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Effect of Interface on Elastic Properties for Hybrid Smart Nanocomposites using Micromechanics based Mori Tanaka Technique

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Carbon nanotube (CNT) reinforced composites are an extensive and convoluted research domain, in particular their modelling and simulation. These nanocomposites have been continuously researched for enhanced mechanical properties. The interface is supposedly the layer created around the CNTs embedded in a matrix with easily distinguishable properties. To exploit the true potential of nanocomposites and their hybrids, the evaluation of their interface characteristics and their effect on mechanical properties is a crucial aspect. A new model consisting of a hybrid smart composite reinforced with CNTs and piezoelectric fibers has been proposed. Understanding the significance of interface in hybrid nano composites is the key concept of this paper. To analyse the mechanical performance in the proposed composite, the evaluation of interfaces is performed using the micromechanics-based Mori Tanaka technique. The results show that both the longitudinal and transverse elastic properties of hybrid smart nanocomposites increase significantly linearly with the use of interface and agree well with the micromechanics-based strength of materials approach. Taking this into consideration, the interface promotes prophecy of nanocomposites for novel structural and wearable smart textile applications.

Keywords: Piezoelectric fiber, Carbon nanotube, Mori Tanaka technique, Interface, Nanocomposite

1 Introduction

The physicochemical aspect of composite interfaces is a conglomerate subject, and understanding this feature is one of the main areas of investigation for the scientific community. The evolution of carbon nanotubes (CNT) have captivated researchers due to their superior properties[1] . In recent years, nanofiber-reinforced composites have appeared in an array of advanced engineering applications due to their distinguished mechanical properties. The mechanical behavior of these nanocomposites is highly reliant on constituting phases of composite and filler and interface used. To discern the origin of properties of a composite, it is imperative to determine which constituents form a particular composite system. Many studies focus on interface between matrix and fiber since competence of stress reassign by using interface performs a consequential task in mechanical response of nanocomposites[2]. Due to improved set of properties, nanocomposites show promising applications in developing advanced textile materials such as- Nanocomposite fibers, nano fibers and other nanomaterial incorporated fibers and coated textiles for applications in medical, defense, aerospace and other technical textile applications such as filtration, protective clothing besides a range of smart and intelligent textiles[3].

The conventional continuum theory offers constraints in characterizing the properties of hybrid composites with CNTs at nanoscale and with polymers as a bulk matrix. Over the last decade, the various simulation method has gained popularity in modeling the elastic moduli of CNT-reinforced nanocomposites[4]. Significance of Alloying Elements on the Mechanical Characteristics of Mg-Based Materials for Biomedical Applications have been presented and review study on epoxy nanocomposites have been carried out[5-7]. To determine the Effective Elastic Properties (EEP) of nanocomposites using carbon fiber, the strength of material based multistage

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modeling had been studied to explore influences of orientation, carbon fiber volume fraction, CNT volume fraction and geometrical structures, polymer/CNT interphase section, and types of carbon fiber arrays on engineering elastic properties of these nanocomposites[8]. Multifunctional Applications of carbon nanotube based polymer composites have been studied to understand their behavior[9]. Efforts were made towards a multiscale micromechanical model to assess characteristics of hybrid nanocomposites using carbon fiber[10]. The various potential applications of these hybrid nanocomposites including textile applications were discussed in[11].

Over the last decade, the analysis of hybrid smart composites has been a vital part of the researchers' investigation. The micromechanical methods used for these composites were developed using piezoelectric (PZT) fibers as a smart material. The strength of material based micromechanical approach had been used to estimate PZT and EEP for hybrid smart nanocomposites, making it the best choice for vast technological applications, including admirable distributed actuation in smart structures with high in-plane actuation capability[12-15]. Further, to enhance the effective properties of these hybrid smart nanocomposites, the interface was taken into consideration, and its effect was analyzed. The modeling of CNT reinforced composites has been performed using continuum modeling to evaluate the effective properties[16].

The experimental and numerical comparison displayed a 6.8% enhancement in predicting mechanical response of composite by considering interphase in glass fiber epoxy composites[17]. Various other models were proposed using theoretical and analytical techniques to understand the damage analysis, mechanical, electrical, and dielectric properties of nanocomposites[18-20]. Woigk et al. investigated the interface behavior and its influence on the mechanical characteristics for flax fiber reinforced polymer composites and it was found that there is a vital enhancement in EEP of these polymer composites with use of interface[21]. The experimental and theoretical studies were carried out with different amounts of multiwall CNTs and graphene nanoplateles in various composites, and it was observed that there was a significant improvement in tensile and compressive mechanical properties in these composites. Effect of stacking sequence on mechanical strength for laminated hybrid composite reinforced with various fibers were studied by T. J. Singh and S. Samanta[22]. Charleston studied the impact of interface configuration on dislocation mechanisms and mechanical characteristics in polymer matrix composites. It was found that enhancements in mechanical properties were similar to experimental results[23].

The micromechanics-based Mori Tanaka (MT) approach can be used to evaluate the EEP of composites accurately[24]. Further, the MT method was reformulated for its application in determining the EEP of various composite materials[25-26]. Sadeghpour et al. proposed an updated MT method to model the elastic retort of CNT graphene reinforced composites under substantial deformation[27]. Wang et al. experimentally depicted a modern advancement in micro scale interface phenomenon for permitting elegant design of nanocomposites. In this regard, authors used implication of competing mechanisms between interfacial shear effects and inherent mechanical properties of nanofillers[28]. Effect of interface properties on micromechanical damage behavior, mechanical properties and interface morphology of fiber-reinforced composites was investigated[29-31]. To satisfy Hill–Mandel's lamina, Tran et al. proposed a conceptual model for homogenization of stress-gradient composites and derived appropriate boundary conditions for the same[32]. Various computational micromechanical studies were investigated to understand the effect of interface, elastoplastic behavior, and stress transfer on nanocomposites and metal matrix composites[33-34].

Wearable electronic textiles are an emerging interdisciplinary research area that requires new design approaches. Smart wearable textiles use piezoelectric fibers (PZT) and have become a major segment of electronic-textiles along with smart clothing and wearable computer. Further, with the use of CNT reinforced fibers with PZT, these wearable textiles can sense, react and adapt themselves accordingly to external conditions or stimuli and can work in conjunction with human brain for cognition, reasoning and capacity activation[35-36].

Therefore, further exploration of these hybrid smart nanocomposites is a challenging task. Nevertheless, this development provides ample enthusiasm and motivation to render research on the effective properties of hybrid smart nanocomposites. It has been revealed from the literature review that interfaces perform an essential task in the macroscopic behavior of nanocomposites. Several numerical and analytical techniques were reported to examine the effect of interfaces. However, computational micromechanics models that consider the modeling of nanocomposites and their effects of fiber volume fraction on the constituting phases are scarce in the literature. The literature shows that the results obtained by this micromechanical approach are very close to experimentally obtained results for the determination of composite properties. Modeling techniques for hybrid composites such as armchair carbon nanotubes and piezoelectric fiber-reinforced composites are still in their nascent stage. This study investigates the impact of incorporation of interface for prediction of effective elastic modulus and piezoelectric constants for the armchair CNT reinforced hybrid smart composites and provide a way for interpreting the existing experimental results properly. For this, a three-phase representative volume element is modeled by employing numerical simulation, comprised of armchair carbon nanotube, piezoelectric fibers, interphase, and matrix materials. This paper establishes a template for the rational design of high-performance hybrid smart nanocomposites.

The paper is organized into five sections. The second section provides details of the proposed hybrid smart nano composite. Another example of the micromechanical-based Mori Tanaka approach is presented in the third section. The discussion of results, material behavior, and properties is presented in the fourth section and conclusions are inferred in the final section.

2 Materials and Methods

2.1 Modeling of Hybrid Smart Nano Composite (HSNC)

The challenging interdisciplinary research in wearable textile field brings together specialists in electronics, materials, information technology, microsystems, and textiles to make an innovation in the development of wearable electronic products. Wearable electronic textiles play a key role among various technologies (clothing, communication, information, healthcare monitoring, military, sensors, magnetic shielding, etc.) as shown in the Fig. 1. It can be depicted from Fig. 1 that CNT reinforced PZT materials are highly attractive to energy harvesting, sensor applications (such as pressure sensor, force sensor, humidity sensor, tactile sensor, medical sensors), intelligent textiles as actuators and various other applications due to their simple and accessible fabrication methods, low cost, and ideal piezoelectric properties. Further, for the enhancement of strength in nanocomposites the interface is used in modeling with incorporation of CNTs and PZT fibers and the resulting composite is termed as HSNC.

The modeling of HSNC lamina consisting the CNTs, interface, PZT fibers in epoxy matrix is illustrated in Fig. 2. The distinctive construction attribute of HSNC represents the PZT fibers which

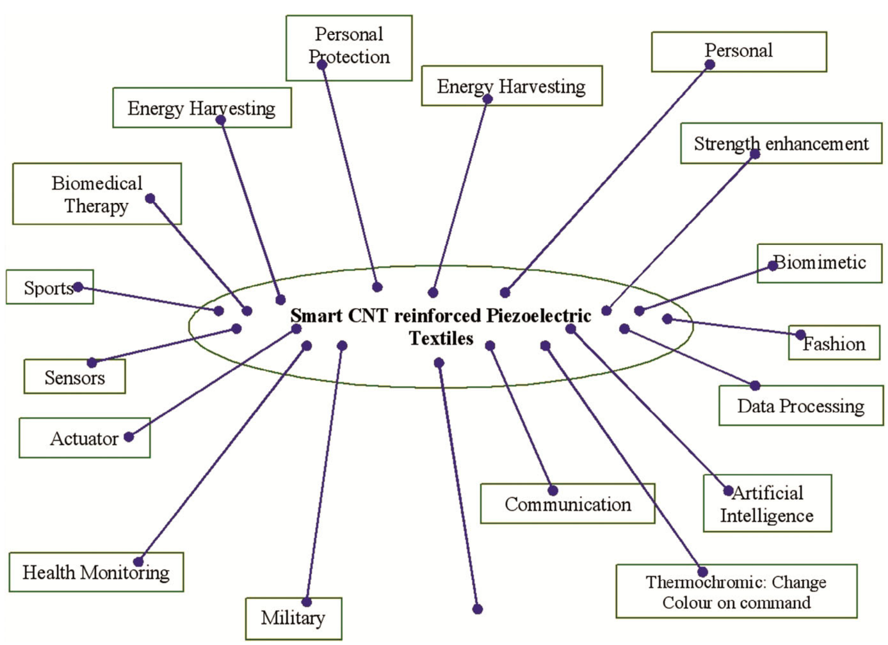

Fig. 1 — Schematic applications: The future of fibers and fabrics.

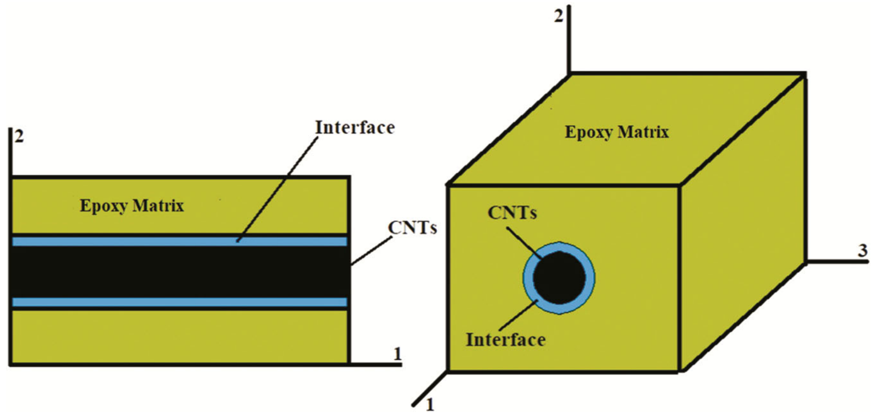

Fig. 2 — Modeling of HSNC lamina.

are employed as longitudinal cylindrical materials. The CNTs are unvaryingly associated with circumferential surface of the PZT fibers in direction of PZT fibers. The material is devised to smear the electric field along epoxy matrix and length of PZT reinforced fibers.

A micromechanical model has been proposed to evaluate transfer of stress between the constituting phases of matrix and fiber within volume fractions and finite thickness of interphase. The elastic properties of interphase are presumed to be power-graded in radial direction, uniform, and homogeneous while other material properties are constants. The bonds between interface and fiber as well as those between matrix and interface are expected to be seamless.

Figure 3 shows the cross-section of the proposed HSNC with transversely isotropic CNTs[37]. They are developed on the PZT fiber surface such that their transverse isotropy axis is perpendicular to the PZT surface. As a result, the obtained nanocomposite can be viewed as a circular cylindrical composite through parallel and continuous PZT reinforced fibers entrenched in hybrid nanocomposite with homogeneous CNT reinforced fibers. Both matrix and fiber materials are assumed to be linearly elastic.

The EEP of intended nanocomposite are evaluated by the MT technique in three steps. In the first step, the three-phase MT technique is used, and in the second and third steps, properties are calculated using two-phase MT technique.

2.2 The MT Approach

The original study of MT[38-39] has been effectively used to estimate the EEP of composites. The MT technique was reformulated by Benveniste[25] to predict the EEP of composites with various shapes and sizes

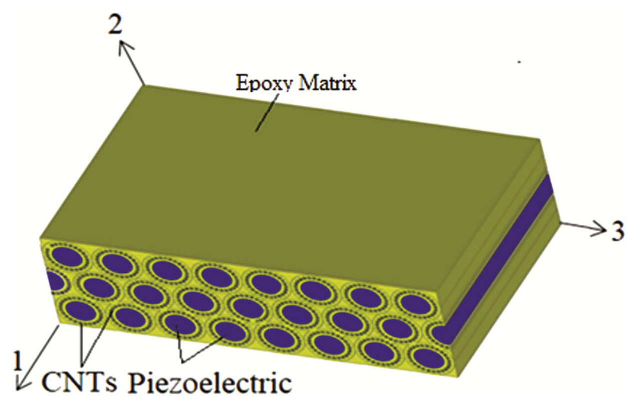

Fig. 3 — HSNC cross section.

of inclusions such as cylindrical fibers, spherical and elliptical fibers. The two-phase MT equations were derived as mentioned in[26].

The scheme of the MT technique for multiple inclusions, i.e., three-phase MT equations, can be derived by estimating the EEP of a three-phase nanocomposite with the help of below equations.

$$C = [C_m] + [(v_f + v_i)([C_i] - [C_m])[A_1] + vfCf{-}Ci[A2]{*}vmI{+}vf{+}vi[A1] \quad \dots (1)$$

$$\{e\} = v_f\,[F_a]\,\{e_1\} \quad \dots (2)$$

Where, C = Elastic constant matrix for the proposed HSNC

{e} is PZT coefficient matrix of proposed composite and v_f denotes the volume fraction of PZT fibers.

$$A_1 = [I] + [S_v]\,[Q_v] \quad ; \quad \text{and } A_2 = [I] + [\Delta S][Q_i] + [S_f]\,[Q_f] \quad \dots (3)$$

$$[Q_f] = -\left[([S_f] + [C_a]) + [\Delta S]\left([S_f] - \frac{v_f}{v_i}[\Delta S] + [C_b]\right)^{-1}\left([S_f] - \frac{v_f}{v_i}[\Delta S] + [C_a]\right)\right]^{-1} \quad \dots (4)$$

$$[Q_i] = -\left[[\Delta S] + ([S_f] + [C_a])\left([S_f] - \frac{v_f}{v_i}[\Delta S] + \right.\right.$$
[Ca]−1Sf−vfviΔS+[Cb]−1 … (5)

$$[Q_v] = \frac{v_f}{v_{i+}v_f}[Q_f] + \frac{v_i}{v_{i+}v_f}[Q_i] \quad \dots (6)$$

$$[\Delta S] = [S_f] - [S_v] \quad \dots (7)$$

$$[C_a] = ([C_f] - [C_m])^{-1}[C_m] \; ; \; [C_b] = ([C_i] - [C_m])^{-1}[C_m] \quad \dots (8)$$

Two-phase Mori Tanaka approach

$$[C] = [C_m] + v_f([C_f] - [C_m])[F_a] \quad \dots (9)$$

where

$$[F_a] = [F_b]\big[v_m[I] + v_f[F_b]\big]^{-1} \quad \dots (10)$$

$$[F_b] = \big[[I] + [S][C_m]^{-1}([C_f] - [C_m])\big]^{-1} \quad \dots (11)$$

Where
C_m= Elastic constant matrix for matrix
C_f= Elastic constant matrix for fiber
C_i= Elastic constant matrix for interphase
v_i= volume fraction of the interphase
v_m= volume fraction of the matrix
$A_1\&A_2$ =Concentration tensors
[I] = Identity matrix
$[S_f]\&[S_v]$ = Eshelby's tensor
$[F_a]\&[F_b]$ = strain concentration factor
$[Q_i]$, $[Q_f]$, $[Q_v]$, $[C_a]$ and $[C_b]$ are constants.

In the MT approach, the Eshelby tensor[40] plays a vital role in solving the inclusion problems, and for HSNC, the two-phase and three-phase MT equations were derived. The Eshelby tensor has numerous uses like multiphase inclusions, fracture mechanics, PZT, study of defects, etc. and is given as follows:

$$[S]=\begin{bmatrix} S_{11}\ S_{12}\ S_{13}\ 0\ 0\ 0 \\ S_{21}\ S_{22}\ S_{23}\ 0\ 0\ 0 \\ S_{31}\ S_{32}\ S_{33}\ 0\ 0\ 0 \\ 0\ 0\ 0\ 2S_{44}\ 0\ 0 \\ 0\ 0\ 0\ 0\ 2S_{55}\ 0 \\ 0\ 0\ 0\ 0\ 0\ 2S_{66} \end{bmatrix} \quad \dots (12)$$

Where

$S_{11} = 0, S_{12} = 0, \ S_{13} = 0,$
$S_{21} = \frac{1}{2(1-\nu)}\left(\frac{2\nu a_3}{a_2 + a_3}\right)$, $S_{22} = \frac{1}{2(1-\nu)}\left\{\frac{a_3^2+2a_2a_3}{(a_2+a_3)^2} + \right.$
$(1-2\nu)$a3(a2+ a3),
$S_{23} = \frac{1}{2(1-\nu)}\left\{\frac{a_3^2}{(a_2+a_3)^2} - \frac{(1-2\nu)a_3}{(a_2+a_3)}\right\}$, $S_{31} = \frac{1}{2(1-\nu)}\left(\frac{2\nu a_2}{a_2+a_3}\right)$, $S_{32} = \frac{1}{2(1-\nu)}\left\{\frac{a_2^2}{(a_2+a_3)^2} - \frac{(1-2\nu)a_2}{(a_2+a_3)}\right\}$,
$S_{33} = \frac{1}{2(1-\nu)}\left\{\frac{a_2^2+2a_2a_3}{(a_2+a_3)^2} + \frac{(1-2\nu)a_2}{(a_2+a_3)}\right\}$, $S_{55} = \frac{a_2}{2(a_2+a_3)}$
and $S_{66} = \frac{a_3}{2(a_2+a_3)}$

Where a_2 = Major axis of ellipse, a_3 = Minor axis of ellipse and ν = Poisson's ratio

Eshel by tensor is dependent on the matrix material properties and shape of the reinforcing fiber. The effective elastic coefficients and piezoelectric properties are determined based on Equation (11). The results are validated using the mechanics of materials (MOM) method[14] and the two-phase MT method[26].

By using the MT approach, the effective elastic coefficients and piezoelectric properties of proposed HSNC are evaluated in three steps: First, the CNTs are employed as reinforcing fibers in epoxy matrix, resulting in the nanocomposite (NC); Second, PZT are used as fibers in a NC matrix forming a piezoelectric nanocomposite (PNC); Third, the PNC operate as reinforcing fibers within an epoxy known as hybrid smart nanocomposite (HSNC). The properties of HSNC are estimated using equations mentioned above to predict effective elastic coefficients and piezoelectric properties of the HSNC.

3 Result and Discussion

3.1 Effective Elastic Properties of Composite

3.1.1 Analytical Validation

In this section, the effect of interface in the modelling of HSNC are illustrated. The results are predicted by the MTM method and are compared with the other established results based on mechanics of materials approach for piezoelectric composites by considering a composite having PZT reinforcement and polymer matrix used in the previous study by Ray[13]. These results for effective elastic constants and effective piezoelectric constants are plotted with the piezoelectric fiber volume fractions (v_f), which are shown in Figs 4 and 5.

The Figs. 4 and 5 confirm that our model gives a good agreement with the results of[13] for the same composite material for all values of v_f. Further, the results were also obtained for other EEP like C_{11}, C_{23} and C_{33} and the same trend was observed in the results obtained from MTM technique and the previously evaluated EEP by Ray[13]. Therefore the MTM equations derived in the previous section can be used for further prediction of EEP of smart nano composites.

3.1.2 Effective properties of HSNC composite

This section presents the results obtained by using the MT approach. The EEP are investigated with two-phase and three-phase MT techniques. Material properties of interfaces, PZT fibers, epoxy matrix, and CNTs[12-14] are given in Table 1. The EEP of purported HSNC is attained with variations in volume fractions of matrix and reinforcing fibers.

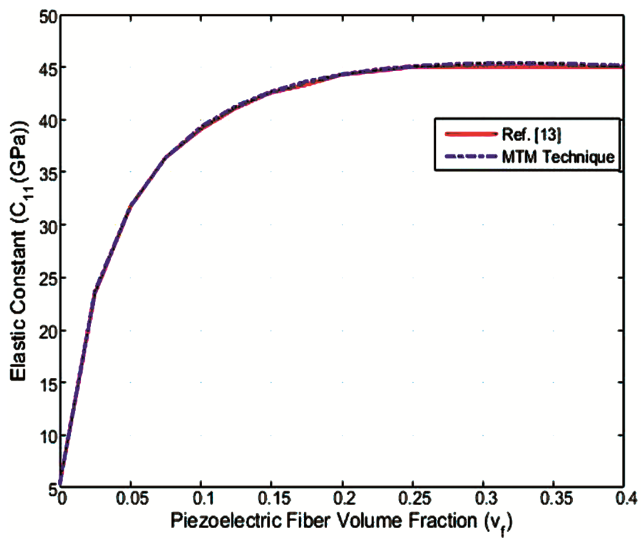

Fig. 4 — Validation of effective elastic constant C_{11}.

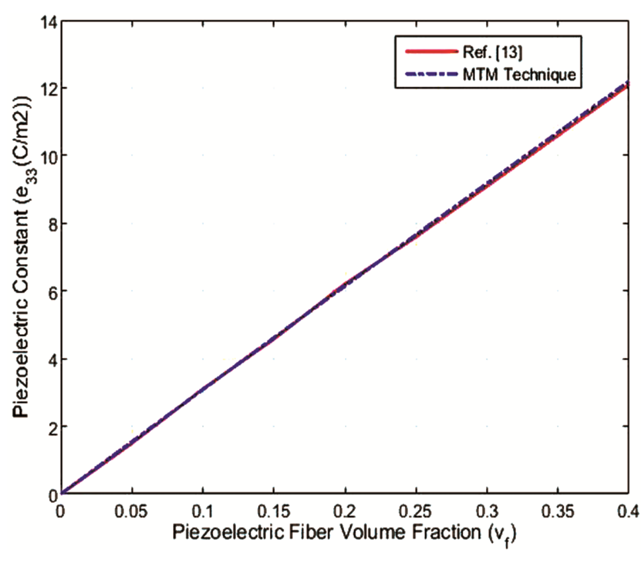

Fig. 5 — Validation of effective piezoelectric constant of the composite e_{33} of the composite.

A CNT (5, 5) and a CNT length of 1.63 nm is taken for the analysis purpose. The CNTs volume fraction in the proposed HSNC is dependent on the nanotubes PZT volume fraction, surface distance amid adjacent CNTs, interface, and diameter. The epoxy matrix fills the gaps between CNTs. The diameter of CNT fibers is assumed to be 0.34 nm, and diameter of PZT fibers as 10,000 nm as given in Table 1.

Figure 6 shows the variation of CNTs volume fraction with v_f. The values of v_f varies from 0.1 to $\pi/2\sqrt{3}$. It is observed that the maximum volume fraction of v_f in the proposed HSNC is 0.9064. Further, authors also observed the maximum value of v_{nt} as 0.039. The maximum value of nanotube volume fraction (i.e. v_{nt} = 0.039) is obtained at 0.23 volume fraction of PZT fiber. This indicates that number of CNTs are maximized at the particular volume fraction. In the beginning, the numbers of CNTs are increasing with PZT fiber diameter but later, it starts decreasing as exhibited in Fig. 6.

The three-phase interface results obtained from the above section have been plotted in Figs. 7 to 16. The piezoelectric fibre volume fraction (v_f) and EEP in GPa are shown on the x-axis and the piezoelectric constants (Coulomb(C)/m^2) are shown on the y-axis. The properties of different constituent phases are

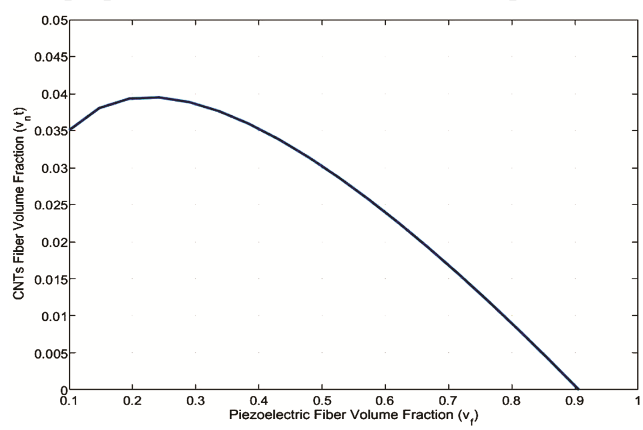

Fig. 6 — Variation of CNTs volume fraction with v_f.

Table 1 — Properties of different constituent phases [12, 14].

Material	Radius (nm)	C_{11} (GPa)	C_{12} (GPa)	C_{23} (GPa)	C_{33} (GPa)	C_{44} (GPa)	C_{66} (GPa)	e_{11} (C/m^2)	e_{13} (C/m^2)
CNT (5, 5)	0.34	668	404	184	2153	984.5	791	-	-
PZT 7A	10000	154.837	83.237	82.713	131.390	25.696	35.80	9.52183	-2.12058
Interface	-	27.55	14.19	14.19	27.55	6.68	6.68	-	-
Epoxy	-	8.0	4.4	4.4	8.0	1.8	1.8	-	-

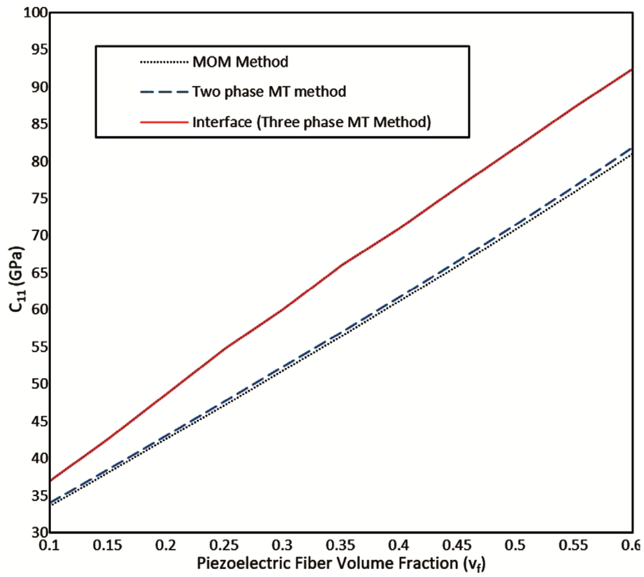

Fig. 7 — Variation of EEP C_{11} of the HSNC with v_f for 3% CNTs.

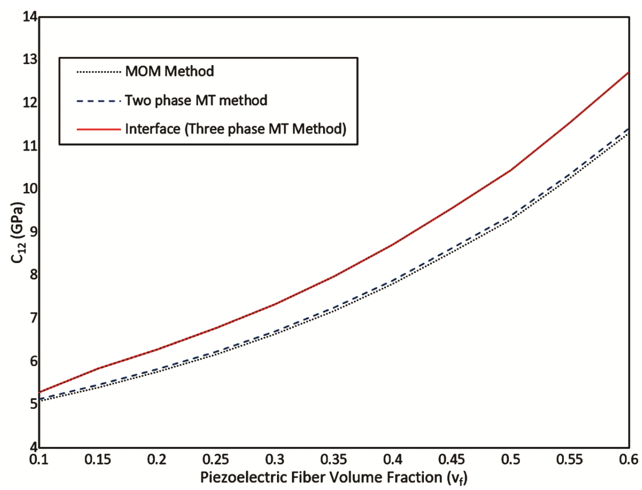

Fig.8 — Variation of EEP C_{12} of the HSNC with v_f for 3% CNTs.

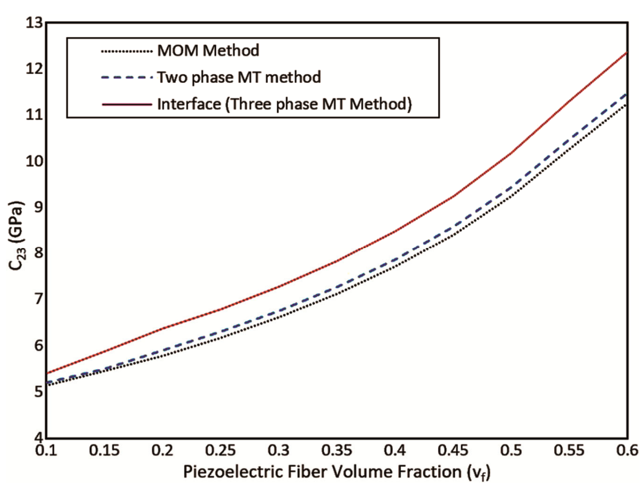

Fig. 9 — Variation of EEP C_{23} of the HSNC with v_f for 3% CNTs.

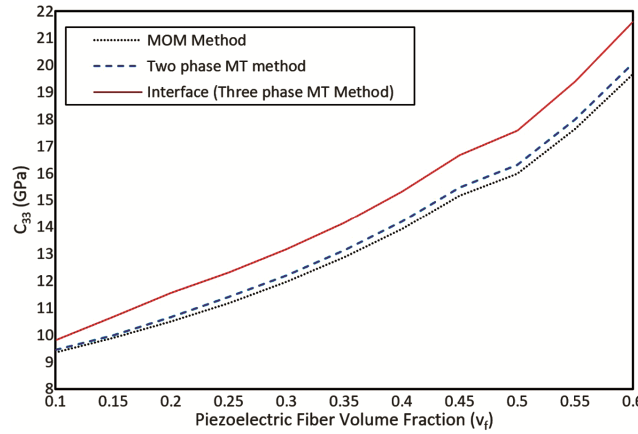

Fig. 10 — Variation of EEP C_{33} of the HSNC with v_f for 3% CNTs.

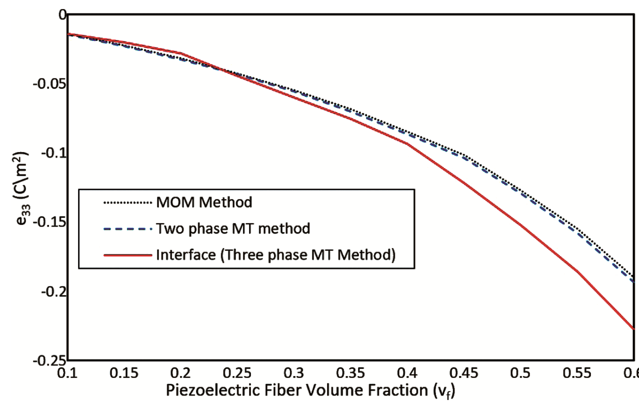

Fig. 11 — Variation of EEP e_{33} of the HSNC with v_f for 3% CNTs.

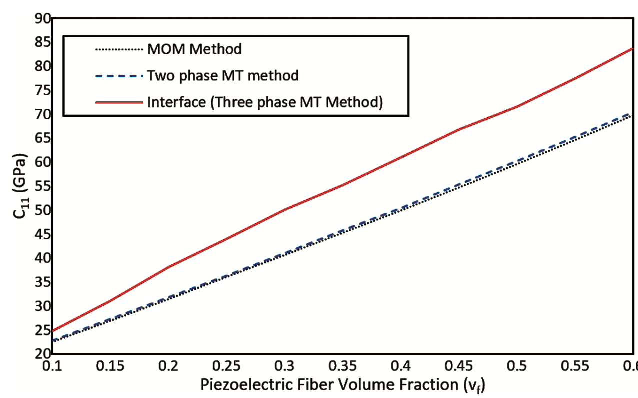

Fig. 12 — Variation of EEP C_{11} of the HSNC with v_f for 1% CNTs.

given in Table 1, and two different volume fractions of CNTs, 3%, and 1%, are taken to compute effect of interface on this hybrid smart nanocomposite. For this, CNT (5, 5) and interface thickness of 0.3126 nm have been used for plotting the results.

The results are plotted using MOM, two-phase and three-phase MT methods as shown from Fig. 7 to Fig. 16. The results of Fig. 7 to Fig. 16 are compared

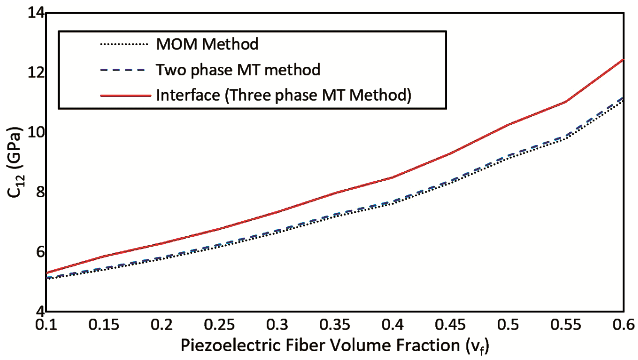

Fig. 13 — Variation of EEP C_{12} of the HSNC with v_f for 1% CNTs.

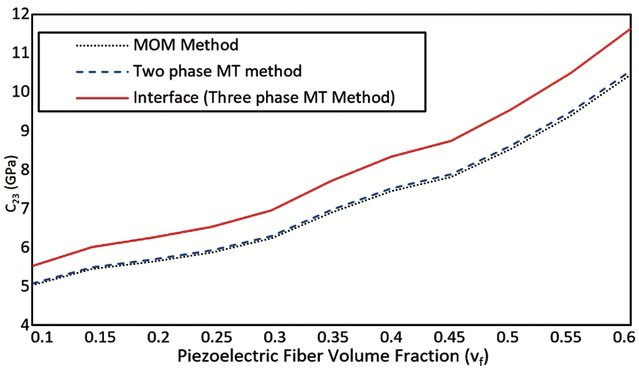

Fig. 14 — Variation of EEP C_{23} of the HSNC with v_f for 1% CNTs.

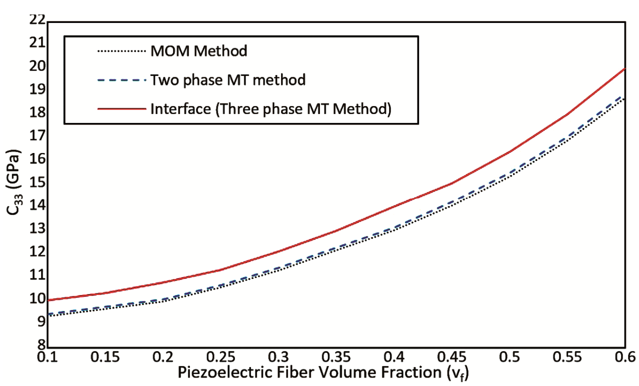

Fig. 15 — Variation of EEP C_{33} of the HSNC with v_f for 1% CNTs.

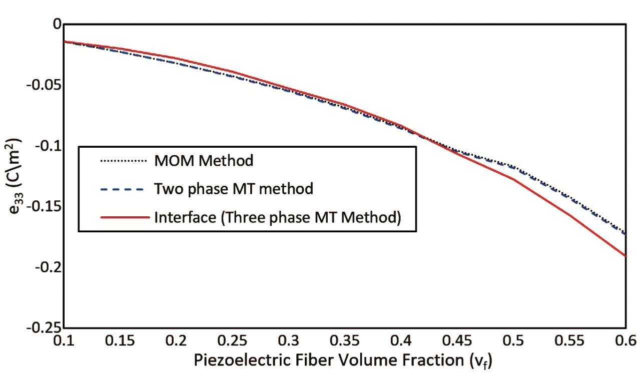

Fig. 16 — Variation of EEP e_{33} of the HSNC with v_f for 1% CNTs.

with the existing results obtained by MOM approach[14] to investigate the effect of interface on HSNC. Fig.7 to Fig. 10 demonstrate the variation of EEP with a 3% volume fraction of CNTs. Figure 7 shows that longitudinal (C_{11}) EEP is considerably increased when interface is used. A rise in longitudinal properties up to 19%, when v_f is 0.60 and significant enhancement at remaining volume fractions of PZT. The reason is that the nanotubes are being aligned with longitudinal direction for purported HSNC. Thus, the longitudinal properties of proposed HSNC are significantly greater than transverse properties. The EEP of HSNC are evaluated by varying volume fractions if CNTs and PZT fibers. It can be seen from the figures that the EEP values of the composite increases with the volume fraction of the reinforcing PZT. The predicted results by MOM method and two phase MTM technique are closer for all volume fractions of $v_{f.}$ It can be seen here that the EEP predictions vary a lot when the PZT volume fraction is high. According to the results obtained for these PZT fiber volume fractions, it is concluded that up to 60% fiber volume fraction, by increasing the fiber volume fraction the maximum strength of the RVE would increase and after that, due to the high fiber clustering and the high-stress concentration areas, the maximum strength of the RVE decreases, hence maximum value of v_f is taken 0.60 i.e. 60% volume fractions of PZT.

Transverse EEP ($C_{12,}$ $C_{23,}$ C_{33}) variations with v_f is shown in Fig. 8 to Fig. 10. This shows an enhancement in transverse properties up to 12% when interface is used at particular value of v_f (i.e. v_f = 0.60). This can be endorsed to the verity that these nanotubes increase the matrix out-of-plane stiffness surrounding piezoelectric fibers. Figure 11 shows variation of PZT constant e_{33} of HSNC along v_f. This can be revealed by the fact that values of effective PZT constant increases with the use of an interface as shown in Fig. 10. The significant enhancement in longitudinal and transverse strengths of HSNC with the use of interface is shown from Fig. 7 to Fig. 16. As durability of finish and retaining the original feel and strength of the fabric are important criteria in nano fillers selection in the textile industrial applications, hence, these HSNC based novel and innovative technologies seem to be closer to achieving these consumer demands. Further, this increased strength will also help in coating of textiles due to higher coat to weight ration of HSNC. Coating is simply the act of covering a material with a layer;

hence, nano coating is either to cover with a layer with thickness on nano meter scale or to cover a surface with a nano scale entity. With the advent of HSNC, a new area can be developed in the realm of textile nano coating, which is really very thin (~50 nm) with significantly optimized or enhanced properties. These nanocomposite fibers show improved mechanical properties as compared with their neat counterparts hence, they have the attractive potential for the continuous expansion of application versatility for industrial textile uses.

Figures 12 to 15 present the variation of EEP with v_f for the 1% volume fraction of nanotubes. The results are obtained for different values of v_f and it is observed that EEP values are increasing with the increase in v_f upto v_f value of 0.60. The properties do not increase beyond the 60% volume fractions of PZT due to bundling of more fibers. It can be seen from these figures that the interface regions of polymer composites and nanocomposites influence the EEP i.e. strength and mechanical properties of these materials to a large degree. It can be noticed that the longitudinal (C_{11}) EEP is significantly increased when interface is used as shown in Fig. 12. There is an observed enhancement in longitudinal properties up to 19% when v_f is 0.60 and significant enhancement at remaining volume fractions of PZT. As the interface is the area of contact between the reinforcement and the matrix materials, and this interface helps to avoid propagation of crack growth through the fibres by providing alternate failure path along the interface between the fibres and the matrix, hence the EEP values increased with the use of interface.

Figs. 13 to 15 shows the variation of transverse EEPs (C_{12}, C_{23}, C_{33}) with v_f. An enhancement in transverse properties up to 12% is observed when an interface is used and v_f is 0.60. This can be ascribed to verity that these CNTs increase the matrix out-of-plane stiffness surrounding the piezoelectric fibres. Figure 15 shows the variation of PZT constant (e_{33}) of HSNC with respect to v_f illustrating that the magnitude of the effective piezoelectric constant increases with the use of an interface. As shown in Figs. 12 to 16 due to enhancement in value of transverse and longitudinal EEP and longitudinal piezoelectric properties, this proposed HSNC can be used for both out-of-plane and in-plane actuation authority as a distributed actuator.

4 Conclusions

In this investigation, the effect of interface on mechanical properties of nanocomposites is discussed.

- For this a new model of HSNC is proposed and results were obtained by using the micromechanics based MOM and Mori Tanaka technique.
- The predicted elastic moduli and piezoelectric constants are validated by mechanics of materials-based predictions for the entire range of piezoelectric fiber volume fractions, showing that accurate predictions can be obtained by using Mori Tanaka technique.
- The current analysis illustrates that the interface affects the effective properties of hybrid smart nanocomposites. The results show a substantial enhancement in elastic and piezoelectric properties when the interface is used.
- The proposed model of hybrid smart nanocomposites demonstrates transverse properties competitive with piezoelectric fibers and can surpass up to 19% in longitudinal and 12% in the transverse directions. This clarifies the importance of the inclusion of imperfect interfaces in the modeling. It can be concluded that interfaces have one of the highest potential amongst the ways to improve the materials properties.
- The proposed multiscale modeling scheme will also facilitate the various multifunctional characteristics and the dynamic response considerations of the interfacial region in the nanocomposites domain.

The experimental investigations of this study may be performed in the future to ensure the accuracy of the present work. Further, the validation of results obtained with the help of numerical finite element analysis and molecular dynamics approach can be done in future scope.

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