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Concept and model of a piezoelectric structural fiber for multifunctional composites

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Abstract

The use of piezoceramic materials for structural sensing and actuation is a fairly well developed practice that has found use in a wide variety of applications. However, just as advanced composites offer numerous benefits over traditional engineering materials for structural design, actuators that utilize the active properties of piezoelectric fibers can improve upon many of the limitations encountered when using monolithic piezoceramic devices. Several new piezoelectric fiber composites have been developed, however almost all studies have implemented these devices such that they are surface-bonded patches used for sensing or actuation. This paper will introduce a novel active piezoelectric structural fiber that can be laid up in a composite material to perform sensing and actuation, in addition to providing load bearing functionality. The sensing and actuation aspects of this multifunctional material will allow composites to be designed with numerous embedded functions including, structural health monitoring, power generation, vibration sensing and control, damping, and shape control through anisotropic actuation. A one-dimensional micromechanics model of the piezoelectric fiber will be developed to characterize the feasibility of constructing structural composite lamina with high piezoelectric coupling. The theoretical model will be validated through finite element (FE) modeling in ABAQUS. The results will show that the electromechanical coupling of a fiber-reinforced polymer composite incorporating the active structural fiber (ASF) could be more than 70% of the active constituent.

Keywords: Multifunctional; Piezoelectric; Composites; Power harvesting; B. Interphase

1. Introduction

The past few decades have seen significant growth in the development and application of active materials to a wide range of host structures due to their superior sensing and actuation properties [1]. While there exists many types of useful active materials, such as shape memory alloys, electrostrictives and magnetorheological fluids, piezoelectric materials remain the most widely used "smart" material for a number of reasons. First, piezoceramics have a high stiffness providing them with strong, voltage-dependent actuation authority. Additionally, piezoceramics are capable of interacting with dynamic systems at frequencies spanning six orders of magnitude, from about 1 Hz–1 MHz. In the past, a good deal of success was obtained in the field of intelligent structures using monolithic wafers of piezoceramic material. However, there are several practical limitations to implementing this delicate type of material, namely the brittle nature of ceramics makes them vulnerable to accidental breakage during handling and bonding procedures, as well as their extremely limited ability to conform to curved surfaces and the large mass associated with using a typically lead-based ceramic.

To resolve the inadequacies of monolithic piezoceramic materials, researchers have developed composite piezoelectric materials consisting of an active piezoceramic fiber embedded in a polymer matrix. Configuration of the material in this way is advantageous because typical crystalline materials have much higher strengths in the fiber form due

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to reduced volume fractions of flaws during fabrication [2]. Also, in addition to providing improved robustness by protecting the fragile fibers, the flexible nature of the polymer matrix allows the material to more easily conform to the curved surfaces found in more realistic industrial applications. These advantages have been capitalized on by the development of a new group of devices called piezoelectric fiber composites (PFC). Research in this area has led to the development of a broad range of active PFC actuators including active fiber composites (AFC) [3–7], macro-fiber composites (MFC) [8], 1–3 composites, and the hollow tube active fiber composite [9]. Each of these piezoelectric fiber actuators have been designed to fulfill the specific purpose of structural sensing and actuation and are typically constructed in the form of a patch of material that can be bonded to the surface of a structure or laid-up as "active layers" along with conventional fiber-reinforced lamina. While the PFCs provide significant advantages over monolithic piezoceramic materials, they are still generally separate from the structural components and are not intended to provide any load bearing functionality.

The use of piezoelectric composite actuators for structural applications was first studied by Bent [6]. The authors constructed piezoceramic fibers that were embedded into a composite helicopter rotor blade to reduce the vibration resulting from aerodynamic loading. In a later study, Wilkie et al. [8] demonstrated the use of the macro-fiber composite actuator to counteract the bending and torsional stresses applied to the vertical tail of a fighter aircraft as a result of buffeting loads. The MFC actuator was also demonstrated to be an effective tool for dynamic testing and control of ultra-lightweight inflatable space structures due to its ability to conform to the surfaces of curved and flexible structures [10,11]. Additionally, piezoelectric fiber actuators were shown to perform well for structural health monitoring [12].

Multifunctional materials are integrated material systems that serve multiple roles such as structural load bearing, energy absorption, thermal management, sensing, power generation, vibration control, etc. The advancement of this field has been rapid due to the significant safety and performance benefits that can be achieved when using this class of materials. Over the past few years several multifunctional material systems have been developed for various applications. Self-healing composite materials have been designed which used a microencapsulated epoxy embedded into a structural composite matrix containing a catalyst capable of polymerizing the healing agent upon contact resulting in polymerization in the damaged region [13]. Structural batteries for the skin of a micro air vehicle (MAV) was developed to increase the flight time while still maintain the total aircraft weight [14]. The authors used laminated polymer lithium ion bicell materials in order to maintain the total weight of the aircraft while increasing flight time. By replacing the conventional batteries of the MAV with the multifunctional battery material the endurance of the aircraft was increased by 9.6%. A similar study was performed by building the thin-film batteries around a metallic fiber that could then be embedded in a composite material [15]. The "power fiber" batteries were constructed with a 150 μm diameter and length of 5 cm and experimentally tested showing a charge capacity of 1.5 μA h.

Current developments in multifunctional materials have lead to a variety of advanced material systems but have not designed materials capable of providing more than two functions of any one application. The piezoelectric structural fiber presented here will be capable of being incorporated into a structural composite such that the load bearing and sensing/actuation functions are performed by the same material. Because the sensing and actuation properties of piezoelectric materials allow them to be used for structural health monitoring (SHM), power generation, damping, dynamic sensing, and vibration control, this load bearing material will be capable of performing each of these different applications. Additionally, weight is a critical element of many engineering design problems, which can be held to a minimum when the sensor and actuator also provide load bearing functionality.

While current PFC devices have made huge advances over monolithic piezoceramic materials, almost all are still implemented as surface-bonded patches used for sensing or actuation, and those that have been embedded provide no additional strength to the composite. The piezoceramic fibers studied here will be coated onto a conductive structural fiber that will enhance the piezoceramics mechanical properties while simultaneously acting as an interior electrode thus simplifying the design and its integration into a composite material, as shown in Fig. 1. The internal structural fiber will also serve as reinforcement to the piezoelectric material which is very brittle, making it susceptible to breakage from the pressure induced during curing of the composites polymer matrix. In addition to providing strength, by using the fiber as an internal electrode, the field required for actuation will be significantly reduced over PFCs which use interdigitated electrodes. The interdigitated electrode pattern has also been shown to negatively affect the power harvesting performance due to increased device impedance [16]. Furthermore, the concept developed

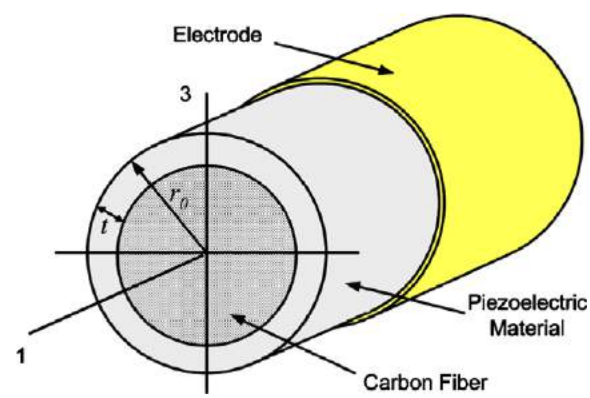

Fig. 1. Schematic showing the cross-section of the novel multifunctional fiber.

here will allow each fiber to be individually controlled or monitored offering the ability to tailor the number and function of fibers included in the composite, whereas the piezoelectric fibers of the AFC and MFC require application of two separate electrodes making the direct integration of fibers rather than a patch of material into the composite difficult.

This study will present a one-dimensional micromechanics model of a structural fiber coated with a piezoceramic interphase layer in order to evaluate the piezoelectric coupling that could be achieved through this design. The model will be validated through finite element simulations and the results will demonstrate that a fiber-reinforced polymer composite incorporating the active structural fiber (ASF) could achieve electromechanical coupling for the bulk composite as high a 70% of the piezoelectric constituent.

2. Micromechanics modeling of the piezoelectric structural fiber

In order to understand the effect of the active fiber parameters such as the fiber geometry, core fiber material and piezoceramic coating thickness on the fiber coupling, micromechanics models were derived to predict the material properties of the active structure fiber. These models will be suited for predicting the active composites actuation and sensing properties. Because the novel active composite is a three phase material with an active interphase layer between the structural fiber and polymer matrix, it is necessary to model the performance of the individual core fiber with the piezoelectric layer before approaching the lamina. Prior efforts have characterized and developed accurate models for a solid piezoceramic fiber [7], however, these models are not applicable to the active fiber developed here, because the fiber is two phase. Prior efforts did not considered the coating aspect ratio, defined as the ratio of the piezoceramic coating thickness to the outside radius of the active fiber, or the non-uniform electric field, caused by different surface area between the inner and outer electrodes. For a specific piezoelectric material which has certain piezoelectric coupling constant d_{31}, these two factors play a dominate role in the response of the active structural fiber.

For the ASF considered here the electric field will be applied along the radial axis or through the thickness of the piezoelectric shell. Because the inner electrode will have a smaller surface area than the outer electrode, the electric field will vary nonlinearly through the thickness of the piezoceramic. This nonlinear field variation must be accounted for such that the breakdown voltage at the inner wall of the fiber is not reached. From Gauss' Law, the thin wall electric field approximation along the radial direction of the active fiber can be expressed as [17]

$$E(r) = \frac{-V}{r\ln(1-\alpha)} \tag{1}$$

where V is the voltage applied across the fiber thickness, r is the radial position, and α is the aspect ratio of the piezoelectric portion of the fiber, equal to t/r_0, where t is the thickness of the piezoelectric coating and r_0 is the total radius of the fiber. This equation assumes that the piezoceramic layer is thin and will therefore not accurately represent the electric field on the material as the wall thickness becomes large. According to Eq. (1), the local electric field is proportional to $1/r$, leading to a higher electric field at the inner wall than that of the outer wall. This leads to a higher actuation strain at the inner wall of the fiber and limits the magnitude of the electric field applied before depoling occurs. A second potential issue that could arise from the higher strain at the fiber boundary is debonding between the piezoelectric shell and the fiber, which must be explored through experimental testing.

Using the thin wall approximation, the longitudinal piezoelectric stress of the piezoelectric shell can be expressed as

$$\sigma(r) = Y^{\mathrm{p}}\varepsilon(r) = Y^{\mathrm{p}}d_{31}E(r) \tag{2}$$

where Y^{p} is the longitudinal modulus of elasticity of the piezoelectric shell, σ is the piezoelectric shell longitudinal stress, ε is the piezoelectric shell longitudinal strain, and d_{31} is the piezoelectric coupling. The subscript *−31* is used to denote that the electric field is applied in the −3 direction while the strain output in is the −1 direction (see Fig. 1). The total piezoelectric force is then determined by integrating the stress over the cross-section area of the piezoelectric shell, defined as

$$F = \int_0^{2\pi}\int_{r_0-t}^{r_0} Y^{\mathrm{p}}d_{31}E(r)r\,\mathrm{d}r\,\mathrm{d}\theta = \frac{-2\pi d_{31}Y^{\mathrm{p}}Vt}{\ln(1-t/r_0)}. \tag{3}$$

The free strain resulting from the total piezoelectric force can then be derived using Eq. (3) and Hook's law as

$$\varepsilon = \frac{\sigma}{Y^{\mathrm{p}}} = \frac{F}{AY^{\mathrm{p}}} = \frac{-2\pi d_{31}Y^{\mathrm{p}}Vt}{\pi[r_0^2-(r_0-t)^2]Y^{\mathrm{p}}\ln(1-t/r_0)} = \frac{-E_{\mathrm{tw}}d_{31}}{(r_o/t-0.5)\ln(1-t/r_0)} \tag{4}$$

where $E_{\mathrm{tw}} = V/t$ is the electric field derived by thin wall approximation, A is the cross-sectional area of the piezoelectric shell, and F is the piezoelectric force. The free strain can be expressed as the product of thin wall electric field E_{tw} and the effective piezoelectric coupling of the ASF $d^{\mathrm{f}}_{31,\mathrm{eff}}$, defined as

$$\varepsilon = \left(\frac{-d_{31}}{\ln(1-\alpha)(1/\alpha-0.5)}\right)E_{\mathrm{tw}} = d^{f}_{31,\mathrm{eff}}E_{\mathrm{tw}} \tag{5}$$

where d_{31} is the piezoelectric coupling coefficient and $d^{f}_{31,\mathrm{eff}}$ is the effective coupling of the piezoelectric shell incorporating the thin wall electric field approximation, $E_{\mathrm{tw}} = V/t$. From Eq. (5), it can be seen that at a certain electric field, the aspect ratio is the only parameter that will influence the effective $d^{f}_{31,\mathrm{eff}}$ of the piezoelectric structural fiber.

The coupling for the piezoelectric shell must be then combined with the core fiber to determine the effective piezoelectric coupling of the piezoelectric structural fiber. The longitudinal elastic modulus of the active fiber containing a core fiber can be defined using the rule of mixtures and written as [18]

$$Y^{\text{multi}} = Y^{\text{p}} v^{\text{p}} + Y^{\text{f}}(1 - v^{\text{p}}) \tag{6}$$

where Y is the longitudinal modulus of elasticity, v is the volume fraction and the superscripts f, p and multi represent the core fiber, piezoelectric, and complete multifunction piezoelectric structural fiber, respectively. The relationship between the fiber aspect ratio and fiber volume fraction is shown in Fig. 2. According to Eqs. (4) and (5), the piezoelectric force generated by the piezoelectric shell can be expressed as

$$F = A\varepsilon Y^{\text{p}} = \frac{-E_{\text{tw}} d_{31}}{(r_o/t - 0.5)\ln(1 - t/r_0)} A Y^{\text{p}} = E_{\text{tw}} d^{f}_{31,\text{eff}} A Y^{\text{p}} \tag{7}$$

Then using the Hook's law the total strain of the ASF caused by the piezoelectric force is

$$\varepsilon^{\text{multi}} = \frac{\sigma^{\text{multi}}}{Y^{\text{multi}}} = \frac{\frac{F}{A/v^{\text{p}}}}{Y^{\text{multi}}} = \frac{d^{f}_{31,\text{eff}} Y^{\text{p}} v^{\text{p}} E_{\text{tw}}}{Y^{\text{multi}}} = d^{\text{multi}}_{31} E_{\text{tw}} \tag{8}$$

therefore, the electromechanical coupling of a piezoelectric structural fiber with a piezoelectric coating can therefore be defined as

$$d^{\text{multi}}_{31} = \frac{d_{31,\text{eff}} Y^{\text{p}} v^{\text{p}}}{(Y^{\text{p}} - Y^{\text{f}}) v^{\text{p}} + Y^{\text{f}}} \tag{9}$$

where Y^{p} and Y^{f} are the elastic modulus of the piezoelectric material and fiber, respectively, v^{p} is the volume fraction of piezoelectric material, d_{31} is the piezoelectric coupling coefficient and $d_{31,\text{eff}}$ is the effective coupling of the piezoelectric shell as defined from Eq. (5).

The piezoelectric coupling term in Eq. (9) predicts the response of a single active fiber, however, in order to determine the coupling when multiple active fibers are embedded in a polymer matrix, the rule of mixtures can be applied again a second time by taking the piezoelectric shell to be an interphase layer. Similar in derivation as Eq. (9), the resulting coupling can then be written as

$$d^{\text{Lam}}_{31} = \frac{d_{31,\text{eff}} Y^{\text{p}} v^{\text{p}}}{(Y^{\text{p}} - Y^{\text{m}}) v^{\text{p}} + (Y^{\text{f}} - Y^{\text{m}}) v^{\text{f}} + Y^{\text{m}}} \tag{10}$$

where Y^{m} is the modulus of elasticity of the matrix material, and v^{f} is the volume fraction of core fiber. Considering the piezoelectric constitutive equation, the lamina stress strain relationship in the *31*-direction can be identified as

$$\varepsilon^{\text{Lam}} = \frac{\sigma}{Y^{\text{Lam}}} + d^{\text{Lam}}_{31} E \tag{11}$$

where σ is the stress. This equation can then be used to obtain the free strain by equating the stress term to zero and the blocked force can be found by equating the strain term to zero and written as

$$\text{Free Strain:} \quad \varepsilon^{\text{Lam}} = d^{\text{Lam}}_{31} E \tag{12}$$

$$\text{Blocked Force:} \quad F_{bl} = -A Y^{\text{Lam}} d^{\text{Lam}}_{31} E \tag{13}$$

The equations defining the electromechanical coupling of the piezoelectric structural fiber can now be applied to study the effect the fiber geometry has on the response of the fiber. The free strain equation can then be used in coordination with FEM analysis or experiments to validate the theoretically predicted electromechanical coupling along the fiber length.

3. Model validation through finite element simulation

In order to validate the one-dimensional micromechanics model, a finite element analysis of both the piezoelectric structural fiber and a composite containing the active fibers was performed using ABAQUS. Material properties of the typical smart material PZT as well as two different core fibers (low-modulus carbon fiber and silicon carbonate fiber) were used in the simulation. It is noted however, that the results identify the ratio of the fiber or composite coupling to the bulk material, making the simulation results non-dimensional with respect to the choice of piezoelectric material. The core fiber, piezoelectric material, and the epoxy matrix were modeled using full three-dimensional, 20-noded quadratic brick elements (type C3D20, C3D20E and C3D20, respectively). Since the model is symmetric, only a quarter of the fiber composite was considered in order to reduce the simulation time. Both the core fiber, piezoelectric shell, and structural fiber lamina epoxy were constrained by the "TIE" command which results in zero relative motion between the surfaces, and a clamped boundary condition (zero displacement and rotation in all the three axes) was applied at one end of the fiber such that the free displacement could be measured at the other.

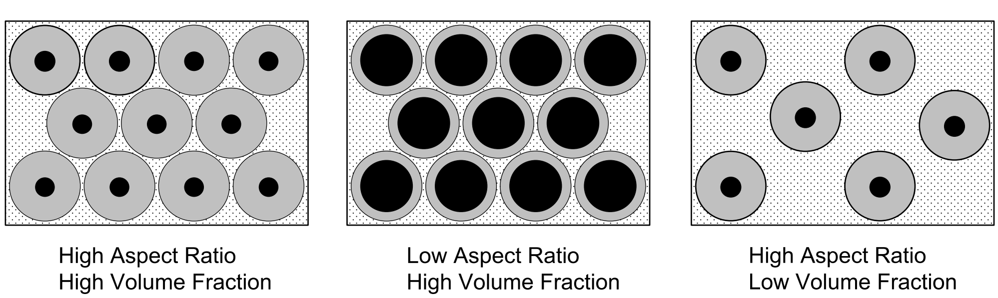

Fig. 2. Schematic demonstrating the relationship between the fiber aspect ratio and fiber volume fraction (figure adapted from Ref. [8]).

Because only the longitudinal piezoelectric deformation is considered here, the boundary conditions for the two side surfaces of the quarter fiber were zero displacement and rotation in transverse directions but free in the longitudinal direction, while the electrical boundary condition for the piezoelectric shell was zero electric potential on the outer surface but with a specified electric potential on the inner surface to generate the desired electric field in the shell. The epoxy matrix around the ASF was modeled in a rectangular shape to form a representative volume element. Electric field was added on the inner and outer surfaces of the piezoelectric shell to generate strain which could then be compared to the free strain predicted by the theoretical model in Eq. (10).

A typical FEA analysis for the single piezoelectric structural fiber is shown in Fig. 3 in both the zero field and displaced cases. Because the modulus of elasticity of the core fiber (inactive) is higher than that of the piezoelectric layer (active), the strain at the inner wall of the piezoelectric layer is constrained. Prior efforts which have

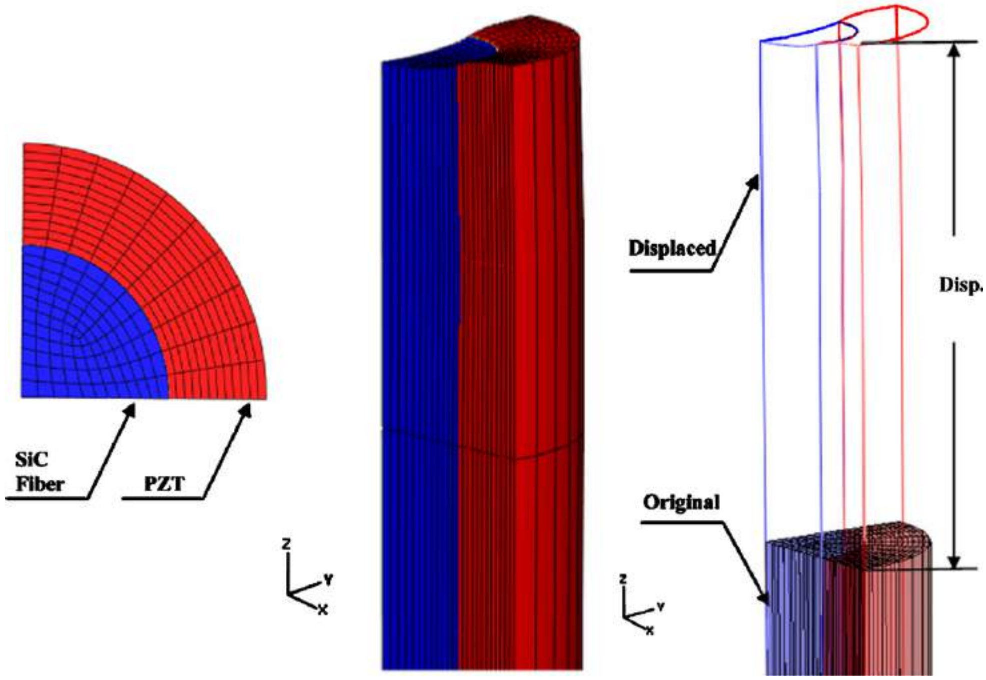

Fig. 3. Finite element model of the structural fiber surrounded by a piezoceramic shell.

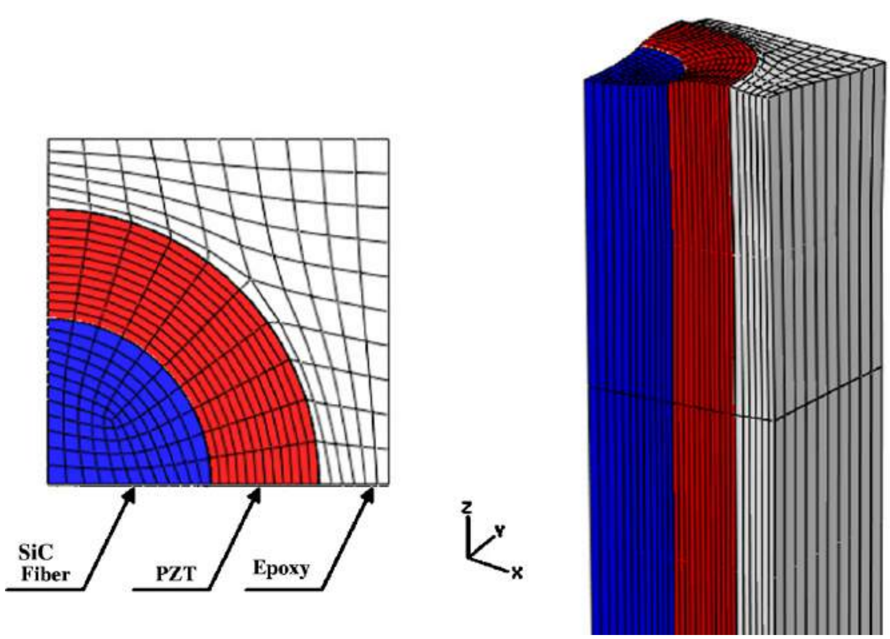

Fig. 4. Finite element model of the piezoelectric structural fiber embedded in a polymer matrix.

studied the response of the hollow fiber actuator experienced significant variation in the fiber strain due to a higher field at the inner wall of the piezoelectric shell, which was termed "end effect". Although our fiber experiences the same variation in electric field, the high modulus structural fiber reduces this variation leading to nearly constant axial strain with respect to the radial position in the piezoelectric shell. The case that the piezoelectric fiber is embedded into a polymer matrix is shown in Fig. 4. Compared to the core fiber, the modulus of elasticity of the epoxy is much lower, therefore, the strain at the piezoelectric shell's outer wall was decreased by the same level as compared to that of the inner wall. The average displacement at the tip of the model was used to determine the strain of the fiber which could then be used with Eq. (12) to determine the effective d_{31} coefficient of the composite.

4. Result and discussion

Once the finite element (FE) model had been created, it could be used to validate the accuracy of the micromechanics model developed. This validation has been performed through a comparison of the electromechanical coupling predicted by the model and the FE code. The resulting electromechanical coupling of the multifunctional fiber is plotted in Fig. 5 with respect to the fiber aspect ratio for two different material core fibers. The y-axis of this plot represents the ratio of the coupling coefficient, d_{31} of the multifunctional fiber to that of active constituent, therefore a coupling ratio of 80% would indicate that an active fiber with a PZT shell could achieve 80% of the coupling of bulk PZT. As expected, the effective d_{31} increased with the aspect ratio, however, the maximum value is obtained at approximately 0.85, which corresponds to the point at which the surface area of the inner wall becomes much less than the outer wall resulting in a break down of the thin wall approximation and leading to very high electric field on the inner wall potentially depoling the piezoelectric material. The results presented in Fig. 5 demonstrate that the micromechanics model formulated to represent the active structural fiber very accuracy estimates the coupling and has a maximum error of 8% with an aspect ratio of 0.9. Although the error is very small, it is most likely caused by the non-uniform strain profile at the tip of the fiber due to the structural fiber constraining the deformation of the piezoelectric shell as well as the thin wall electric field approximation becoming less accurate as the piezoelectric shell thickness increases under high aspect ratio.

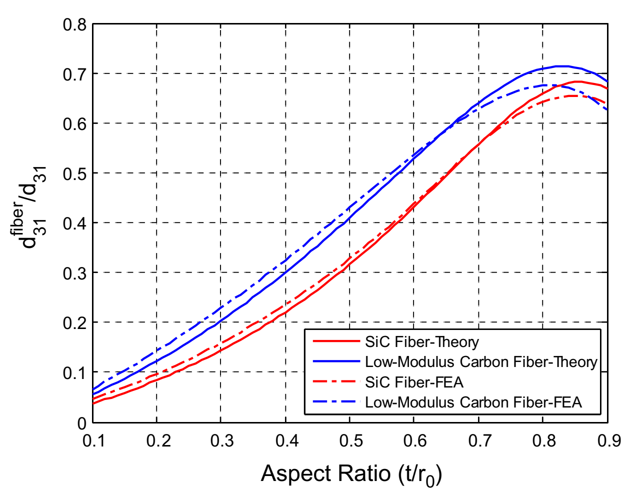

Fig. 5. Comparison of theoretical model and the FEA result for active fiber coupling with respect to the aspect ratio (t/r_0) of the piezoelectric material.

Considering the fabrication process, the ability to produce active structural fibers (ASFs) with very high aspect ratio fiber is not practical due to the difficulty during the poling process resulting from higher field at the inner wall leading to either breakdown of the material at the inner wall or only partial poling at the outer radius. For all poling techniques, the resulting polarization of the fiber would inevitably be partial [19]. The agreement between the theoretical and FE models demonstrates that the model is accurate enough to drive the geometry of the fibers for fabrication.

Since the modulus of the low-modulus carbon fiber (250 GPa) is lower than that of the SiC fiber (380 GPa), the low-modulus carbon fiber effective d_{31} is higher at the same aspect ratio. According to Eq. (6), this can be explained because the low-modulus core fiber will reduce the modulus of the whole piezoelectric structural fiber. Furthermore, the result shows that higher aspect ratios will lead to higher coupling until a critical point (around 0.85) at which the thin wall approximation breaks down and the non-uniform electric field has to be considered, therefore, the piezoelectric coupling will be sacrificed even the aspect ratio is higher. The coupling ratio showing in Fig. 5 indicates that for the low-modulus carbon fiber, the optimum aspect ratio is around 0.83, while for the SiC fiber, the optimum aspect ratio is around 0.85 where the maximum coupling is about 70% of the bulk piezoelectric materials.

As before, the FE model was used to validate the micromechanics model's prediction of the coupling for a laminate incorporating the active structural fibers. The electromechanical coupling ratio or ratio of the coupling of a lamina consisting of the active structural fibers to the coupling of the bulk active constituent for various ASF volume fractions with a carbon fiber core (250 GPa) is shown in Fig. 6. The maximum error between the theoretical model and FEA is less than 4%, however, the error is large at aspect ratios between 0.8 and 0.9 for reasons previously described. From Fig. 6 it can be seen that the aspect ratio of the fiber plays a far larger role in the electromechanical coupling of the composite material. The choice of fiber would need to be weighted to account for a multitude of parameters including, coupling, weight, strength,

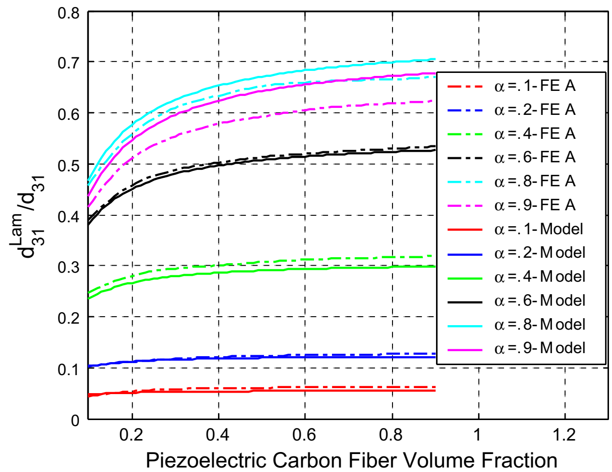

Fig. 6. Comparison of the theoretical model and the FEA result for the active fiber coupling of a lamina consisting of the active structural fiber to that of bulk piezoelectric material, with respect to the volume fraction of the active fiber for various fiber aspect ratios.

modulus, etc. However, the results presented show that the active structural fiber proposed here could lead to structural composites with piezoelectric coupling coefficients for the entire material as high as 65–70% of the active constituent. Therefore, if PZT was used as the active material a composite laminate could be fabricated which offered a d_{31} piezoelectric coefficient as high as 224×10^{-12} m/V or almost four times more than barium titanate ($BaTiO_3$). A composite material with coupling levels this high could be used for a wide variety of applications including structural sensing, actuation, self-monitoring materials, power harvesting, or shape control through anisotropic actuation.

5. Conclusion

Multifunctional materials are integrated material systems that provide load bearing in addition to some secondary functionality. The advancement of this field has been rapid due to the significant safety and performance benefits that can be achieved when using this class of materials. One material which can be used for a variety of purposed in mechanical systems are piezoelectric materials which have the ability to interchange electrical and mechanical energy. This effort has investigated the development of a multifunctional material made from a conductive structural fiber surrounded in a piezoelectric shell, which would then be embedded into a polymer matrix to form an active structural fiber (ASF) composite. In order to evaluate the potential of this materials system, theoretical and finite element models have been developed to predict the electromechanical coupling available from the ASF and a composite made from the fibers. The two models were shown to be in agreement (max. 8% for the piezoelectric structural fiber model and max. 4% for the whole lamina model) indicating that the micromechanics model is valid for use in the design of the material. The results of the two models demonstrated that a composite material made from these ASFs could achieve piezoelectric coupling coefficients for the entire composite as high as 65–70% of the active constituent. Therefore, the system theoretically developed here would lead to structural materials with substantial coupling, clearly high enough to be used for vibration control, damping, power harvesting, or structural health monitoring.

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