + (1 - V_f)\sigma_m' \tag{1}$$

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 $V_f > V_{\min}$ regime, failure of the fibres leads to complete composite failure and $\varepsilon_c^* = \varepsilon_f^*$. Composite failure strength is dominated by the fibre properties.

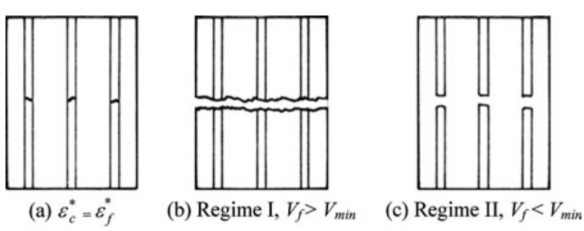

Figure 1. Diagram of possible failure mechanisms for composite system with ($\varepsilon^*_f < \varepsilon^*_m$). The fibres are considered to have uniform strength.

If V_f is below $V_{\min}$ (Regime II) the fibre fraction is sufficiently low that the polymer matrix is able to carry the applied load after fracture of the piezoelectric fibres (Fig. 1c). Failure of the fibres at ε_f^* does not lead to composite failure; it merely increases the stress and strain in the polymer matrix. The failed fibres, which now carry no load, can be regarded as holes in the polymer matrix and the tensile strength of the composite is described by Equation 2 [16].

$$\sigma_c^* = (1 - V_f)\sigma_m^* \tag{2}$$

Where σ_m^* is the matrix failure stress.

In the $V_f < V_{\min}$ regime (II), composite failure occurs when $\varepsilon_c^* = \varepsilon_m^*$ resulting in a more ductile, less catastrophic failure mode. Since it is possible that an active composite with IDE can still actuate after individual fibre failures, this is potentially the most appropriate range of fibre volume fractions for the active fibre composites. While this regime provides improved toughness, the composite tensile strength will actually decrease with increasing fibre volume fraction within the range $0 < V_f < V_{\min}$.

2.2. Predicted Mechanical Behaviour

The minimum volume fraction ($V_{\min}$) determines the transition from each regime and failure mechanism and corresponds to the lowest composite strength. It may be calculated from the intersection of Equations 1 and 2 [16]:

$$V_{\min} = \frac{\sigma_m^* - \sigma_m'}{\sigma_f^* + \sigma_m^* - \sigma_m'} \tag{3}$$

To predict the 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 are required. These parameters were determined by the author in previous work [15], through tensile testing individual PZT-5A fibres and fabricating tensile test specimens of the epoxy polymer matrix. The failure strength of the PZT-5A fibres (σ_f^*) was determined to be 40 MPa from the Weibull scale parameter (σ_0). Values reported for similar fibres varied from $\sigma_0 \sim 50$ to 64 MPa [14], and tensile strengths reported for bulk materials suggest a 'static' strength of ~76 MPa and a 'dynamic' strength of ~28 MPa [18], which is comparable to the value selected.

The elastic modulus for the unpoled PZT-5A material was estimated as 65 GPa, 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 ~ 0.06%. This assumption neglects additional strain due to domain wall motion under the applied stress (ferroelastic behaviour).

The epoxy tensile strength (σ_m^*) was 57 MPa with a standard deviation of ±2 MPa. Assuming linear elastic behaviour and taking the measured elastic modulus of the matrix 3 GPa, the stress levels in the polymer at the fibre failure strains (σ_m') of 0.06% is 1.8 MPa. The ultimate failure strain of the matrix (ε_m^*) was typically 2–3%, two orders of magnitude greater than that of the brittle fibres.

The predicted composite strength as a function of fibre volume fraction is shown in Figure 2 for the PZT-5A – epoxy system. The relatively low strength of the fibres leads to a high value of $V_{\min}$ ~58%, compared to engineering composites such as carbon fibre – epoxy. Minimum volume fractions are typically less than 3% for structural materials, due to the much higher tensile strength of the fibre (>2 GPa) compared to the matrix [16].

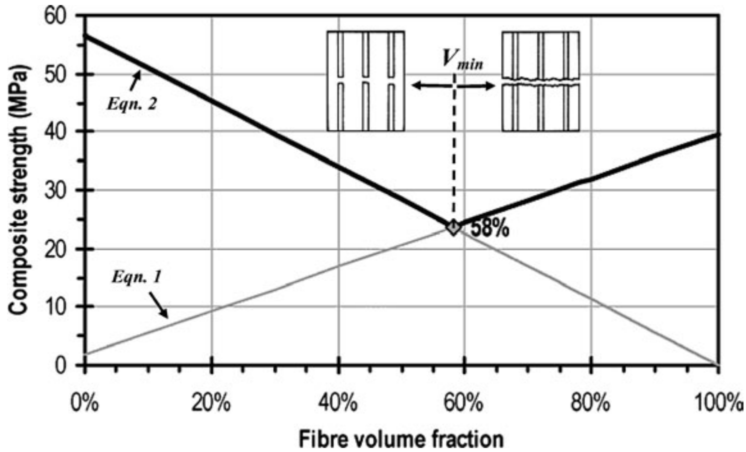

Figure 2. Predicted strength for PZT-5A—epoxy composites with different fibre volume fractions. Parameters used: $\varepsilon_f^* = 0.06\%$, $\sigma_f^* = 40$ MPa, $\sigma_m^* = 57$ MPa and $\sigma_m' = 1.8$ MPa.

The behaviour predicted suggests an advantage of the high $V_{\min}$ for the active composite, since relatively high fibre volume fractions can be tolerated while still within Regime II (ductile and not catastrophic failure). If active fibre composites are designed to fail in this mode (as in Fig. 1c) it is less likely to act as a point of weakness in a host structure. In addition, since the IDE enables the device to continue operating as a sensor or actuator after fibre fracture, this is the preferred failure mode for operation. The use of a lower fibre volume fraction is, however, likely to reduce the piezoelectric performance of the device.

3. Experimental

To further investigate the proposed model for AFC strength, it was necessary to characterise the tensile strength of active composites experimentally. Samples were fabricated that spanned a range of volume fractions, from 1 to 75% V_f (Fig. 3). The PZT-5A fibres examined in this study were produced by the Alceru route, selected due to their availability in large quantities [4, 15]. To minimise errors in cross sectional area, relatively large fibres were chosen (800 μm diameter, 150 mm length), which also proved easier to handle during composite lay-up. Composites were produced by first positioning fibres manually into a

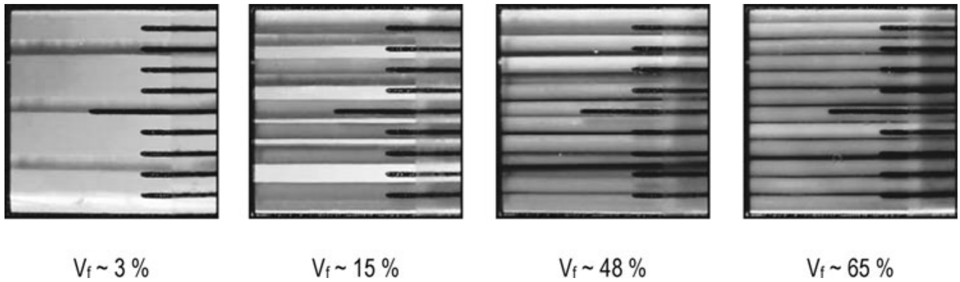

Figure 3. Photographs show sections of composites produced at various volume fractions (V_f). Scale is indicated by 1 mm divisions. (See Color Plate XXX)

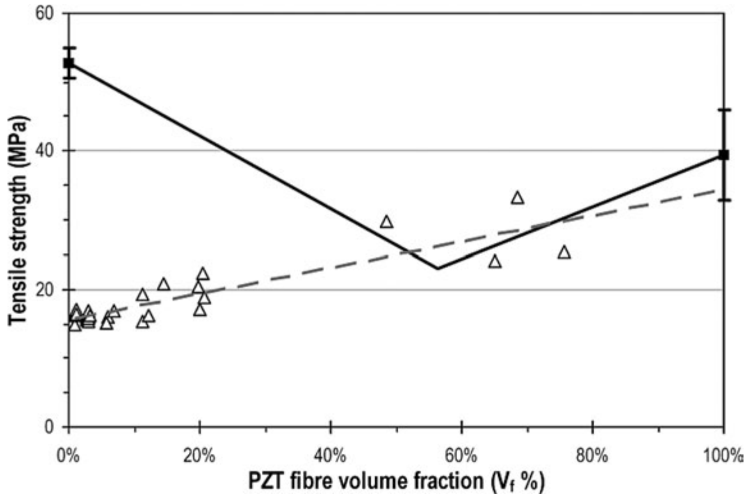

Figure 4. Measured tensile strength of PZT-5A – epoxy composites as a function of fibre volume fraction. Experimental results (Δ) were found to differ from predicted behaviour (solid line) due to the matrix material selected.

mould of suitable shape and then impregnated with a low viscosity epoxy resin (Struers, Specifix-40) to produce a tensile test piece in accordance with EN ISO 527–2:1996 [19]. The composite was then allowed to cure at room temperature for 48 hours. A further period of 1 month conditioning at ambient conditions was found to be beneficial for the composite to develop maximum, stable mechanical properties. Aluminium end tabs were adhered onto the test pieces to improve gripping and avoid damage during tensile testing.

Testing was performed using an Instron 1195 with a 500 kg load cell and self-centering grips. Testing was performed with a crosshead speed of 5 mm/min to avoid possible creep effects in the sample and minimise ferroelastic (plastic) deformation of the PZT fibres. Data was recorded digitally for analysis.

4. Results and Discussion

The experimentally determined composite strengths for varying volume fraction have been plotted in Fig. 4. The experimental points (Δ) have been plotted against the predicted strength (solid line) for comparison. It is apparent that the data does not follow the behaviour predicted (Figure 2). Initially it is worth noting that the few samples tested around and above $V_{\min}$, are of the correct magnitude and indicate that the data gathered and the model are in agreement at high volume fractions. From the predicted composite behaviour, the high value of $V_{\min}$ would suggest that from low to relatively high fibre fractions (∼60%), the failure mode would be within Regime II. However, a drastic reduction in strength is observed at low PZT fractions, where the composite strength (∼15 MPa) is substantially less than that of the epoxy matrix (57 MPa). With the addition of a single fibre, the mode of failure was brittle and catastrophic. This cannot be accounted for by the simple composite approach applied.

The cause of this discrepancy is the simplifications made about the composite response during the described Regime II (Eqn. 2). This assumes that the only effect of the broken fibres is to decrease the area of the matrix that can be loaded. However, depending on the toughness of the matrix, it is possible that the discontinuities introduced by the broken fibres can cause stress concentrations that significantly weaken the matrix. While it is unfortunate that the matrix chosen exhibited this brittle behaviour, it is representative of low viscosity epoxies generally employed for active composites due to the good encapsulation they provide [5, 8].

Results in Fig. 4 suggest that optimum strength is achieved by maximising the PZT volume fraction. This increases the effective composite stiffness and therefore a greater load is required before the composite strain reaches the failure strain of the fibres. Utilising a higher volume fraction of PZT fibres also provides greater piezoelectric performance, which is often critical for AFC applications [5, 8].

5. Conclusions

In this work, the effect of composite architecture on tensile strength and fracture mechanism was predicted by simple composite theory. However, experimental results were found to contradict the predicted behaviour. This was due to the significant stress concentrations generated by the inclusion of the PZT fibres, coupled with the properties of the epoxy material. The current practise of using high fibre fractions for the production of devices with greater piezoelectric response may not influence the composite strength as significantly as was believed. With the materials used in this study, a high fraction of PZT fibres was shown to improve strength.

An important aspect of this research has been to demonstrate the role of the matrix material on the ultimate strength of the AFC. In the composites produced, the low toughness of the epoxy material resulted in active composites that failed in Regime I, where failure of the piezoelectric fibres (at ε_f^*), leads to catastrophic failure of the composite device. The brittle failure of active fibre composites and the low strength (40 MPa) and low strain of the PZT fibres implies that such devices could potentially act as a significant weakness when embedded into a host structure. The selection of an appropriate matrix material with improved toughness should significantly increase composite strength, by reducing the effect of the fibre inclusions and ensuring that composite failure occurs in Regime II (ductile and not catastrophic). Future work will investigate the benefits of toughened epoxies and develop a revised model to account for the stress concentration effect of the fibre inclusion.

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References

1. H. B. Strock, M. R. Pascucci, M. V. Parish, A. A. Bent, and T. R. Shrout, Active PZT fibers, a commercial production process. *SPIE Conf. Proc.* **3675**, 22–31 (1999).
2. R. Meyer, T. Shrout, and S. Yoshikawa, Lead zirconate titanate fine fibers derived from alkoxide-based sol-gel technology. *J. Am. Ceram. Soc.* **81**, 861–868 (1998).
3. J. D. French and R. B. Cass, Developing innovative ceramic fibers. *Am. Ceram. Soc. Bull.* **77**, 61–65 (1998).
4. F. Meister, D. Vorbach, F. Niemz, T. Schulze, and E. Taeger, Functional high-tech-cellulose materials by the ALCER (R) process. *Materialwiss. Werkst.* **34**, 262–266 (2003).
5. A. A. Bent, Active fibre composites for structural actuation. PhD thesis, Massachusetts Institute of Technology (1997).

6. N. Hagood and A. A. Bent, Composites for structural control. US Pat. No. 6,048,622, (2000).
7. A. A. Bent and N. W. Hagood, Piezoelectric fiber composites with interdigitated electrodes. *J. Int. Mat. Syst. Struct.* **8**, 903–919 (1997).
8. L. J. Nelson, Smart piezoelectric fibre composites. *Mat. Sci. Tech.* **18**, 1245–1256 (2002).
9. A. A. Bent, N. W. Hagood, and Rodgers, Anisotropic actuation with piezoelectric fibre composites. *J.P., J. Intell. Mat. Sys. Struct.* **6**, 338–349 (1995).
10. A. Schonecker, U. Keitel, W. Kreher, D. Sporn, W. Watzka, and K. Pannkoke, Smart structures by integrated piezoelectric thin fibres (II): Properties of composites and their physical description. *Ferroelectrics* **224**, 435–440 (1999).
11. R. W. Moses, C. D. Wieseman, A. A. Bent, and A. E. Pizzochero, Evaluation of new actuators in a buffet loads environment. *Proc. of SPIE* **4332**, 10–21 (2001).
12. L. J. Nelson and C. R. Bowen, Determination of the piezoelectric properties of fine scale PZT fibres. *Key. Eng. Mat.* **206**, 1509–1512 (2002).
13. L. J. Nelson, C. R. Bowen, R. Stevens, M Cain, and M. Stewart, High field behaviour of piezoelectric fibre composites. *Proc. of the SPIE* **5053**, 544–555 (2003).
14. X. Kornmann and C. Huber, Microstructure and mechanical properties of PZT fibres. *J. Euro. Ceram. Soc.* **24**, 1987–1991 (2004).
15. C. R. Bowen, A. C. Dent, L. J. Nelson, R. Stevens, M. G. Cain, and M. Stewart, Failure and volume fraction dependent mechanical properties of composite sensors and actuators. *Proc. IMechE, Part C: J. Mech. Eng. Sci.* **220**(C11), 1655–1663 (2006).
16. B. Harris, Engineering Composite Materials, Institute of Materials, London, (1986).
17. R. M. Jones, Mechanics of composite materials, 2nd edn, Taylor & Francis, Philadelphia (1999).
18. D. A. Berlincourt, H. H. A. Krueger, and C. Near, Properties of Piezoelectric Ceramics, Morgan Electro Ceramics, Technical Publication 226 (1999).
19. European Standard EN ISO 527–2:1996E, Plastics-Determination of tensile properties- Part 2: Test conditions for moulding and extrusion plastics (1996).