CHARACTERIZATION OF THE ROLE OF ADHESIVE BONDING ON PIEZOELECTRIC ACTUATION OF BEAMS

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Abstract

Piezoelectric actuators are one of the smart/intelligent materials which can be used as "Induced Strain Actuators" for structural members like beams, plates and shells. These piezoelectric actuators (PZT) can be bonded or embedded in the structure. The adhesive bonding between the piezoceramics and the substrate could significantly affect the strain transfer from the actuator to the substrate. The present work is an effort in experimental characterization of piezoelectric actuation of beams. A cantilever beam with surface bonded piezoelectric actuators is considered. In order to observe the effect of adhesive properties, three different adhesives viz. cyano-acrylate, epoxy resin and a structural film adhesive are used. Experiments are performed on these specimens with piezo patches in series as well as in parallel configurations, over complete cycles of the applied field. The experimental findings are compared with an existing two-dimensional Finite Element model. It is observed that cyano-acrylate bonding is the closest to the perfect bonding case. It is also observed that piezoelectric actuation exhibits significant hysterisis.

Introduction and Literature Review

A smart structure involves distributed actuators and sensors and one or more microprocessors that analyze the response from the sensors and use distributed-parameter control to command the actuators to apply localized strains in order to minimize system response. A smart structure has the capability to respond to a changing external environment (such as loads and shape changes) as well as to a changing internal environment (such as damage or failure). It incorporates smart actuators that allow the alteration of system characteristics (such as stiffness or damping) and thus system response in a controlled manner. Among the various candidate actuator / sensor materials, piezoelectric materials have distinct advantages (e.g. Crawley [1994], Rao and Sunar [1994], Tani et.al. [1998]).

Bailey and Hubbard [1985] studied the response of a cantilever beam with a layer of PVDF bonded to one complete side of the beam. Three control algorithms were implemented and simultaneous control of the first three modes of the beam was experimentally demonstrated. Burke and Hubbard [1987] reported results of experiments on a simply supported beam with a PVDF film actuator bonded to one face of the beam and a controller based on Lyapunov direct method. They observed that the effective loading of the actuator on the beam can be represented as two opposing point moments at the ends of the actuator.

Crawley and de Luis [1987] followed by Crawley and Anderson [1990] developed analytical models of the strain transfer mechanism of a piezoelectric sensor/actuator bonded to or embedded in a beam. They considered a finite thickness bonding layer and in the limit, the perfectly bonded case. Modeling the adhesive as a linear elastic, isotropic material, they assumed that the adhesive would be in pure shear. The piezoactuator itself could be under uniform strain or linearly varying strain. They proceeded to develop a one-dimensional analytical model and obtained certain crucial closed form expressions for the strain induced in the beam. They found that the uniform strain model accurately predicted extension actuation case but not bending actuation. The Euler-Bernoulli model predicted both extension and bending accurately. These studies considered simple beams with a pair of actuators bonded on top and the bottom. Considering the application of a helicopter rotor blade control, Park et.al. [1993] extended these models for a beam with extension, bending and torsion coupling. They studied the case of a single piezoelectric actuator bonded at an angular offset to the
beam axis. Their model accounted for the case when the actuator might not cover the full width of the beam.

All these studies considered single layer of piezoelectric actuator bonded to a beam. Richard and Cudney [1993], adopting a strain energy based approach, extended these models to consider the dynamics of multi-layer piezoelectric actuator elements bonded on beams. Timoshenko theory was used to include the effects of shear deformation and rotary inertia. The natural frequency and frequency response estimates from the analytical model were experimentally verified on an aluminum beam with PZT G 1195 actuator elements. The actuators were bonded onto the beam using cyanoacrylate adhesive. It was observed that the multiple layer actuator could induce more response in the beam than a single layer configuration by a maximum of about 5 dB.

Normally piezoelectric actuators are assumed to be directly bonded to or embedded in the substrate structure. Alternative configurations have also been proposed and studied. Chaudhry and Rogers [1993] proposed a configuration wherein the actuator is bonded to the structure only at discrete points using spacers. Because of the offset of the actuator, the effective bending moment applied on the beam under an applied electric field increases. They observed that a 20-30% increase in the beam bending displacement, compared to the case of completely bonded actuator, was feasible. They conducted experiments on a relatively thick aluminum beam. Commercially available 0.25mm thick PZT G-1195 actuators were used.

Varadan et. al. [1993] conducted experiments on cantilever beams and frames. Using a simple linear velocity feedback control (i.e., actuator excitation voltage proportional to beam velocity), their results showed that the damping factors with control were a few orders of magnitude more than those without control. Yang and Lee [1994] conducted analytical and experimental studies on the vibration characteristics of a cantilever beam with a surface bonded piezoelectric actuator. Using Timoshenko beam theory, they modeled the beam as a stepped beam taking into account the piezoelectric actuators and the bonding layer. Experiments were conducted on a stainless steel beam with PZT G 1195 actuators bonded on to it using an epoxy adhesive. A non-contact electro-optical displacement pickup was used to measure the tip displacement. Their analytical predictions indicated that the first natural frequency could vary by about 5% compared to the uniform beam.

Seshu and Naganathan [1996] presented results of a two dimensional finite element analysis of strain transfer in an induced strain actuator such as a piezoelectric patch bonded on to a beam, with a finite thickness adhesive layer. Gandhe et al. [1999] extended this model to include viscoelastic behavior of the adhesive layer. In the present research work, detailed experimental studies have been carried out on three different beam specimens with three different adhesive bonding materials. Both static and dynamic deflection responses are studied. Experimental results are compared with the finite element predictions.

Two Dimensional Finite Element Model

In the present study, experiments have been conducted on a cantilever beam with piezoelectric patch actuators bonded on its top and bottom surfaces. A 9 nodded two-dimensional Lagrangian element as shown in Fig.1 is used (Seshu and Naganathan [1996]) for modeling this specimen structure. A typical finite element mesh of the beam, adhesive and piezoactuators is shown in Fig.2. Each node has two degrees of freedom viz. u and w.

Fig.1 Nine nodded 2-D element

Fig.2 FE Discretization of cantilever beam with bonded piezoelectric actuators
These degrees of freedom $u$ and $w$ are interpolated using the standard shape functions $N_i$ [Cook et al. 1989]. The piezoelectric actuation is modeled as an initial strain, i.e., all the finite elements corresponding to the piezoelectric actuators are assumed to experience an initial strain

$$\varepsilon_{pf} = d_{31} \frac{V}{t_p}$$

where $d_{31}$ is the piezoelectric coefficient, $V$ is the applied voltage and $t_p$ is the thickness of the piezo patch. Full details of the finite element formulation are available in (Seshu and Naganathan [1996]).

**Experimental Investigations**

**Experimental Set up**

The experimental set-up is shown in Fig.3. The beam is electrically isolated from the piezoelectric actuators by the non-conductive adhesive layer. The specimen is further electrically sequestered from the clamping vice with the help of thin acrylic sheets. A series resistance provided in the circuit protects the piezoelectric actuators from sudden charging or discharging. Electric field is applied to the piezoelectric actuators using a high voltage (200 volts), high frequency (300 kHz), and low current (200mA) piezo amplifier. It can also supply a high (200 volts) D.C. voltage if no input signal is supplied to the amplifier. Displacement of the beam is measured using a non-contact type magnetic exciter was used to determine the fundamental natural frequency of the cantilever beam specimen. Using standard formulae for cantilever beam fundamental frequency, the ratio of Young’s modulus to density was then estimated. For the beam specimen used in the experiments,

$$\sqrt{\frac{E}{\rho}} = 4642.6 \text{ m/s.}$$

This was used in all the finite element computations. The PZT actuators used (PSI-5A-S4-ENH) (Piezo Systems Inc, USA, www.piezo.com) were of the dimensions 72.40 x 23.8 x 0.267 mm. The properties of the adhesives used for bonding the piezo actuators onto the beam specimens are given in Table-1 [Young et al. 1996].

**Calibration and Setting of Non-contact Fiber Optic (FO) Displacement Sensor**

The FO displacement sensor (Philtec Inc, USA, www.philtec.com) is reflectance dependent, i.e. the intensity of the light received at the sensor tip (or the output voltage) depends on the distance between the sensor tip and the target surface as well as on the reflectivity of the target surface. Also the perpendicularity of the target surface with respect to the FO displacement sensor tip plays an important role in the output voltage of the sensor. When a target surface is in contact with the sensor tip, the light rays are blocked and thus the output from the sensor will be close to zero. As the target surface moves away from the sensor tip, light rays from each individual transmitting fiber begin to illuminate adjacent receiving fibers. The output voltage of the sensor increases with increasing

<table>
<thead>
<tr>
<th>Type of Adhesive</th>
<th>Cyano-Acrylate (FEVIKWIK)</th>
<th>Epoxy-Resin (Commercial Araldite)</th>
<th>Structural Film Adhesive (REDUX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity (N/mm²)</td>
<td>$0.0178 \times 10^{15}$</td>
<td>$0.026 - 0.032 \times 10^{15}$</td>
<td>$0.039 \times 10^{15}$</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
<td>0.35</td>
<td>0.407</td>
</tr>
<tr>
<td>Density (Kg/m³)</td>
<td>1050</td>
<td>1190</td>
<td>985</td>
</tr>
</tbody>
</table>
gap as more and more receiving fibers become illuminated with light from more and more of the transmitting fibers till an "optical peak" is reached. As the target surface moves further away from the sensor tip, past the optical peak, the sensor output voltage decreases with the increasing tip-to-target gaps. This is due to the fact that an increasing portion of light rays incident on the target surface will be reflected beyond the sensor tip area and the intensity of reflected light decreases with the increasing distance. Thus it is necessary to properly position the sensor so that the entire range of motion of the target surface is accurately captured. This becomes even more critical in the present case because the beam tip has a finite slope after deflection, which could adversely affect the reflection of light into the sensor. In order to ensure the reliability of beam deflection measurement using the FO probe, three types of experiments (static, repeatability and dynamic) have been conducted as described below.

**Applying Known Deflection to the Beam**

A known deflection is applied to the beam and the same is measured using FO displacement sensor. The experimental set up is shown in Fig.4. Fig.5 shows the comparison of applied and measured deflections. The fifth degree polynomial curve fit as provided by the manufacturer has been used in generating these plots. It is observed that the response from FO displacement sensor is close to the actually applied deflection in the far-side linear region of the FO displacement sensor i.e. between the output voltages range 4.6 - 4.95 volts. Based on this experiment, the initial standoff distance has been appropriately adjusted during the actual experiments with piezo actuation.

**Repeatability of Measurement**

A DC voltage was applied in steps to the piezoelectric actuators and the output from the FO displacement sensor was noted for each voltage. The same experiment was repeated several times and the results were plotted in Figs.6 and 7. If the applied field is in the direction of the polarization of the piezo actuator on the top surface of the beam, it is considered positive. It is observed that the maximum spread over the mean observed value at 70% of the depolarization field is ±5.8 % and ±5.1 % respectively for the positive and negative applied fields.

**Dynamic Response of the FO Displacement Sensor**

The cantilever beam is actuated at a known frequency with the aid of the piezoelectric actuators. The output
deflection at the tip of the cantilever is sensed by the FO displacement sensor as well as using a light weight accelerometer. The displacement outputs from both the sensors are seen to match well as shown in Fig.8.

**Results and Discussion on Static Actuation**

Several sets of experiments have been conducted on the beam specimens, with different types of adhesives used for bonding the piezoelectric actuators. The maximum applied voltage across each of the piezoactuators is limited to 70% of the depolarization limit and all the comparisons are made with respect to the present Finite Element predictions. These experiments can be broadly grouped under the following heads.

- Piezoelectric actuators arranged electrically in series combination (where the applied voltage is divided across the piezoactuators) or in parallel combination (where applied voltage is same across either of the piezoactuators).

- Actuation voltage independently applied in the direction of polarization of top actuator (i.e. positive direction) and then in the direction opposite to polarization (i.e. in negative direction). This change in the direction of application of actuation voltage changes the direction of tip deflection of the cantilever beam specimen.

- Actuation voltage applied quasi-statically over a continuous cycle (i.e. zero to positive max. to zero to negative max.) to observe the hysteresis behavior of the system.

**Series and Parallel Combinations of PZT with Positive Applied Field**

Typical results are shown in Figs.9 and 10. For parallel (series) combination of PZT actuators and positive applied field, the variation in the observed deflection and F.E finite thickness bonding prediction is 9.14% (10.20%). Theoretically it is expected that series combination will require twice the voltage compared to the parallel combination, yet in the experiments this ratio was observed to be 1.91 instead of 2.

**Series and Parallel Combinations of PZT with Negative Applied Field**

Typical results are plotted in Figs.11 and 12. For parallel (series) combination of PZT actuators and negative applied field, the variation in observed value and the FE finite thickness bonding prediction is 3.14% (3.34%). Compared to positive applied field case, the experimentally observed response in negative applied field is thus much closer to FE predictions. Theoretically it is expected that series combination will require twice the voltage compared to the parallel combination, yet in the experiments this ratio was observed to be 2.14 instead of 2.

![Fig.8 Comparison of dynamic response of FO displacement sensor and accelerometer](image1)

![Fig.9 Response of beam with cyano-acrylate bonding, actuators in series combination and positive applied field](image2)

![Fig.10 Response of beam with cyano-acrylate bonding, actuators in series combination and positive applied field](image3)
Positive Applied Field to Different Beam Specimens

For beam specimens with piezoelectric actuators bonded using epoxy-resin and structural film adhesives, deviation between the experimentally observed deflections and FE finite thickness bonding predictions are 20.05% and 13.38% respectively as can be observed from Fig.13 and 14. The deviation in the response (13 to 20%) is much more as compared to that in cyano-acrylate adhesive bonding (3 to 10%). The inaccuracies in the assumed adhesive material property could have contributed to this large variation.

Negative Applied Field to Different Beam Specimens

For beam specimens with piezoelectric actuators bonded using epoxy-resin and structural film adhesives, the deviation between the experimentally observed deflections and FE finite thickness bonding predictions are 10.53% and 7.25% respectively as can be observed in Figs.
15 and 16. Compared to the positive field case, the response in negative field is closer to FE prediction. However the deviation in response (7.00 to 10.00%) is still more than that of cyano-acrylate adhesive bonding (3% with negative field).

Actuation Field Applied in a Continuous Cycle on Positive and Negative Sides

The percentage ratio of deflection at zero volts to the maximum achievable deflection in a cycle is found to be 2.86 % for the beam specimen with cyano-acrylate bonding (Fig.17). For the beam specimens with structural film and epoxy resin adhesive bonding (Fig.18 and 19) these ratios of deflections at zero volt to the maximum achieved deflection in the cycle are 3.57 % and 7.14 % respectively.

Comparison of Responses of all the Beam Specimens

Typical results are shown in Figs.20 and 21. The specimen with cyano-acrylate adhesive for bonding PZT has the maximum cantilever tip deflection and hence maximum strain transfer from the piezo to the beam. The epoxy-resin adhesive shows minimum strain transfer from PZT to beam surface.

Effect of Added Mass and Stiffness on Natural Frequencies

Dynamic deflection of the tip of the cantilever beam has been measured using the FO displacement sensor with its initial standoff set in the linear range of operation on the far side of the response peak. Bonding of PZT on beam surface changes the local stiffness and mass of the beam specimen, in effect changing the resonance frequencies of the configuration. Table-2 lists the fundamental resonance frequency of various specimens with different adhesives used for bonding the PZT. It is observed that the finite element and experimental results are in close match and depending on the type of adhesive, a shift in frequency of about 7-13% is observed. Yang and Lee [1994] observed that for a beam with bonded piezoelectric actuators, first resonance varies by about 5% over that of uniform beam (i.e. only beam without PZT bonded on it).
In the present experimental studies on cantilever beam specimens with bonded piezoelectric actuators, the tip deflection was the parameter used to characterize the strain transfer from the piezoelectric actuators to the substrate. Three different types of adhesives viz. cyano-acrylate, epoxy-resin and structural film adhesive were used to study the effect of adhesive bonding material. Experimental results were compared with those of a two dimensional finite element analysis.

Experimental results for static actuation and the finite element predictions match very well when the finite thickness adhesive layer is included in the model. In general, the experimental response is closer to the FE prediction when the field is applied in a negative direction (i.e. opposite to the polarization direction of top actuator). When the actuation electric field is applied in a continuous cycle, the system exhibits significant hysteresis behavior, the maximum effect being observed in the specimen with epoxy resin bonding.

Best results were obtained with the cyano-acrylate adhesive with 85% of the limiting value of strain transfer (corresponding to perfect bonding) achieved under positive applied field and 90% of the strain limit realized under negative applied field. Corresponding figures for structural film adhesive were 76% (positive field) and 90% (negative field) and epoxy resin were 74% (positive field) and 87% (negative field).

The experimental observations and FE prediction of the shift in fundamental resonance due to the bonding of piezo actuator agree very well. The maximum shift in fundamental resonance was found to be 13.21% for the specimen with structural film adhesive bonding.

Summary and Conclusions

In the present experimental studies on cantilever beam specimens with bonded piezoelectric actuators, the tip deflection was the parameter used to characterize the strain transfer from the piezoelectric actuators to the substrate. Three different types of adhesives viz. cyano-acrylate, epoxy-resin and structural film adhesive were used to study the effect of adhesive bonding material. Experimental results were compared with those of a two dimensional finite element analysis.

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