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Electro-Mechanical Responses of Dielectric Elastomers

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Electroactive polymers (EAPs) have been widely employed as smart material for actuation and sensing in recent years. Dielectric elastomers (DEs) are a type of smart material which belongs to the class of EAPs. Their applications include soft sensing and actuation which require high sensitivity, flexibility and strechability. They can be actuated under electric field responding to electrostatic force. Compared with other electrical actuation technologies, the advantages of dielectric elastomer actuators include: light weight, good compliancy, high energy density, large actuation strain, quiet operation and low cost. The current research focuses on the electro-mechanical actuating behaviour of DEs embedded with composite using finite element approach. Analyses are carried out with three different support conditions of the composite, on which the elastomer is mounted, and with varying thickness and positions of elastomer on the composite at various voltage levels.

***Keywords*:** Electroactive polymer; dielectric elastomer; electro-mechanical actuation

1. Introduction

Dielectric elastomers are a type of smart material which belongs to the class of electroactive polymers, which are made up of soft materials and are capable of changing their dimensions upon an electric stimulation. When in the generator mode, DEs convert mechanical energy to electrical energy, while they can also convert electrical energy to mechanical energy in actuator mode. DEs are a type of field-activated polymers that belong to the family of EAPs [1]. The typical assembly of a DE includes a dielectric material and two electrodes, wherein the dielectric material is sandwiched between the electrodes. These structures have high electromechanical efficiency and can produce a large strain response i.e., hyperelastic in nature. DEs can be used as generators, sensors and actuators based on the electromechanical effect. DEs have received significant interest in recent years for applications as electromechanical transducers, actuators, sensors and energy harvesters. The interest arises due to its attractive properties such as the ability to achieve large strains by inducing voltage, the fast deformation response, light weight, and cost effectiveness.

DEs can be used in wide range of applications which include structural health monitoring, robotic arms, energy harvesting, power generation, electronic skin and muscles, self-sensing actuators, sensors etc. Some of these applications involve use of composites. This allows an opportunity to the test the elastomers when mounted on composites. The primary objective of this research is to study the electromechanical behaviour of dielectric elastomers.

2. Literature Review

2. 2. On Dielectric Elastomer Actuators

Dielectric elastomer actuators (DEAs) gained popularity in the field of sensing and actuation since R. Pelrine et al. published their work on electrostriction of polymer dielectrics with compliant electrodes in 1999 [2]. DEAs are made of a rubbery soft dielectric elastomer sandwiched between two complaint electrodes. The two complaint electrodes act as a capacitor. The columbic force, generated due to the electric field, generates Maxwell stress between the two plates, compressing the dielectric elastomer layer due to the attraction of both the plates. This induces expansion in the DEA due to the incompressibility of the elastomer. In general, the operating voltage of DEAs is as high as ~1-10 kV [3] which is around 100 MV/m of electric field and considerably high actuation strain over 100% [4] can be reached in the meantime.

2. 3. On Modelling of Elastomers

Design and optimization are the important steps in the modelling and simulation of DE systems. This can be described by mainly two challenges. They are (i) the passive mechanical response of elastomer with history and time dependence and with large strains, (ii) the mechanical response generated by the application of electric field (electromechanical coupling). A vast research have been done on the mechanical characterization of the elastomers [5]–[10] but no researchers focused on the electromechanical coupling behaviour of elastomers. No research exists on simulation of elastomers on composites, although only a few works exists on the modelling and simulation of dielectric elastomers [11]–[15].

3. Materials and Methods

3. 1. Materials

The elastic properties of 3M VHB tapes allow to distribute loads over larger area by accommodating differential expansion and absorbing dynamic loads. Composite made of MWCNT embedded in epoxy is used in this study. Table 1 shows the properties of 3M VHB tapes and the composite material.

Table 1: VHB tape and composite properties [16-18]

Property	Elastomer	Composite	Unit
Young’s Modulus	3.6e6	0.465e9	Pa
Poisson’s ratio	0.4999	0.3	
Relative electrical permittivity	8.8		
Free-space permittivity	8.854e-12		F/m
Density	720	1158	kg/m3

3. 2. Methodology

A dielectric elastomer is placed between two compliant electrodes which is in turn attached to a composite beam represented in figure 1. An applied electric field causes the dielectric elastomer to elongate in length and compress in thickness which is represented in figure 2, due to Maxwell stress. This deformation in the elastomer causes the composite to bend or elongate based on the boundary conditions of the composite beam.

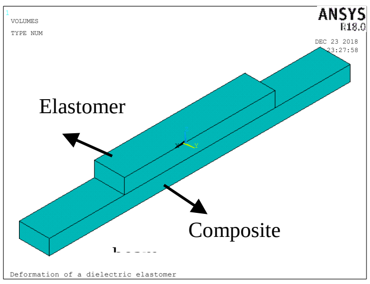


Figure 1: Elastomer on composite beam

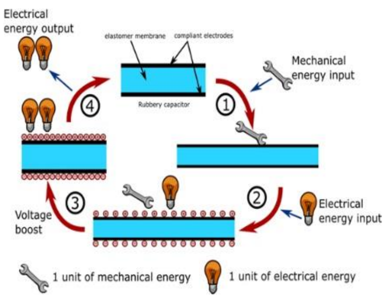


Figure 2: Working of a dielectric elastomer

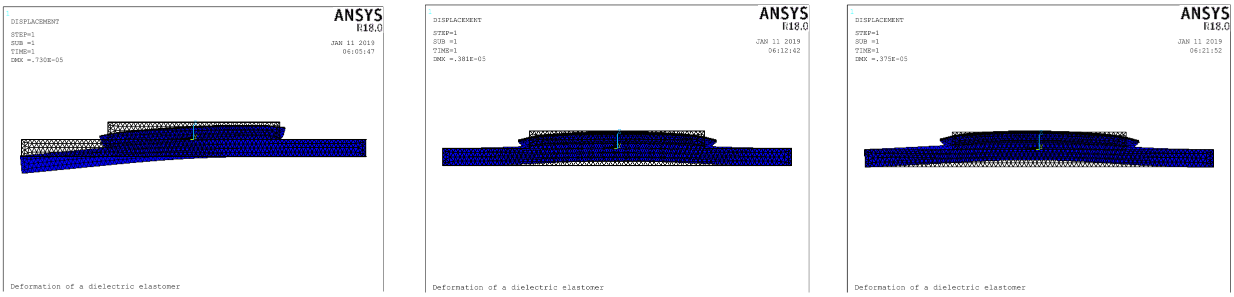
An electroelastic analysis is performed to determine the deformed shape and strain in the thickness direction (ε_z) for a static load. The position of the elastomer is varied namely, two end positions and middle position. The elastomer and the composite beam is meshed accordingly.

Boundary conditions are applied based on the different supports namely, cantilever, both sides fixed and fixed roller beam.

For the cantilever support, one side of the beam end is fixed in all the directions and the other end is kept free. For the both ends fixed support, both the ends are fixed in all the directions. One side of the beam is fixed in all directions, the other end is fixed in y and z directions and allowed to move in x direction in fixed roller support. The nodes are coupled in the top and bottom surfaces of the elastomer separately, in order to model the two complaint electrodes. For both the compliant electrodes to work, the least node on the respective faces are coupled with all the other nodes on the particular face on the elastomer. Voltage is applied on both the least nodes of both the coupled surfaces. As a voltage difference is created between the two faces, the elastomer tends to expand or compress based on the voltage difference created. The voltage is varied from 500V to 5500V.

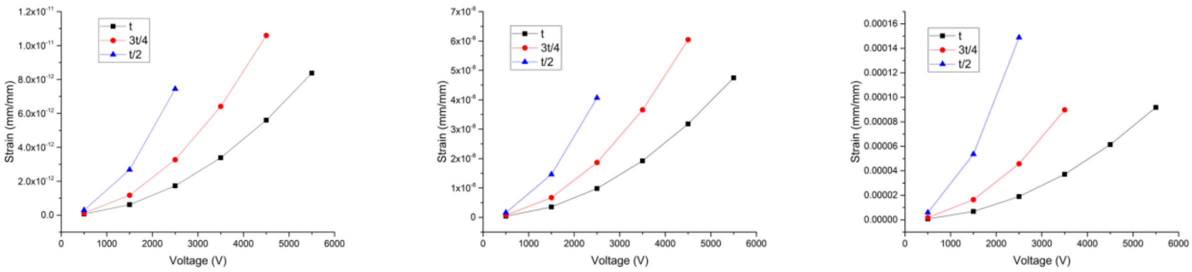
4. Results and Discussion

The deformation of the beam is measured on the free side of the cantilever beam, bottom side (i.e., side opposite to the side of the attached elastomer) of the beam with both sides fixed and on both the roller and bottom side for fixed roller beam support. Figure 3 depicts the deformation of the composite beam in cantilever support, both ends fixed support and fixed roller support when voltage is applied on the elastomer (middle position) with thickness ‘t’.



(a) (b) (c)

Figure 3: (a) Cantilever support, (b) both ends fixed support and (c) fixed roller support

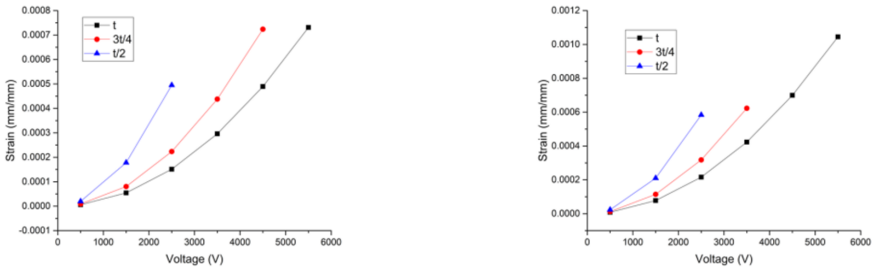


(a) (b) (c)

Figure 4: Strain in cantilever beam when elastomer position is at (a) fixed end, (b) middle and (c) free end

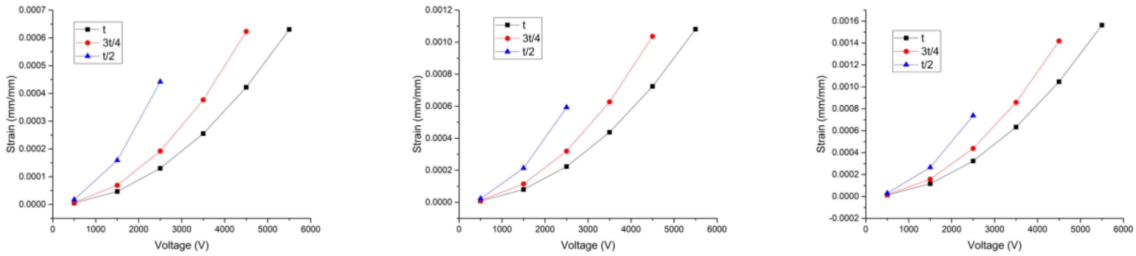
Figure 4 shows the strain in the cantilever beam for various voltages when the elastomer position is at fixed end, middle and free end. From figure 4 it is evident that as voltages increases, strain in the composite beam also increases. It is inferred that with reduction in the thickness of the elastomer, a higher strain can be obtained in the composite beam for a particular voltage level. This is due to the fact that the same amount of electromotive force acts on the elastomer even if the thickness varies. So, a greater deformation is obtained for a low thickness elastomer than a higher thickness elastomer for the same voltage level. It can also be seen that, elastomers with higher thickness can withstand higher voltage levels.

Figure 5 and 6 shows the strain for various positions of elastomer at different voltage levels for both ends fixed beam and fixed roller beam respectively. The strains in both the cases follow the same trend as in the case of cantilever beam.



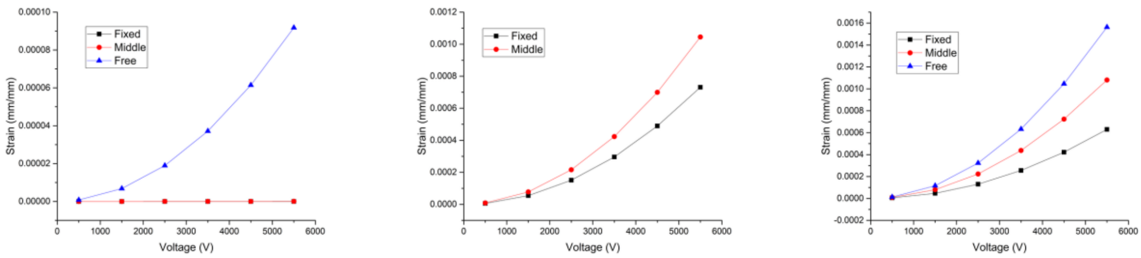
(a) (b)

Figure 5: Strain in both ends fixed beam when elastomer position is at (a) fixed end and (b) middle



(a) (b) (c)

Figure 6: Strain in fixed roller beam when elastomer position is at (a) fixed end, (b) middle and (c) roller end



(a) (b) (c)

Figure 7: Strain for various voltages in composite for different positions of elastomer and at thickness ‘t’ for (a) cantilever, (b) both ends fixed and (c) fixed roller support

Figure 7(a) shows the strain in composite beam in cantilever support for elastomer thickness ‘t’ at different positions. From the graph, it can be inferred that strains are very high when elastomer is placed at free end as compared to that of the other two cases. We know that maximum displacement occurs at free end in a cantilever beam and as the elastomer position moves from free end to fixed end, the point of application of forces moves from free end to fixed end, which in turn increases the displacement in the cantilever beam at the free end. Figure 7(b) shows the strain in composite beam in both ends fixed support for elastomer thickness ‘t’ at different positions. From the graph, it is evident that strain is more in the case of elastomer at middle position. In general, when both the ends are fixed, maximum deformation occurs at the middle. And if the elastomer is placed in the middle position, more force is acting at that position, which in turn produces more deformation. The variation in deformation for various positions is less as compared to that of the other supports. Figure 7(c) shows the strain in composite beam in fixed roller support for elastomer thickness ‘t’ at different positions. This case similar boundary conditions as that of the both ends fixed support, but only horizontal movement is allowed at the roller end. Similar trends in strains are observed as cantilever support. Similar trends are observed for other elastomer thickness ($\frac{3t}{4}$, $\frac{t}{2}$) for their respective beam supports.

5. Conclusion

The present research on the elastomers led to the following conclusions:

- Modelling and electro-elastic analysis of dielectric elastomer on composite through finite element approach has been done for various composite beam supports and different elastomer positions and thickness.
- It is observed that, elastomers with low thickness tend to produce more deformation at lower voltages than elastomers with higher thickness, but they fail at higher voltages. For higher thickness elastomers, they have low deformations at lower voltages but the deformations increase exponentially with increasing voltage. They sustain higher voltages than low thickness elastomers and fail way above them.

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