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A Theoretical Study on Bending Behaviour of Conducting Polymer Actuator

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Abstract. Conducting polymer actuators are of vital importance to the future of many engineering developments in a range of different fields especially micro applications. To allow for the use of conducting polymer actuators in practical applications a reliable and accurate model to predict the applied voltage, output force and bending motion relationship must be established. In current research, we are aiming to contribute to the fundamental understanding of the mechanical behaviour of such conducting polymer actuators under a range of different conditions and material properties. To achieve this goal it is vital to formulate a model that accurately represents the relationship between the applied voltage, output force and the resulting bending displacement of the conducting polymer actuator. Two different theoretical models have been developed and compared; one consisting of an analytical solution and the other involving a range of different finite element models solved using a commercial finite element analysis package–Abaqus. A new modelling method involving the meshing of a multilayered rectangular cross section that can be used for the analysis of a beam-like model is presented with satisfactory results. This numerical method allows for the complex structure of the conducting polymer actuator to be analysed using three dimensional beam elements available in Abaqus/Standard and allowing for the principles of classic beam theory to be implemented.

Introduction

Conducting polymer actuators allow for the creation and improvement of many exciting possibilities in a wide range of different fields from micro/nano robotic applications to developments in fuel storage cells. The attention on conducting polymer actuators have gained is largely as a result of their unique properties of electro activity, conductivity, physical size and other chemical properties. It is the ability of conducting polymer actuators to respond to a small voltage with a relatively large bending motion that is responsible for the excitement surrounding their use and development. Over last decade a significant amount of research has focused on optimising the structure of conducting polymer actuators to allow for the largest bending motion possible as well as the highest force output relative to the applied voltage. Current research has also focused on reducing the physical size of conducting polymer actuators to improve their voltage displacement relationship.

In this study, we firstly focus on the finite element modeling of compounding casting of Al and Mg with the employment of the birth and death element technique and then apply the devised finite element models to investigate the temperature and stress fields to further analyse the distribution of residual stresses especially along the interface of two metals. Lastly we perform a parametric study by varying the thickness of Mg and the temperature of Al substrate to find out the effective ways to reduce the residual stresses at most in such a compound casting.

Analytical analysis of electro-mechanical behaviours of a conducting polymer actuator

Due to the complexity of electro-chemical-mechanical behaviour of a conducting polymer actuator which usually is treated as a multiple-layer structure, i.e., three or five layers through thickness and the main parameters can only be determined via experimental results. Therefore, to simply the analysis, we start with an analytical analysis focusing on bending behavious of a typical conducting polymer actuator in terms of the applied voltage with an assumption of a force-voltage relationship determined in experiment already. Based on these, the conducting polymer actuator can be modelled as a cantilever beam and therefore a structure with a certain length as the predominant feature when compared to its cross section dimensions. Its bending behaviours can be then described using two beam theories: a) the Euler Bernoulli model and b) the Timoshenko model.

In the Euler Bernoulli model, the relationship between the bending moment in the beam and the radius of curvature along its length is given as, in the beam and the radius of curvature along its length is given as

$$1/\rho = M/EI \tag{1}$$

where, ρ denotes the radius of curvature at a specific point, M stands for the bending moment in the beam, E is the materials modulus of elasticity and I is the beam's area moment of inertia about the neutral axis. We can determine the maximum displacement y_{max} of the actuator for a given force are

$$y_{\max} = -\frac{FL^3}{3EI} \tag{2}$$

The Timoshenko model accounts for shear deformation within the actuator. Similarly, we can also get the explicit expression of the maximum displacement y_{max} of the actuator as

$$y_{max} = -\frac{FL}{\kappa GA} - \frac{FL^3}{3EI} \tag{3}$$

where, κ represents the shear correction factor with respect to Poisson's ratio ν as $\kappa = (5+5\nu)/(6+5\nu)$ and G is the shear modulus and given as $G = E/[2(1+\nu)]$ for a linear, isotropic and homogeneous material.

The above-mentioned Euler Bernoulli and Timoshenko models both represent the force-displacement relationship of the conducting polymer actuator. To correctly model the bending behaviour of the actuators, a parameter for the applied voltage, V, needs to be included into the given equations. The electro-mechanical behaviour of conducting polymer actuators can be described using a linear relationship with a certain scope which can be determined through experimental results and it can be expressed as

$$F = \alpha V \tag{4}$$

where α equals a constant related to the material properties of the actuator, which is assumed constant for applied voltages and hence once determined for a given actuator can be used to calculate the actuator's performance under a range of applied voltages.

Substituting Eq. (4) to Eqs. (2) and (3), we can have

$$y_{\max} = -\frac{\alpha VL^3}{3EI} \tag{5}$$

$$y_{max} = -\frac{\alpha VL}{\kappa GA} - \frac{\alpha VL^3}{3EI} = -\alpha VL\left(\frac{1}{\kappa GA} + \frac{L^2}{3EI}\right) \tag{6}$$

Eqs. (5) and (6) describe the electro-mechanical behaviour of the conducting polymer actuator.

Finite element modelling of a conducting polymer actuator

There are in total four types of finite element models developed in present study: a) three-dimensional solid model; b) two-dimensional equivalent single-material beam model; c) two-dimensional equivalent cross-section beam model; and d) two-dimensional meshed cross-section beam model. For all these four models we developed the five-layer model and three-layer model and the difference between the five-layer model and three-layer model is the latter excludes the two thin conductive gold or platinum layers.

In the 3-D solid model, considering the three or five layers through thickness of the actuator, the beam is partitioned into three or five sections (layers) and each section is defined using appropriate material properties, i.e., Young's modulus and Poisson's ratio, etc. These models are both meshed using an eight-node linear brick element – C3D8R available in Abaqus/Standard and the size of the elements of 0.1×0.1×0.1 mm was chosen based on a convergence check. As for the 2-D equivalent single-material beam model, the actuator is treated as a single-material beam with an equivalent Young's Modulus defined by $E = \left(EI_{PPy} + EI_{PVDF} + EI_{Conductive\ Material}\right) / I$ and we used a two-node linear beam element – B31 with a rectangular cross section to discritise the model. For the two-dimensional equivalent cross-section beam model, we used the I beam to simulate the actuator and determined the width of the beam considering the equivalent stiffness of the beam and in these models the B31 beam element was still used but with an I-shaped cross section. In the two-dimensional meshed cross-section beam model, the function of meshed beam cross section offered by Abaqus/Standard allows us to model the complex cross section of the beam either made of several materials or complex geometry whilst still utilising the features of beam elements. However this function is not directly available in Abaqus/CAE but can be implemented via editing the input file properly with additional information. For the meshed cross section, the element types used were B31 and WARP2D4, and the latter is a special-purpose two dimensional four-node quadrilateral element, which only has one degree of freedom per node representing the value of the out of plane warping function. For all the 2-D beam models, the size of the elements of 0.1 mm was used based on a convergence check.

Results and Discussion

To validate and verify the accuracy and reliability of both the proposed analytical and numerical models on modelling of the voltage-force-displacement relationship of conducting polymer actuators, we picked up two different actuators studied in literature: a) Actuator 1 has a five layer structure consisting of two PPy layers, a PVDF layer and two platinum layers for enhanced conduction capabilities; and b) Actuator 2 also has a five layer structure consisting of two PPy layers, a PVDF layer but two gold layers for enhanced conduction capabilities.

Table 1 Material property and geometric configuration of Actuators 1 and 2

Actuator 1					
Length	10 mm	E_{PPY}	80 MPa	H_{PPY}	0.025 mm
Width	2 mm	E_{PVDF}	440 MPa	H_{PVDF}	0.11 mm
Height	0.16 mm	$E_{PLATINUM}$	171 GPa	H_{GOLD}	0.000005 mm
Actuator 2					
Length	10 mm	E_{PPY}	90.71 MPa	H_{PPY}	0.025 mm
Width	2 mm	E_{PVDF}	66.75 MPa	H_{PVDF}	0.11 mm
Height	0.16 mm	E_{GOLD}	79G Pa	H_{GOLD}	0.000005 mm

Both two actuators are 10 mm long by 2 mm wide and 0.16 mm high with the constantly uniform cross section and their main parameters are listed in Table 1. Reported in literature, the values of α were chosen as 0.0006 and 0.001453 for actuators 1 and 2, respectively.

The results of the Euler Bernoulli and Timoshenko models for maximum displacement for a range of applied voltages for Actuators 1 and 2 are given in Table 2. The analytical results of the voltage displacement relationship of the conducting polymer actuator have good agreement with those experimental data. For Actuator 1, the maximum error of 9.13% relates to a variation in the maximum displacement of the conducting polymer actuator between the experimental data and the analytical analysis of 0.411 mm. The maximum error for Actuator 2 is found 16.86% which corresponds to 1.01 mm. The Euler Bernoulli and Timoshenko models produces very close results.

Table 2 Analytical analyses of Actuators 1 and 2

Voltage (V)	Experimental Data (mm)	Euler Bernoulli Model (mm)	Percentage Error	Timoshenko Model (mm)	Percentage Error
Actuator 1					
0.25	4.5	4.0893523	9.13%	4.0891521	9.13%
0.50	8.25	8.1787047	0.86%	8.1783043	0.87%
0.75	12.25	12.268057	-0.15%	12.26746	-0.14%
1.00	15.5	16.357409	-5.53%	16.356609	-5.53%
Actuator 2					
0.10	0.875	0.855507845	2.23%	0.855743322	2.25%
0.20	1.5	1.711015691	-14.07%	1.711486645	-12.36%
0.30	2.5	2.566523536	-2.66%	2.567229967	-2.62%
0.40	3.15	3.422031382	-8.64%	3.42297329	-7.98%
0.50	4.5	4.277539227	4.94%	4.278716612	5.17%
0.60	5.5	5.133047073	6.67%	5.134459934	7.12%
0.70	7	5.988554918	14.45%	5.990203257	16.86%
0.80	7.75	6.844062764	11.69%	6.845946579	13.21%

The results of Actuator 1 extracted from the models using 3D beam elements in finite element analyses are compared with the experimental data in Figure 1. It is clear to see that the equivalent beam model produces extremely close results to those obtained during experimental testing. The other two models underestimate the maximum displacement of the conducting polymer actuator and the results of the five layer meshed model are having largest discrepancies compared to others. From a direct comparison between the three layered meshed beam cross section and the five layered meshed beam cross section it is once again evident that the additional platinum layers cannot be ignored in calculations. The relatively large Young's modulus of platinum significantly increases the stiffness of the conducting polymer actuator and hence reduces its maximum bending motion. Different from the results of Actuator 1, the numerical results for Actuator 2 are all much close to those from experiment reported in literature although the 5-layer model is still having the maximum discrepancies. Overall the results generated using both the analytical solutions and finite element analyses can capture the electro-mechanical behaviour of the conducting polymer actuator within a reasonable level of error.

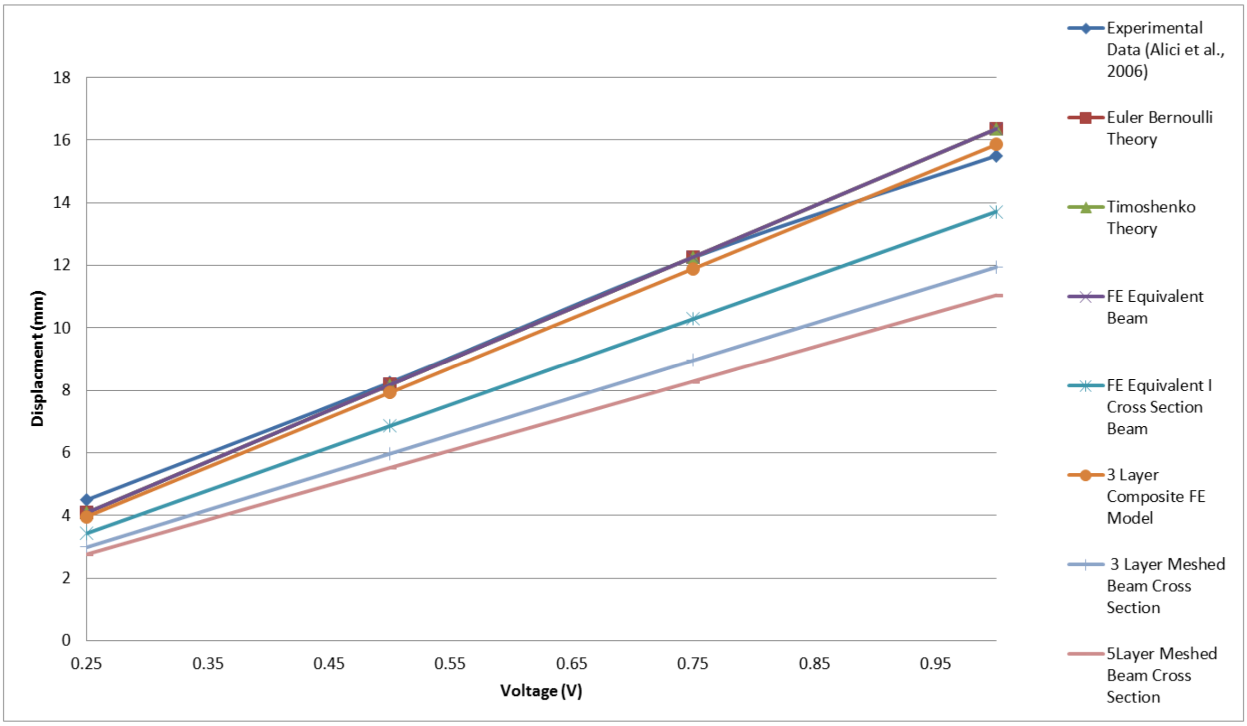

Figure 1 Comparison on Voltage-displacement relationship of Actuator 1

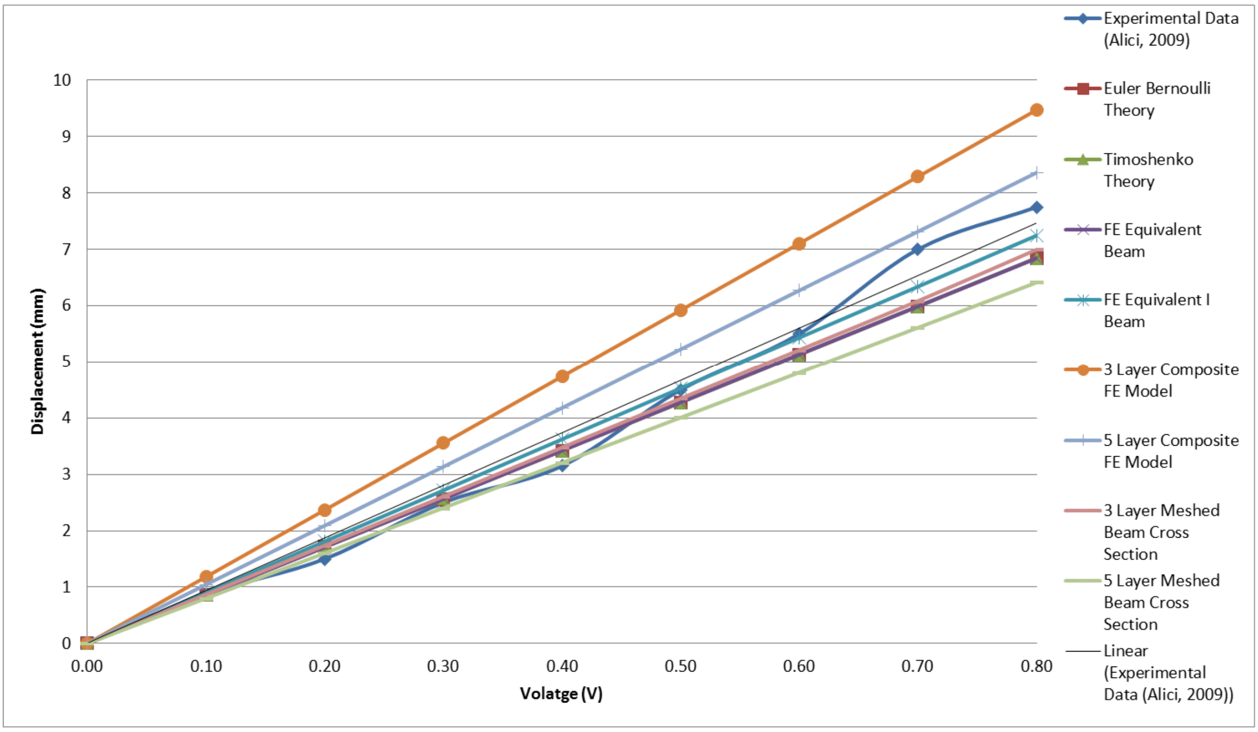

Figure 2 Comparison on Voltage-displacement relationships of Actuator 2

Summary

In this study, we have analytically and numerically investigated the relationship of the electro-chemical-mechanical properties of conducting polymer actuators via developing analytic models and finite element models. These models, both analytical and numerical, are able to predict the electro-mechanical bending displacement of the actuators for a range of applied voltages. Once the force-voltage relationship of the conducting polymer actuator is determined, the analytic and numerical models then can be used for optimal design purpose. The excitement surrounding the development of conducting polymer actuators is due to their wide range of potential applications in engineering areas, including batteries, photovoltaic devices, light emitting displays, printing sensors, fuel cells, medical and robotics, and so on. The benefits of conducting polymer actuators over other types of actuators include their low voltage input, and reasonable mechanical outputs.

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