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Modified Strength of Materials and Energy Approach to Determine Effective Properties of Piezoelectric Fiber Reinforced Composite

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Abstract:
On this paper, modified energy of substances and strain energy-based totally method are wont to decide effective electro-mechanical residences of piezoelectric fiber strengthened composites. Based totally upon these techniques, Micromechanics model has been formulated employing a square consultant extent element which includes each fiber also as matrix levels. Result obtained has been compared with energy of materials approach to the comparable problems available in Literatures. Consequences recommend that there is extensive variant in estimation of homes received through electricity of substances approach to the strategies followed in the course of this work. Electricity of substances technique in maximum of cases overestimates or underestimates the particular result. Though each of such methods has its personal barriers, the followed method at some stage in this paper refines result obtained via energy of materials, as it takes beneath attention of the several conditions, which has no longer been dealt while analyzing with energy of substances approach. Both changed energy of materials and energy method reduces aberration generated in end result, way to era of unequal strain in matrix and fiber stages additionally as poison's ratio mismatch between fiber and matrix levels.

Keywords:*Micromechanics, Piezoelectric Composites & Structural Mechanics*.

1. Instruction

Piezoelectric materials have a remarkable property of doing reciprocity of electricity between the mechanical areas to electrical domain and the other way around. This makes piezoelectric ceramics like lead zirconium titanate very appealing substances closer to sensors and actuators programs. Piezoelectric substances have several programs in traditional as nicely as advanced engineering applications like aerospace, microphones, ultrasonic transducers, automatic control of remote explorations. These extensive applications make piezoelectric substances a category of materials that desires attention for studies and improvement closer to miniaturization of homes of those ceramics. At the same time as using in pure form, those substances have certain barriers, like low piezoelectric constants, form manage and excessive specific acoustic resistance, this could be overcome by using combining those materials with non-piezoelectric substances.

This outcomes into piezoelectric composites bearing advanced mechanical and electric houses to the previous one. The take a look at of electromechanical properties of piezoelectric fiber bolstered composites has drawn an outstanding deal of interest in recent years in kind of mathematical modelling of behavior of these composites. Diverse numerical techniques also as analytical strategies has

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been wont to describe the behavior of such factors, even though these strategies have limitations of their own. Presently, there was growing studies interest in growing analytical fashions to decide the powerful electro-mechanical residences of such magnificence of materials.

In micromechanical technique, the general properties of the composite are said to be volume average sum of the homes of a unit consultant quantity detail created from each fiber and matrix surrounding it. Effective residences are frequently derived from the outcomes obtained by means of the analysis of the RVE. Type of such efforts for determining powerful Electro-mechanical homes of such composites are suggested in the literature. All of such models have many assumptions, which can be common to all or any as a way to simplify the complex calculations. In real exercise, those assumptions do have their own impact on very last outcome. One in every of such assumption is that the effective coefficients are calculated as regards to common subject within the homogenized piezoelectric composite. In real exercise, there's a good sized distinction infield in fiber and matrix levels thanks to striking comparison in their dielectric residences. Authors have used those equal set of assumptions to predict normal effective properties of PFRCs.

Few enhancements of homes have additionally been pronounced, via doing sure change to earlier fashions. Kumar and Chakraborty have extended look at of Malik and ray to work out the general thermo-electro-elastic residences, which relies on energy of substances technique. Gift work targets at developing a micromechanics-primarily based version for the evaluation of effective electromechanical residences of PFRCs, which might be utilized in accurate evaluation of PFRCs as actuators in clever applications. Micromechanics version for predicting the powerful properties of the piezoelectric composite is predicated upon changed energy of materials and electricity technique. Effects received has been as compared to the effective houses acquired through strength of substances technique.

2. Micromechanics

Piezoelectric fiber reinforced ceramics consists of piezoelectric fibers aligned parallel to every other in longitudinal direction, surrounded by matrix phase. Bulk materials are often visualized as an assembly of an oblong representative volume element (RVE) containing both fiber and matrix which may be repeated in three dimensions to get the majority material. Figure 2 shows the transverse cross-section of such a representative volume element during a PFRC. This section contains micromechanics modelling of such RVE with modified strength of fabric method. The effective coefficients obtained using modified strength element would be same as that of RVE in average sense.

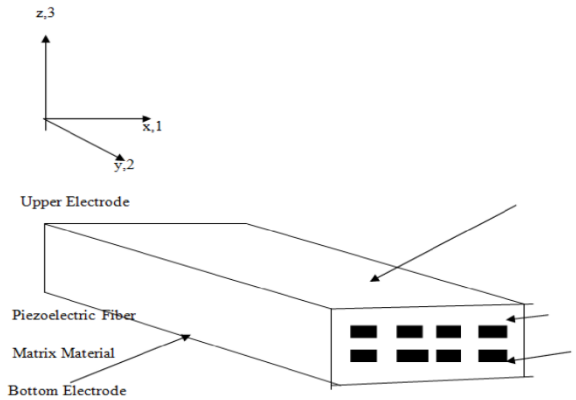

Fig.1: Figure 1: Schematic Diagram of PFRC Lamina

For simplification, few assumptions are made during this study. It's assumed here that the composite is subjected to a continuing field within the direction transverse thereto of fibers, field is same in both matrix and fiber. Piezoelectric composite is uniform throughout, behaves in linear elastic manner, and there's no slippage between fibers and matrix. Also, fibers are continuous and aligned parallel in longitudinal direction.

Figure 1 shows a square array of fibers of circular cross-section and figure 2 gives representative volume element (RVE) of such an array. The circular cross-section of fiber is converted into square with equivalent area, and therefore the RVE is split into sub regions a shown long of side of RVE is figure 2. Figure 2 illustrates that RVE can be subdivided into sub regions I and II, region I is matrix dominated while II is a composite consisting both fiber and matrix phases. In this approach, firstly effective properties of sub region II are computed as series connection of fiber and matrix subjected to transverse normal stress, which is followed by calculation of overall effective properties taking sub region I and II as parallel connection subjected to transverse normal stress.

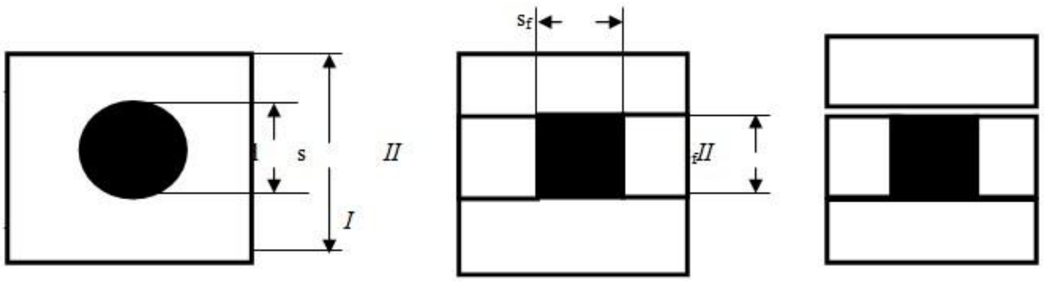

Fig. 2: Transverse Cross-section of a Representative Volume Element of PFRC.

Constitutive equations for transversely isotropic piezoelectric active fibers in Voigt's two index notation are

$$\begin{Bmatrix} \sigma_{11}^f \\ \sigma_{22}^f \\ \sigma_{33}^f \\ \sigma_{23}^f \\ \sigma_{31}^f \\ \sigma_{12}^f \end{Bmatrix} = \begin{bmatrix} C_{11}^f & C_{12}^f & C_{13}^f & 0 & 0 & 0 \\ C_{12}^f & C_{22}^f & C_{23}^f & 0 & 0 & 0 \\ C_{13}^f & C_{23}^f & C_{33}^f & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^f & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^f & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^f \end{bmatrix} \begin{Bmatrix} \epsilon_{11}^f \\ \epsilon_{22}^f \\ \epsilon_{33}^f \\ \epsilon_{23}^f \\ \epsilon_{31}^f \\ \epsilon_{12}^f \end{Bmatrix} - \begin{bmatrix} 0 & 0 & e_{31}^f \\ 0 & 0 & e_{32}^f \\ 0 & 0 & e_{33}^f \\ 0 & e_{24}^f & 0 \\ e_{15}^f & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} E_1^f \\ E_2^f \\ E_3^f \end{Bmatrix} \tag{4}$$

$$\begin{Bmatrix} D_1^f \\ D_2^f \\ D_3^f \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15}^f & 0 \\ 0 & 0 & 0 & e_{24}^f & 0 & 0 \\ e_{31}^f & e_{32}^f & e_{33}^f & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \epsilon_{11}^f \\ \epsilon_{22}^f \\ \epsilon_{33}^f \\ \epsilon_{23}^f \\ \epsilon_{31}^f \\ \epsilon_{12}^f \end{Bmatrix} + \begin{bmatrix} \kappa_{11}^f & 0 & 0 \\ 0 & \kappa_{22}^f & 0 \\ 0 & 0 & \kappa_{33}^f \end{bmatrix} \begin{Bmatrix} E_1^f \\ E_2^f \\ E_3^f \end{Bmatrix} \tag{5}$$

The constitutive equations for isotropic passive matrix phases in Voigt's two index notation are

$$\begin{Bmatrix} \sigma_{11}^m \\ \sigma_{22}^m \\ \sigma_{33}^m \\ \sigma_{23}^m \\ \sigma_{31}^m \\ \sigma_{12}^m \end{Bmatrix} = \begin{bmatrix} C_{11}^m & C_{12}^m & C_{13}^m & 0 & 0 & 0 \\ C_{12}^m & C_{22}^m & C_{23}^m & 0 & 0 & 0 \\ C_{13}^m & C_{23}^m & C_{33}^m & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^m & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^m & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^m \end{bmatrix} \begin{Bmatrix} \epsilon_{11}^m \\ \epsilon_{22}^m \\ \epsilon_{33}^m \\ \epsilon_{23}^m \\ \epsilon_{31}^m \\ \epsilon_{12}^m \end{Bmatrix}$$

$$\begin{Bmatrix} D_1^m \\ D_2^m \\ D_3^m \end{Bmatrix} = \begin{bmatrix} \kappa_{11}^m & 0 & 0 \\ 0 & \kappa_{22}^m & 0 \\ 0 & 0 & \kappa_{33}^m \end{bmatrix} \begin{Bmatrix} E_1^m \\ E_2^m \\ E_3^m \end{Bmatrix} \tag{6}$$

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Superscript R denotes piezoelectric fiber (f) or matrix (m) phases, respectively. The resultant constitutive equations of composite can be written as

$$\begin{Bmatrix}\sigma_{11}^c\\ \sigma_{22}^c\\ \sigma_{33}^c\\ \sigma_{23}^c\\ \sigma_{31}^c\\ \sigma_{12}^c\end{Bmatrix}=\begin{bmatrix}C_{11}^c & C_{12}^c & C_{13}^c & 0 & 0 & 0\\ C_{12}^c & C_{22}^c & C_{23}^c & 0 & 0 & 0\\ C_{13}^c & C_{23}^c & C_{33}^c & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44}^c & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55}^c & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}^c\end{bmatrix}\begin{Bmatrix}\epsilon_{11}^c\\ \epsilon_{22}^c\\ \epsilon_{33}^c\\ \epsilon_{23}^c\\ \epsilon_{31}^c\\ \epsilon_{12}^c\end{Bmatrix}-\begin{bmatrix}0 & 0 & e_{31}^c\\ 0 & 0 & e_{32}^c\\ 0 & 0 & e_{33}^c\\ 0 & e_{24}^c & 0\\ e_{15}^c & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}E_1^c\\ E_2^c\\ E_3^c\end{Bmatrix}$$

$$\begin{Bmatrix}D_1^c\\ D_2^c\\ D_3^c\end{Bmatrix}=\begin{bmatrix}0 & 0 & 0 & 0 & e_{15}^c & 0\\ 0 & 0 & 0 & e_{24}^c & 0 & 0\\ e_{31}^c & e_{32}^c & e_{33}^c & 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}\epsilon_{11}^c\\ \epsilon_{22}^c\\ \epsilon_{33}^c\\ \epsilon_{23}^c\\ \epsilon_{31}^c\\ \epsilon_{12}^c\end{Bmatrix}+\begin{bmatrix}\kappa_{11}^c & 0 & 0\\ 0 & \kappa_{22}^c & 0\\ 0 & 0 & \kappa_{33}^c\end{bmatrix}\begin{Bmatrix}E_1^c\\ E_2^c\\ E_3^c\end{Bmatrix} \qquad (7)$$

To be determined in order to evaluate complete electro-mechanical behavior of the composite. Considering series connection of fiber and matrix in sub region II subjected to transverse loading, geometric compatibility requires.

Table 1: Elastic Properties of Piezoelectric Fibers and Matrix

Material	^{xx}(GPa)	^{xy}(GPa)	^{xz}(GPa)	^{zz}(GPa)	$^{\{\{}$(GPa)	$^{\|\|}$(GPa)
PZT-5	121	75.4	75.2	111	22.8	21.1
Epoxy	3.86	2.57	2.57	3.86	0.64	0.64

Table 2: Piezoelectric and Dielectric Properties of Fibers and Matrix

Material	^{zx}(C/m^2)	^{zz}(C/m^2)	$^{x\sim}$(C/m^2)	^{xx}(10^{-9} C/Vm)	^{zz}(10^{-9} C/Vm)
PZT-5	-5.4	15.8	12.3	8.11	7.35
Epoxy	0	0	0	0.0797	0.0797

The study carried here provides a comparative study of variation in effective properties as a function of fiber volume fraction and matrix properties among strength of materials, modified strength of materials and energy method. The following non-dimensional parameters have been used in the analysis.

$$R_{31}=\frac{e_{31}^c}{e_{31}^f}$$

$$R_{32}=\frac{e_{32}^c}{e_{32}^f}$$

$$R_{33}=\frac{e_{33}^c}{e_{33}^f}$$

Figures 3–6 show the comparative study of effective elastic coefficient of composite with respect to change in fiber volume fraction. Results clearly shows that modified strength of method and energy

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method are close in values, while shows effective coefficient estimated from strength of materials method is in close proximity with modified strength of materials overestimates the effective coefficient 66 while it underestimates effective coefficient 6).

Figure 5 method and energy method. Again, a huge underestimation of effective coefficient is reported as shown in figure 6. These wide deviations of effective properties occur due to fact that in strength of material approach, there has been certain assumptions which provide very poor results. In strength of materials approach it is assumed that, equal strains are produced in fiber as well as matrix phases when stress is applied, while in actual practice these strains ought to be different. Modified strength of materials approach refines result for transverse stresses, while energy approach also gives better result, as ratio Poisson's mismatch is tackled to a great degree through this model.

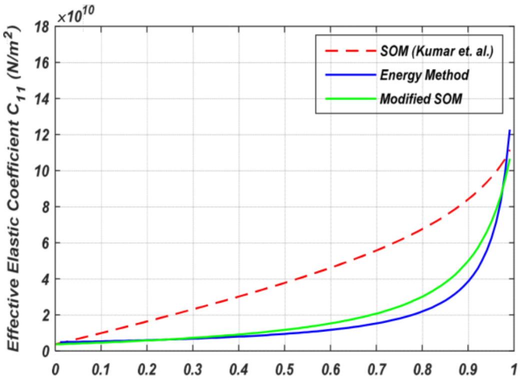

Figure 3: Variation of Elastic Coefficient C_{11} of PZT-5/Epoxy Composite with Fiber Volume Fraction.

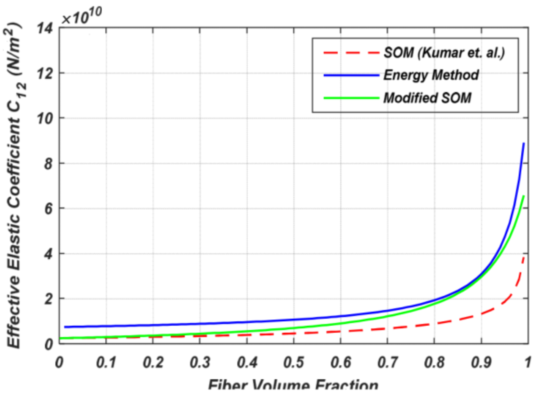

Figure 4: Variation of Elastic Coefficient C_{12} of PZT-5/Epoxy Composite with Fiber Volume Fraction.

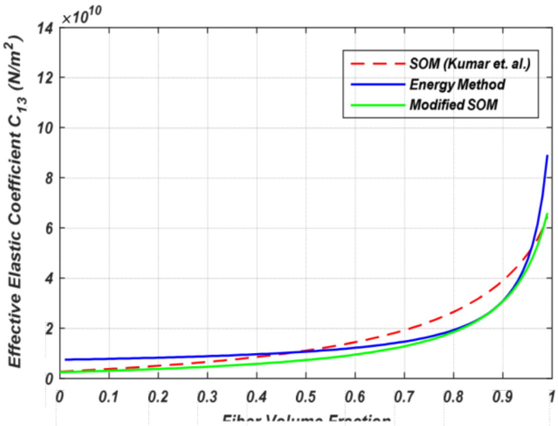

Figure 5: Variation of Elastic Coefficient C_{13} of PZT-5/Epoxy Composite with Fiber Volume Fraction.

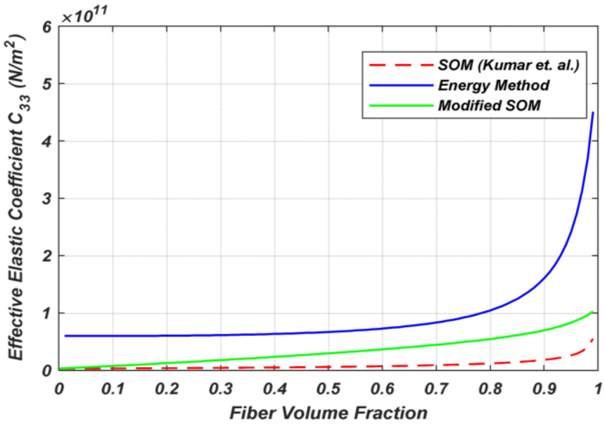

Figure 6: Variation of Elastic Coefficient C_{33} of PZT-5/Epoxy

3. Piezoelectric Composites

Comparable tendencies of overestimation and underestimation is additionally pronounced for "seventy six, "7), and "seventy seven for electricity of substances as compared with changed energy of materials and electricity method. Figure 7 shows value of ratio of piezoelectric coefficient "76 which has been fairly hyped up in power of substances approach in comparison with changed energy of substances and energy method.

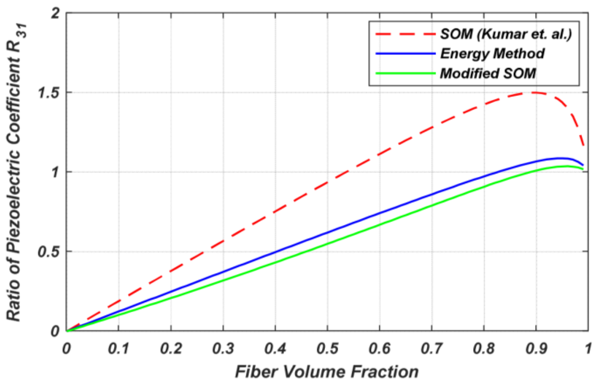

Figure 7: Variation of Ratio of Piezoelectric Coefficient $- e_{31}^{c}/e_{31}^{f}$ PZT-5/Epoxy Composite with Fiber Volume Fraction.

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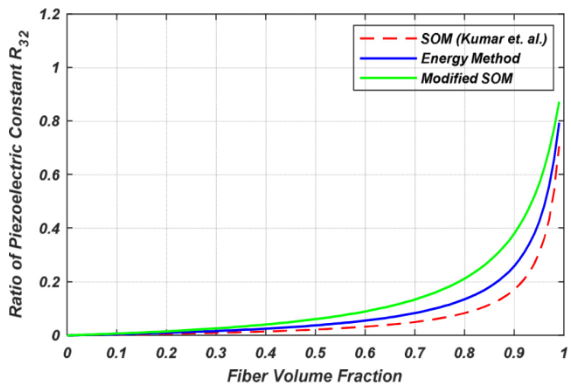

Figure 8: Variation of Ratio of Piezoelectric Coefficient e^c_{32}/e^f_{32} PZT-

While results shown in determine 8 shows the values of "7) are truly in accurate settlement with one another, at extremely decrease and higher values of fiber quantity fraction. In mid degrees of fiber volume fraction, there may be symmetric divergence of residences between these 3 methods. For the duration of this situation, electricity of materials method and modified power of materials approach forms lower and boundary of energy technique, respectively. Figure 9 suggests ratio "seventy seven is in correct settlement for strength of substances method and strength approach, at the same time as there's a divergence of changed power of materials results from those two methods.

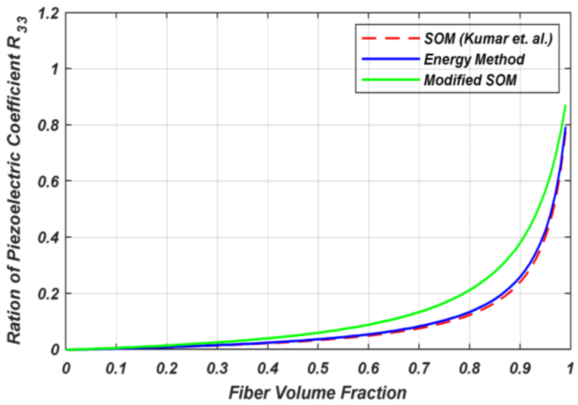

Figure 9: Variation of Ratio of Piezoelectric Coefficient e^c_{33}/e^f_{33} PZT-5/Epoxy Composite with Fiber Volume Fraction.

4. Structural Mechanics

Though there is a huge variation in dielectric properties of the constituent phases of PFRC, figure 10 shows that the overall dielectric coefficient of composites is in good agreement with each other for all three methods i.e. strength of materials, modified strength of materials and energy method.

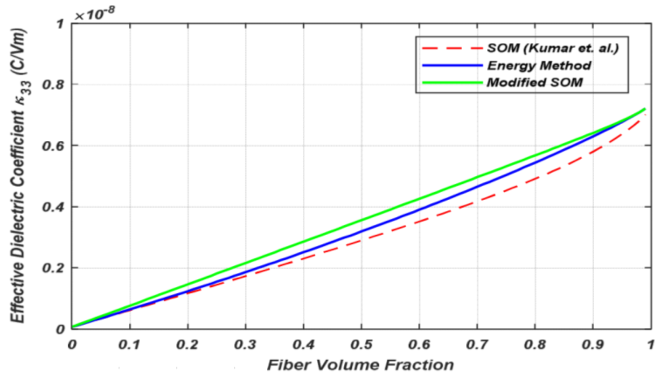

Figure 10: Variation of Dielectric Coefficient κ^c_{33} PZT-5/Epoxy Composite with Fiber Volume Fraction.

5. Conclusion:

In this paper, two distinguished method of micromechanics i.e. modified strength of materials and energy method have been used to study the effective properties of piezo fiber reinforced composites. The results have been used to analyses deviation of effective properties estimated in earlier works using strength of materials method. In various works, the strength of materials method models the problem on assumptions that the equal strains are produced in both fiber and matrix phases, while this assumption doesn't have significant effects on results while the longitudinal stress is applied to the composite. In case of transverse loading, the results obtained from strength of material would be far from accurate. Modified strength of materials method refines the result obtained from strength of materials method and provides a better estimated effective property. Energy method modelling of the problem eliminated the effect of Poisson's ratio mismatch between fiber and matrix phases. Thus, present study reveals better models for micromechanics analysis than the reported strength of materials methods for various coefficients, and expected to give more precise results than existing method.

It makes tailoring of properties of piezoelectric composites that contains piezoelectric fibers in piezoelectric ally-inactive matrix, having superiors and improved effective electrical and mechanical

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properties. In addition, these models could be served as a benchmark for numerical analysis of PFRC problems and can be utilized to model coupled more piezoelectric composite problems, subjected to more complex boundary conditions.

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