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**Effect of piezoelectric actuation on curved beams and single lap joints**

Calicia Johnson

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EFFECT OF PIEZOELECTRIC ACTUATION ON CURVED BEAMS AND SINGLE LAP JOINTS

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for degree of
Master of Science in Mechanical Engineering

in

The Department of Mechanical Engineering

by

Calicia L. Johnson
B.S., Florida Agricultural and Mechanical University, 2008
May, 2011
This thesis is dedicated

to my parents

Calvin Johnson

and

Marcia Johnson

as well as

my younger brother

Travon Johnson
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# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iii

LIST OF TABLES ................................................................................................................. vi

LIST OF FIGURES .............................................................................................................. vii

ABSTRACT ........................................................................................................................ xi

CHAPTER 1: INTRODUCTION TO PIEZOELECTRIC MATERIALS ........................................ 1
  1.1 HISTORY ....................................................................................................................... 1
  1.2 PIEZOELECTRIC AND CONVERSE EFFECTS .......................................................... 2
  1.3 PIEZOELECTRIC MATERIALS ..................................................................................... 4
    1.3.1 SINGLE CRYSTALS ............................................................................................. 5
    1.3.2 PIEZOELECTRIC CERAMICS ............................................................................. 5
    1.3.3 PIEZOELECTRIC POLYMERS .......................................................................... 7
    1.3.4 PIEZOELECTRIC COMPOSITES ..................................................................... 8
    1.3.5 PIEZOELECTRIC THIN FILMS ......................................................................... 8
  1.4 PIEZOELECTRIC COEFFICIENTS ............................................................................. 9
    1.4.1 PIEZOELECTRIC CHARGE COEFFICIENT ($d_{ij}$) ........................................... 10
    1.4.2 PIEZOELECTRIC VOLTAGE COEFFICIENT ($g_{ij}$) .......................................... 10
    1.4.3 DIELECTRIC CONSTANT ($K_{ij}$) ..................................................................... 10
    1.4.4 COUPLING COEFFICIENT ($k_{ij}$) .................................................................... 10
  1.5 PIEZOELECTRIC CONSTITUTIVE EQUATIONS ......................................................... 11
  1.6 PIEZOELECTRIC SENSORS ....................................................................................... 12
  1.7 PIEZOELECTRIC ACTUATORS ................................................................................. 13
  1.8 PREVIOUS STUDIES IN PIEZOELECTRIC ACTUATION ........................................ 15
  1.9 CONCLUSION ............................................................................................................ 22

CHAPTER 2: THE SINGLE LAP JOINT ............................................................................... 24
  2.1 INTRODUCTION TO SMART STRUCTURES ......................................................... 24
  2.2 SMART MATERIALS ................................................................................................. 24
  2.3 PIEZOELECTRIC ACTUATORS .................................................................................. 25
  2.4 EXPERIMENTAL EQUIPMENT ................................................................................. 27
  2.5 CANTILEVER SINGLE LAP JOINT COMPOSITE BEAM ........................................ 28
  2.6 SINGLE LAP JOINT EXPERIMENTATION ............................................................... 34
  2.7 SINGLE LAP JOINT ACTUATION RESULTS ............................................................ 38
    2.7.1 TENSILE TEST ACTUATION RESULTS ........................................................... 38
    2.7.2 BENDING TEST ACTUATION RESULTS .......................................................... 38
  2.8 CONCLUSION .............................................................................................................. 52
LIST OF TABLES

Table 1.1 Advantages and disadvantages of piezoelectric ceramics, polymers and composites (Source: Webster, John. “The measurement, instrumentation and sensors handbook”, 1998) .......9

Table 2.1 Dimensions of piezoelectric actuators .................................................................26

Table 2.2 Properties of Quick Pack piezoelectric actuators ..............................................27

Table 2.3 Prepreg properties .................................................................................................31

Table 2.4 Results from specimen tensile test ....................................................................33
LIST OF FIGURES

Figure 1.1 Illustration of direct and converse piezoelectric effect (http://bme240.eng.uci.edu) .......................................................... 2

Figure 1.2 Piezoelectric disk used as a guitar pickup (http://www.websters-online-dictionary.org/definitions/piezeoelectricity) ......................................................... 3

Figure 1.3 Piezoelectric ink jet (Society of Imaging Science and Technology) ................................................................. 4

Figure 1.4 Piezoelectric transducer (http://www.applied-piezo.com/about/piezoelectric-effect.php) ................................................................. 4

Figure 1.5 Poling phenomena (http://www.pc-control.co.uk/piezoelectric_effect.htm) ......................................................... 6

Figure 1.6 Lead Zirconate Titanate (PZT) above and below its Curie Temperature (http://www.physikinstrumente.com) ................................................................. 7

Figure 1.7 PVDF Sensor (Ktech Corporation) ...................................................................................................................... 8

Figure 1.8 Piezoelectric accelerometer (http://www.automation.com) ................................................................................ 13

Figure 1.9 Piezoelectric stack actuator (http://www.electronics-manufacturers.com) ......................................................... 14

Figure 1.10 Piezoelectric bender actuators (Piezo Systems) ............................................................................................. 14

Figure 1.11 Dynamic and static test specimens (Crawley and DeLuis, 1987) ................................................................. 15

Figure 1.12 The smart single-lap joint with anti-symmetric surface bonded piezoelectric patches (Cheng, et al, 2006) ........................................................................................................ 16

Figure 1.13 Experimental set up (Ryu and Wang, 2002) ............................................................................................. 17

Figure 1.14 Effect of radius (Ryu and Wang, 2002) ......................................................................................................... 18

Figure 1.15 Effect of actuator thickness (Ryu and Wang, 2002) ................................................................................ 19

Figure 1.16 Effect of bonding layer thickness (Ryu and Wang, 2002) ............................................................................. 19

Figure 1.17 Total displacement responses of curved beam with single actuators (Y-D Kuang et al, 2007) ................................................................. 20

Figure 1.18 Radial and tangential displacement responses of the curved beam with symmetric actuators (Y-D Kuang et al, 2007) .............................................................................. 21

Figure 1.19 Piezoelectric element bonded to beam (Dosch and Inman, 1992) ................................................................. 21
Figure 1.20 First mode cantilever beam response with and without self-sensing actuator (Dosch and Inman, 1992)

Figure 1.21 Second mode cantilever beam response with and without self-sensing actuator (Dosch and Inman, 1992)

Figure 2.1 Configuration of Quick Pack piezoelectric actuators (MIDE Technology)

Figure 2.2 Quick Pack 20w piezoelectric actuator

Figure 2.3 Quick Pack 20n piezoelectric actuator

Figure 2.4 Power supply

Figure 2.5 Amplifier

Figure 2.6 Data acquisition unit

Figure 2.7 Glass epoxy prepreg on teflon sheet

Figure 2.8 Hot press

Figure 2.9 Illustration of single lap joint

Figure 2.10 Beginning of prepreg tensile test

Figure 2.11 Prepreg tensile test complete

Figure 2.12 Prepreg after tensile test

Figure 2.13 Stress vs. strain curve for glass epoxy prepreg

Figure 2.14 Piezoelectric actuator forces

Figure 2.15 Piezoelectric actuator and strain gage placement on beam

Figure 2.16 Strain gage

Figure 2.17 Bending actuation in initial position

Figure 2.18 Stress vs. time graph for tensile loading

Figure 2.19 QP20w preload effect on region 1

Figure 2.20 QP20n preload effect on region 1
Figure 2.21 QP20w preload effect on region 2 ................................................................. 40
Figure 2.22 QP20n preload effect on region 2 ................................................................. 41
Figure 2.23 QP20w preload effect on region 3 ................................................................. 41
Figure 2.24 QP20n preload effect on region 3 ................................................................. 42
Figure 2.25 QP20w post load effect on region 1 .............................................................. 43
Figure 2.26 QP20n post load effect on region 1 .............................................................. 44
Figure 2.27 QP20w region 1 post load strain recovery ......................................................... 44
Figure 2.28 QP20n region 1 post load strain recovery ......................................................... 45
Figure 2.29 QP20w post load effect on region 2 .............................................................. 45
Figure 2.30 QP20n post load effect on region 2 .............................................................. 46
Figure 2.31 QP20w region 2 post load strain recovery ......................................................... 46
Figure 2.32 QP20n region 2 post load strain recovery ......................................................... 47
Figure 2.33 QP20w post load effect on region 3 .............................................................. 47
Figure 2.34 QP20n post load effect on region 3 .............................................................. 48
Figure 2.35 QP20w region 3 post load strain recovery ......................................................... 48
Figure 2.36 QP20n region 3 post load strain recovery ......................................................... 49
Figure 2.37 QP20w preload vs. post load in region 1 ......................................................... 49
Figure 2.38 QP20n preload vs. post load in region 1 ......................................................... 50
Figure 2.39 QP20w preload vs. post load in region 2 ......................................................... 50
Figure 2.40 QP20n preload vs. post load in region 2 ......................................................... 51
Figure 2.41 QP20w preload vs. post load in region 3 ......................................................... 51
Figure 2.42 QP20n preload vs. post load in region 3 ......................................................... 52
Figure 3.1 Pipe cut into fourths for small curve beam ....................................................... 54
ABSTRACT

Piezoelectric materials have seen a significant usage increase over the past decade. They have been found to be effective as either sensors or actuators in smart structure applications, which allows them to act more as an adaptive system rather than a passive system. Piezoelectric materials are very effective transducers which convert mechanical energy into electrical energy, known as the direct piezoelectric effect or they have the ability to convert electrical energy to mechanical energy, known as the converse piezoelectric effect. The absence of additional mechanical parts, its lightweight and high strength to weight ratio is what make piezoelectric materials so attractive for many applications. Many existing studies have focused on surface bonding or embedding piezoelectric actuators to straight structures but in recent years, piezoelectric actuator performance has been investigated for curved beam applications.

The aim of this thesis is twofold; first, the performance of piezoelectric actuators and their capability to reduce strain and counter balance an external load for both a tensile configuration and a bending configuration is investigated. Secondly, the performance of the piezoelectric actuator on a curved beam structure when system parameters are varied will be investigated. An analytical model, FEM and experimental results are obtained and compared for the curved beam.

It was shown that when the piezoelectric actuator is placed at the joint location, it is more effective for the tensile configuration rather than the bending configuration. For the bending actuation, it was experimentally shown that the most effective actuator placement on the composite beam was region 1 in order to recover the most strain due to the external load. Preload actuation deemed more effective compared to post load actuation for both the single lap joint and curved beam. It was also shown that the deflection of the curved beam increased as the
length of the piezoelectric actuator was increased. An actuator with a length of 15 mm positioned near the beam’s free end, proved to be the best choice for the beam configuration selected. The analytical model provided the total deflection, including the x and y component, which can be calculated by knowing $F_p$, $\beta_1$, $\beta_2$ and $\beta_3$ respectively. The location of the actuator, as well as its size can be changed with $\beta_1$ and $\beta_2$. By altering the system parameters, parametric studies can be conducted to find the optimal location and size of the actuator that will provide the greatest deflection and find the minimal voltage required by the actuator. Therefore by performing the parametric studies, optimization can be obtained by using the piezoelectric actuator to counterbalance the external force and return the free end to its initial position. If multiple actuators are available, this study will not only be able to return the free end to its initial position but multiple actuators can be placed along the beam in order to bring multiple points back to its initial position.
CHAPTER 1: INTRODUCTION TO PIEZOELECTRIC MATERIALS

1.1 HISTORY

Piezoelectric materials are not widely known to the average person, but yet they have become a driving force in innovation and cutting edge technology. Piezoelectricity has grown into a multibillion dollar industry while new applications continue to emerge. The emergence of wireless communication has a significantly high demand for the use of piezoelectric materials. They are also used in video game applications, as well as, the automotive and medical industries among many others.

Piezoelectricity was first introduced in 1880 by two brothers, Pierre and Jacques Curie. The brothers used their knowledge of pyroelectricity, the process of a material to generate a voltage when it is heated or cooled, to develop piezoelectricity. The word piezoelectric is derived from the Greek word “piezein”, which means to squeeze or press, and “piezo”, which is Greek for push. Their experiment consisted of a precise measurement of charges found on the surfaces of specially prepared crystals such as tourmaline, quartz, topaz, cane sugar and Rochelle salt. The charges were a result of a direct proportional relationship with the mechanical force being applied to the crystal. This phenomenon later became known as the direct piezoelectric effect. Their initial results showed that quartz and Rochelle salt illustrated the most piezoelectric ability at the time (Piezo Systems, Nanomotion Ltd).

In 1881, a scientist by the name of Lippmann explored the idea that a crystal will deform upon an electric field being applied to certain faces on the crystal. He based his predictions mathematically on thermodynamic considerations. The Curie brothers, later confirmed Lippmann’s theory and it became known as the converse piezoelectric effect, which is opposite of the direct piezoelectric effect (Piezoelectric Sensorics).
Over the next few decades, scientists became more interested in piezoelectric materials and conducted many experiments in order to learn more about their capabilities and applications where they can be useful. The first major breakthrough of piezoelectric materials came during World War I when they were used as ultrasonic submarine detector transducers. The piezoelectric materials were used to determine the depth of water by sending a high frequency sound wave through the water and timing its echo. This caught the attention of many and has led to the development of many circuit systems, transducers and materials that are still used today.

1.2 PIEZOELECTRIC AND CONVERSE EFFECTS

![Piezoelectric Effect Diagram]

*Figure 1.1 Illustration of direct and converse piezoelectric effect*  
(Picture Source: http://bme240.eng.uci.edu)

As mentioned before, the direct piezoelectric effect refers to a voltage being produced upon an applied stress of either tension or compression. A crystal is comprised of many molecules, each of which has a polarization with one end being negative while the other end is
positively charged. This separation of negative and positive charges creates an electric dipole where there is a pair of electrical charges with equal magnitude but opposite sign, separated by some distance. When a mechanical stress is applied to the poled piezoelectric ceramic, an electric field is produced and the material becomes electrically polarized. In the absence of an electrical field, the dipoles have random orientation of polarization with zero piezoelectricity activity. Piezoelectric sensors are based on the direct piezoelectric effect because it is able to measure pressure, acceleration and strain, among many others, by converting them into an electrical signal. Some applications for piezoelectric sensors include aerospace instrumentation, guitar pickups and they are also used in the automotive industry to monitor combustion in engines.

![](image1.png) **Figure 1.2 Piezoelectric disk used as a guitar pickup**

(Picture Source: http://www.websters-online-dictionary.org/definitions/piezoelectricity)

The converse piezoelectric effect does the opposite. Instead of converting strain into electrical energy, a large potential difference is applied across the material, which in turn, creates a very large force and is able to move the dipoles into a different arrangement. This causes the material to become strained. If an alternating voltage is applied, the material will lengthen and
shorten accordingly, at the frequency of the applied voltage. This phenomenon is what is used for piezoelectric actuation. Applications that use the converse piezoelectric effect include piezoelectric motors, loud speakers and inkjet printers.

![Figure 1.3 Piezoelectric ink jet](Picture Source: Society of Imaging Science and Technology)

![Figure 1.4 Piezoelectric transducer](Picture Source: http://www.applied-piezo.com/about/piezoelectric-effect.php)

### 1.3 PIEZOELECTRIC MATERIALS

The piezoelectric industry and many of its applications require continuous improved performance, an increase in movement and a longer life expectancy. For this reason there are
many different types of materials used for piezoelectricity in order to meet that demand. The most commonly used piezoelectric materials can be placed in two main groups; single crystals and polycrystalline ceramics. Some popular crystals include quartz (SiO$_2$) and lithium tantalite (LiTaO$_3$), while popular ceramics are barium titanate (BaTiO$_3$) and lead zirconate titanate (PZT). There are many other types of piezoelectric materials which include Zinc Oxide (ZnO), Aluminum Nitride (AlN), Polyvinylidene Fluride (PVDF) and Cadmium Sulphide (CdS). A more detailed review of the two main material groups in piezoelectricity will be explored in the following sections.

### 1.3.1 SINGLE CRYSTALS

The most successful single crystal piezoelectric material is quartz. It possesses ideal characteristics that lead to widespread use in narrowband filters, oscillators, telephones, computers and radios. One distinctive characteristic of quartz is its zero temperature coefficient of frequency, which allows it to be used in a variety of applications including those that require high temperature stability. Although nonferroelectric piezoelectrics like quartz do not display high piezoelectric coefficients, they are still used extensively. Other popular single ferroelectric crystals include lithium niobate (LiNbO$_3$) and lithium tantalite (LiTaO$_3$). Both are widely used for surface acoustic device applications (Fjeldly 2001, Schwartz 2008).

### 1.3.2 PIEZOELECTRIC CERAMICS

In the case of polycrystalline ferroelectric ceramics, piezoelectric activity is prompted by the process of polarizing the ceramic material. As long as the grain orientation is random, no
piezoelectric activity can be seen, but when an electric field is applied, the grains are aligned in the direction of the applied electric field.

Among the class of piezoelectric ceramics, the most important are the perovskites, which is a material having the same crystal structure of calcium titanium oxide (CaTiO$_3$). The chemical formula for perovskite structures is ABO$_3$, where $A = \text{Na, K, Rb, Ca, Sr, Ba, Pb, etc.}$ and $B = \text{Ti, Sn, Zr, Nb, or W}$. In an ideal cubic unit cell, the large cation “A” sits at the corner of the face, the smaller cation “B” sits in the body center of the cell and the oxygen atom sits in the center of each face. With each perovskite, there is a critical temperature, which is also known as the Curie temperature, named after Pierre Curie. When the perovskite crystal is raised above their designated Curie temperature, a simple cubic symmetry is formed. When the crystal is cooled below its Curie temperature, the cubic symmetry transforms into a tetrahedral or rhombohedral symmetry.

![Figure 1.5 Poling phenomena](http://www.pc-control.co.uk/piezoelectric_effect.htm)

One example of a perovskite is Barium Titanate (BaTiO$_3$), which was also the first piezoelectric ceramic to be developed in the 1940s. Barium Titanate has very high piezoelectric coefficients, as well as, high dielectric constants, which make it a material of choice when
manufacturing capacitors. Another common piezoelectric ceramic used is Lead Titanate (PbTiO$_3$), which like Barium Titanate, has high piezoelectric coefficients but its dielectric constants are fairly low. Lead Titanate does however pose a high voltage piezoelectric coefficient [PC in Control, American Piezo].

**Figure 1.6 Lead Zirconate Titanate (PZT) above its Curie temperature (left), PZT below its Curie temperature (right)**


### 1.3.3 PIEZOELECTRIC POLYMERS

Polymers from the Polyvinylidene fluoride (PVDF) family, have dominated the science and technology of piezoelectric polymers. As the polymer is stretched, the crystalline regions become polar and with an electric field applied, these regions become poled. Piezoelectric polymers exhibit electromechanical characteristics significantly lower than piezoelectric ceramics, but their Curie temperature and coupling coefficient are around the same value. Due to a polymer’s high flexibility, large sheets can be manufactured and thermally formed into complex shapes. Piezoelectric polymer applications include flexible keypads, pressure sensors for diesel injection lines, traffic counting and proximity sensing. Other types of piezoelectric polymers include polypropylene and polystyrene (Heywang 2008, Schwartz 2008).
1.3.4 PIEZOELECTRIC COMPOSITES

Piezoelectric composites are mainly comprised of a combination of the piezoelectric ceramic and polymer. This particular composite allows the best piezoelectric properties from both materials to be modified in order to form a very strong and diverse product.

They complement each other well, by one being strong when the other is weak. For instance, piezoelectric ceramics are less expensive to fabricate but are brittle and stiff. The piezoelectric polymer is able to balance those limitations by being flexible and stronger. The high electromechanical properties of the ceramic are able to account for the low dielectric properties of the polymer. With the pros and cons of both, the piezoelectric ceramic and polymer makes use in a wide variety of applications, two of which are underwater sonar transducers and medical diagnostic ultrasonic transducers (Schwartz 2008, Websters Dictionary).

1.3.5 PIEZOELECTRIC THIN FILMS

Piezoelectric thin films were first used as very high frequency (VHF) and ultra high frequency (UHF) bulk wave transducers for physical acoustics and delay line applications. Zinc
oxide (ZnO) and aluminum nitride (AlN) are among the most popular piezoelectric thin films with zinc oxide being the most promising. One important characteristic regarding thin piezoelectric films is that only a thin layer with a small area is needed for most of its practical applications. By using composites as a thin film, better electromechanical properties can be obtained (Taylor 1985).

Table 1.1 Advantages and disadvantages of piezoelectric ceramics, polymers and composites.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ceramic</th>
<th>Polymer</th>
<th>Ceramic/Polymer Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Impedance</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Coupling Factor</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Dielectric Constants</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Stiff</td>
<td>Flexible</td>
<td>Flexible</td>
</tr>
<tr>
<td>Cost</td>
<td>Cheap</td>
<td>Expensive</td>
<td>Medium</td>
</tr>
</tbody>
</table>

1.4 PIEZOELECTRIC COEFFICIENTS

The performance characteristics of a piezoelectric material rely heavily on the value of its piezoelectric coefficients. These variables assist in determining the type of piezoelectric that would be a good fit for a particular application. The coefficients $d_{ij}$, $g_{ij}$, $K_{ij}$ and $k_{ij}$ will be discussed in the preceding sections. To identify directions in a piezoelectric material, three axes are used. These axes, termed 1, 2, and 3, correspond to $X$, $Y$, and $Z$ in the conventional three dimensional orthogonal set of axes. It is also important to note the piezoelectric coefficients with double subscripts, which link the electrical and mechanical quantities. The first subscript gives the direction of the electric field associated with the voltage applied, while the second subscript gives the direction of the mechanical stress or strain (PiezoSystems).
1.4.1 PIEZOELECTRIC CHARGE COEFFICIENT \((d_{ij})\)

The “\(d\)” coefficients, also known as the strain constant, relate the mechanical strain produced by an applied electric field. It is defined as the ratio of the electric charge generated per unit area to an applied force. This charge coefficient is usually important in the use of transducers and the piezoelectric material’s ability to perform as an actuator. The units are usually coulombs per newton (Piezo Institute).

1.4.2 PIEZOELECTRIC VOLTAGE COEFFICIENT \((g_{ij})\)

The piezoelectric voltage coefficient “\(g\)” is defined as the ratio of the electric field produced to the mechanical stress applied. High “\(g\)” coefficients are a result of producing large output voltages, which are necessary for sensor applications. Its units are volt meter per newton (Piezo Institute).

1.4.3 DIELECTRIC CONSTANT \((K_{ij})\)

The relative dielectric constant is defined as the ratio of the permittivity of the material \((\varepsilon)\) to the permittivity of free space \((\varepsilon_0)\). This is generally measured well below mechanical resonance. This variable is dimensionless (Seacor Piezo Ceramics).

1.4.4 COUPLING COEFFICIENT \((k_{ij})\)

The electromechanical coupling coefficient “\(k\)” is defined as the ratio of the mechanical energy stored, to the electrical energy applied or vice versa. Since this coefficient uses the relationship of energy ratios, the units are dimensionless (Seacor Piezo Ceramics).
1.5 PIEZOELECTRIC CONSTITUTIVE EQUATIONS

This section will define the piezoelectric constitutive equations. A mechanical constitutive equation describes how a material deforms upon stress, or vice-versa. An electrical constitutive equation describes how charge moves in a dielectric material upon a voltage being applied, or vice versa. The piezoelectric constitutive equations combine both the electrical and mechanical equations to illustrate the coupling effect between the two (Efunda).

\[ S = sT \]
(Mechanical constitutive equation) \hspace{1cm} (1-1)

Where, \( S \) = strain (m/m), \( s \) = compliance (m\(^2\)/N), and \( T \) = stress (N/m\(^2\)).

\[ D = \varepsilon E \]
(Electrical constitutive equation) \hspace{1cm} (1-2)

Where, \( D \) = charge density (V/m), \( \varepsilon \) = permittivity (F/m), and \( E \) = electric field (C/m\(^2\)).

Equations (1-1) and (1-2) come together to form the piezoelectric constitutive equations as,

\[ S_1 = s_{11}E_1 + d_{31}E_3 \]
\[ D_3 = d_{31}E_1 + \varepsilon_{33}E_3 \]
(1-3)

Where, \( d \) = piezoelectric charge constants (C/N) and gives the relationship between electrical charge and mechanical stress.

As mentioned before, the first subscript relates to the direction of the electric field associated with the voltage applied, while the second is the direction of the mechanical stress. These directions are based off the conventional three dimensional orthogonal set of axes. The variable represented as a superscript, indicates that it is constant. For example, \( \varepsilon_{33}E_3 \) implies that the permittivity measurement is taken at constant stress along the \( z \) direction.

The first term in equations (1-3) and (1-4) relates to the converse piezoelectric effect. It shows that a strain will result from an electric field in the material, as well as, a stress. The direct
The piezoelectric effect is described in the second term of Eqs. (1-3) and (1-4) and shows that a charge density field results from not only an electric field but also a stress in the material (Busch-Vishniac 1999, Inman 2008, Efunda).

### 1.6 PIEZOELECTRIC SENSORS

The first applications of piezoelectric sensors started to appear after World War I. Sensors that measure pressure and acceleration were among the first to be designed. Single crystals and piezoelectric ceramics are the two main groups of materials used to manufacture piezoelectric sensors. Piezoelectric ceramics are often used for sensors that do not require high precision, while the less sensitive single crystals offer longer stability and repeatable operation. Piezoelectric sensors rely on the direct piezoelectric effect. When a mechanical force is applied to a polarized crystal, mechanical deformation takes place in the polarized crystal, which leads to electric charge generation. The charge and/or the mechanical deformation can then be measured using a piezoelectric sensor. However, once the force is applied, the electrical signal generated by the crystal reduces significantly with time, which makes piezoelectric sensors better suited for dynamic applications compared to static. There are many different types of piezoelectric sensors such as those used to measure pressure, acceleration, strain or force. They have proven to be very versatile tools used as quality assurance, process control and process development in many various industries. Piezoelectric pressure sensors are currently being embedded underneath touch screen cellular phones. The sensors convert the mechanical energy of the persons touch (vibration) into an electrical signal, which in turn, allows the user to access various applications. The more piezoelectric sensors, the better, because it does not allow the user to use much force or touch the screen repeatedly due to the high sensitivity of each sensor. Accelerometers are
used to measure acceleration, shock or vibration. Under acceleration the accelerometer is subjected to a “g” force, which in turn compresses the crystal and allows the crystal to emit an electrical signal. Accelerometers are used widely in industrial environments to perform predictive maintenance on rotating equipment, including vibration analysis. There are also used in motion sensing video game controllers such as the Nintendo Wii.

![Piezoelectric accelerometer](http://www.automation.com)

**Figure 1.8 Piezoelectric accelerometer**
(Picture Source: http://www.automation.com)

### 1.7 PIEZOELECTRIC ACTUATORS

Piezoelectric actuators offer a number of advantages such as being inexpensive, lightweight, easily bonded to plates and/or beams and they do not take up much space. Piezoelectric actuators use the principle behind the converse piezoelectric effect, in which electrical energy is converted into mechanical energy or displacement. They are very efficient; obtain high mechanical durability and rapid response times. There are three main types of piezoelectric actuators; stacks, benders and linear motors. A piezoelectric stack actuator is composed of several layers of piezoelectric layers stacked on top of each other. The size of the stack varies with the application but typically the height of a stack ranges from 2-3 mm with up to 100 ceramic layers glued together. The use of piezoelectric stacks is the easiest way to get
linear motion using a piezoelectric actuator. The size of the stack varies with the application. One disadvantage of using the stack type is its inability to produce high strain. Piezoelectric stack actuators are used in telecommunication, instrumentation and automotive applications.

![Piezoelectric stack actuator](Picture Source: http://www.electronics-manufacturers.com)

**Figure 1.9 Piezoelectric stack actuator**
(Picture Source: http://www.electronics-manufacturers.com)

Piezoelectric benders, also known as, piezoelectric cantilevers or piezoelectric biomorphs, include piezoelectric layers in which upon an electric field being applied, one layer expands while the other layer contracts. This causes curvature in the individual layers. When more than two piezoelectric layers are used, the bender is referred to as multilayer, which requires less voltage to generate an electric field. Piezoelectric benders provide the user with high displacement but at the sacrifice of force and speed.

![Piezoelectric bender actuators](Picture Source: Piezo Systems)

**Figure 1.10 Piezoelectric bender actuators**
(Picture Source: Piezo Systems)
1.8 PREVIOUS STUDIES IN PIEZOELECTRIC ACTUATION

One of the first experimental developments of piezoelectric actuators as elements of intelligent structures was conducted by Edward F. Crawley and Javier de Luis [4]. They were able to manufacture three dynamic test specimens, which consisted of an aluminum beam with surface bonded actuators, a glass/epoxy beam with embedded actuators and a graphite/epoxy beam with embedded actuators. The piezoelectric actuator pairs were bonded or embedded at opposite but equal distance from the neutral axis of the beam and were used individually, as well as, simultaneously.

![Figure 1.11 Dynamic and static test specimens](image)

(Crawley and DeLuis, 1987)

The location of the actuators was determined based on the mode shapes and surface strain distributions for the first and second cantilevered beam modes. The driving voltages were equal in phase for the first mode tests and were set 180° out of phase for the second mode test. Through this experiment, Crawley and Luis were able to show that segmented piezoelectric actuators are a viable concept for shape control of structures. By using the segmented actuator
technique, they proved that it would always be more effective than a continuous actuator since the output of each actuator can be individually controlled. They also conducted a series of static tests to determine how the elastic properties of the glass/epoxy laminate are affected by the presence of the embedded actuators, in which it resulted in the ultimate strength being reduced by 20%.

In 2006, Jinquan Cheng and Farid Taheri, explored the previous works of stress concentrations always existing in the adhesive layer of a joint and that it is the main cause of joint failure but they decided to consider the anti-symmetrical structural characteristic of a single lap joint shown in Figure 1.12.

![Figure 1.12 The smart single-lap joint with anti-symmetric surface bonded piezoelectric patches (Cheng., et al, 2006)](image)

They proved analytically that the use of piezoelectric actuator patches located anti-symmetrically on a smart single-lap adhesive joint could adaptively control the joint-edge force and bending moment by adjusting the applied electric field, thereby reducing the joint’s edge stress concentration. For their analysis, two types of piezoelectric patches were used which include the common piezoelectric patch with a fully covered single-polar electrode and a bimorph piezoelectric patch with a partly covered bipolar electrode. Through their numerical analysis, they proved that the bimorph piezoelectric layer could induce more drastic changes on the shear forces and bending moments than the single polar piezoelectric layer. They also showed that when the electric field and distance from joint edges remains constant, the shear
force and bending moment could be increased with an increase in piezoelectric length. The actual bond location of the piezoelectric patch only proved to have a minimal effect on the joint shear forces and bending moments. It was also shown that increasing the applied positive electric field could reduce the maximum peel and shear stresses in the joint’s edges.

With many studies being based on piezoelectric actuator’s performance on a straight beam, D.H. Ryu and K.W. Wang, focused their research on surface-bonded piezoelectric actuators on curved beams and discussed the effects that various system parameters have on piezoelectric actuation.

![Figure 1.13 Experimental set up](Ryu and Wang 2002)

Parametric studies were performed using three different types of actuator configurations, SI, SO and RO. Both the SI and SO are flat actuators and RO is a curved actuator. One study showed that as the beam’s radius increased, the moment from the curved actuator decreased. Both flat actuators, SI and SO had an increasing moment as the beam’s radius increased.
The moment vs. beam thickness was also analyzed in which the performance of the RO type saw no change. It was also shown that as the actuator thickness increased, the average moment decreased for all three actuator configurations.

Bonding layer thickness also played a significant role in which type RO moment decreased with increasing bonding layer thickness. Type SI could have either the best or worst performance among the three actuators depending on the beam’s thickness.

An experimental study was also performed to investigate the ratio tip displacement against the curved beam thickness. The experimental study showed that as the curved beam thickness increased, the ratio tip displacement increased as well. It was concluded that between the three actuators, the moment achieved by the curved actuator, RO, would be best design for a thin curved structure and either RO or SI would work well for thick curved beams.
Figure 1.15 Effect of actuator thickness
(Ryu and Wang 2002)

Figure 1.16 Effect of bonding layer thickness
(Ryu and Wang 2002)

Another study performed on curved beams was done by You-Di Kuang. Through this static analysis study, the tip displacement of an aluminum and steel beam was found using both
experimental and finite element results. The aluminum beam was analyzed using single actuators and the steel beam was analyzed using segmented actuators. The radial, tangential and total displacement responses for the curved beam with symmetric actuators were also investigated.

In addition, an equation for the optimal voltage was obtained in order to control the displacement at the free end by piezoelectric actuation. It was found that the expression is independent of the material properties of the middle elastic layer.

\[ V_c \bigg|_{\theta_1=\theta_0} = \frac{\rho r R \sin(2\theta_0) - 2\theta_0}{4N_3} \frac{1 - \cos(\theta_0)}{} \]  

(1.5)

**Figure 1.17 Total displacement responses of curved beam with single actuators**

(Picture Source: Y-D Kuang *et al*, 2007)
By far the most investigated application for the use of piezoelectric actuators is for vibration control. One example is the experiment done by Jeffery Dosch and Daniel Inman, in 1992 where they had success with using a piezoelectric element concurrently as a sensor and actuator to suppress vibration in a cantilever beam.
The piezoelectric element on top of the beam functioned as both an actuator and a sensor while the piezoelectric element on the base of the beam was used to excite a disturbance vibration in the beam, as well as, act as a strain sensor for testing. The first and second modes of vibration were suppressed, reducing the settling time for both modes significantly. The results can be seen in Figures 1.20 and 1.21 for the first and second modes, respectively.

Although piezoelectric actuators have been analytically and experimentally researched, there are limited studies of piezoelectric actuators being used on smart composite joints, as well as, experimented on curved beams composed of composite materials. Also, many of the existing and previous studies focus on the actuator’s performance on the beam alone, rather than observing the performance when an external load is present. The aim of this thesis is to experimentally investigate the piezoelectric actuator’s performance on a curved composite beam and perform a finite element simulation to determine the actuator effect when various parameters are varied. These parameters include actuator length, different materials, curve fitting the deflection against various curves, actuator location and trying to predetermine the voltage needed to correct the beam if the applied load is known, which as not been done before. This thesis will also investigate the actuator’s ability to reduce strain in a single lap joint and counterbalance an external tensile load, as well as, bending.

1.9 CONCLUSION

The basic fundamental concepts of piezoelectric materials were introduced in this chapter. Piezoelectric materials are used in a wide variety of applications and they still have a growing popularity in many different fields. Piezoelectric composites can be used in order to enhance the physical properties of different materials for the assortment of applications, while
piezoelectric polymers can be formed into various complex shapes for many complex applications. A literature review was also done in order to identify previous and current research being conducted regarding piezoelectric actuators. The next chapter will discuss the single lap joint and describe the experiment performed.

Figure 1.20 First mode cantilever beam response with and without self-sensing actuator (Dosch and Inman, 1992)

Figure 1.21 Second mode cantilever beam response with and without self-sensing actuator (Dosch and Inman, 1992)
CHAPTER 2: THE SINGLE LAP JOINT

2.1 INTRODUCTION TO SMART STRUCTURES

Smart structures have enhanced capabilities that produce sensing, actuation and feedback control logic. The control algorithm determines the appropriate actuation based on the information received by the sensor. Diagnosis of a change in specific variables (temperature, pressure, etc.) at critical locations commands appropriate action in order to preserve the structural integrity during the operational life of the system. Defects such as cracks forming and propagating through the material or excessive vibration are examples of protecting the structural integrity of the system. Traits of a smart structure include the ability to self-diagnose, repair, recover, report and learn. Smart structures are seen in numerous applications such as aircrafts, buildings, pipelines and medical devices. In aircrafts, smart structures have the ability to alert the pilot of any potential damage such as crack propagation and wing deformation. Smart windows are used in buildings that can automatically adjust light and heat based on weather changes. Underground pipelines used in the oil and gas industry also have the capability of using smart materials to detect leaks and structural damage. Piezoelectric materials are of particular interest when developing smart structures due to their electrical and mechanical characteristics and their lightweight, which enables them to be embedded in various systems (Chee 1998, Srinivansan 2000).

2.2 SMART MATERIALS

Smart materials have one or more properties that can change significantly in response to changes in their environment by an external stimulus. Temperature, stress, electric and mechanical fields are all examples of an external stimulus. Piezoelectric materials are
considered smart materials due to their direct and converse piezoelectric effect. Piezoelectric composites are more popular in the use of smart materials than piezoelectric ceramics and polymers because they combine excellent electromechanical properties of both. They have been used in snow skies, car tires, buildings and bridges to reduce vibration. Besides piezoelectric materials, other smart materials include magnetostrictive materials and shape memory alloys. Magnetostrictive materials exhibit a strain when subjected to a magnetic field. This effect, known as the Magnetostrictive Effect, always results in a positive elongation strain no matter what the magnetic field sign may be. The Magnetostrictive Effect is widely used in the production of axial actuators due to the high young modulus seen compared to ceramic materials. Shape memory alloys are lightweight materials that undergo heating to return to their original shape. They are especially useful in the aerospace industry (Gaudenzi 2009, Schwartz 2008).

Analytically, it has been shown that forces and bending moments at the edges of the smart joint can be controlled by adjusting the electric field applied to the piezoelectric material. This will increase the strength and durability of the joint by introducing counterbalancing forces upon undesired external loading. The first experiment presented in this thesis explored the piezoelectric actuator’s behavior when the beam is subjected to a tensile load of 1 N. The next experiment subjected the specimen to bending with various loads applied, in order to observe if the actuator will be more or less effective than when tensile loading is applied (Cheng 2006).

2.3 PIEZOELECTRIC ACTUATORS

Two different sets of piezoelectric bonded actuators were purchased from MIDE Technology Corporation. They both contain one stack of two ten milliliters type PZT-5A piezoelectric material. The Quick Pack items used were QP20w and QP20n. Both are
specifically designed for strain actuator applications. Table 2.1 gives the dimensions of both devices. Figure 2.1 illustrates the configuration of the *Quick Pack* piezoelectric bonded actuators, while Figures 2.2 and 2.3 show an actual photo of the *Quick Pack* actuators used for the experiments. Both actuators were manufactured with an Espanex and Epoxy protective layer, which adds to the flexibility of the overall product. The layers are single and double sided, which in turn, feature excellent electrical performance, as well as, good dimensional stability and thermal resistance.

**Table 2.1 Dimensions of piezoelectric actuators**

<table>
<thead>
<tr>
<th>Device</th>
<th>Device Size (mm)</th>
<th>Piezo Wafer Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QP20w</td>
<td>51 x 38 x 0.76</td>
<td>46 x 33 x 0.25</td>
</tr>
<tr>
<td>QP20n</td>
<td>51 x 25 x 0.76</td>
<td>46 x 21 x 0.25</td>
</tr>
</tbody>
</table>

![Figure 2.1 Configuration of *Quick Pack* piezoelectric actuators (MIDE Technology)](image)

![Figure 2.2 *Quick Pack* 20w piezoelectric actuator](image)
Table 2.2 Properties of *Quick Pack* piezoelectric actuators

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>Quick Pack Actuators</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{31}$ (coupling factors)</td>
<td>n/a</td>
<td>0.36</td>
</tr>
<tr>
<td>$k_{33}$ (coupling factors)</td>
<td>n/a</td>
<td>0.72</td>
</tr>
<tr>
<td>$d_{31}$ (strain constant)</td>
<td>C/N or m/V</td>
<td>$-190E-12$</td>
</tr>
<tr>
<td>$d_{33}$ (strain constant)</td>
<td>C/N or m/V</td>
<td>$390E-12$</td>
</tr>
<tr>
<td>$g_{31}$ (voltage constant)</td>
<td>Vm/N</td>
<td>$-11.3E-3$</td>
</tr>
<tr>
<td>$g_{33}$ (voltage constant)</td>
<td>Vm/N</td>
<td>$24E-3$</td>
</tr>
<tr>
<td>$S_{11}$ (compliance)</td>
<td>m$^2$/N</td>
<td>$16.4E-12$</td>
</tr>
<tr>
<td>$S_{33}$ (compliance)</td>
<td>m$^2$/N</td>
<td>$18.8E-12$</td>
</tr>
<tr>
<td>$\rho$ (density)</td>
<td>kg/m$^3$</td>
<td>7800</td>
</tr>
<tr>
<td>$T_c$ (curie temperature)</td>
<td>°C</td>
<td>350</td>
</tr>
<tr>
<td>$\varepsilon_{33}$ (permittivity)</td>
<td>n/a</td>
<td>$-0.9$</td>
</tr>
</tbody>
</table>

2.4 EXPERIMENTAL EQUIPMENT

For both tensile and bending experiments, a Tektronix CPS250 Triple Output Power Supply was used to actuate the piezoelectric material. The tracking error is ± 0.2% and has an analog front panel meter display. Since the maximum voltage on the power supply is only 20 volts, a PI Physik Instrumente amplifier was connected to the power supply in order to produce a higher voltage output. The amplifier ranged from 0-1000 V, which was needed since the maximum voltage for the piezoelectric actuator was 200 volts. A Yokogawa Model DC-100, Style S-10 data acquisition was used to collect the strain gage data. This data collector unit has a
measurement interval as low as 0.5 seconds, an integrated construction of up to 40 channels, as well as, flexible inputs of DC voltage, thermocouples, RTDs, mAmps, AC voltage, AC current, strain and pulse (Electro-Meters).

Figure 2.4 Power supply

2.5 CANTILEVER SINGLE LAP JOINT COMPOSITE BEAM

Over the years, the aerospace industry has seen an increase in the use of adhesively bonded joint structures. This is due to their ease to manufacture and ability to possess excellent strength-to-weight ratios. A single lap joint configuration was formed using a glass unidirectional epoxy prepreg purchased from Adhesive Prepregs for Composites Manufacturers. Special precautions
had to be taken for the beam specimen preparation since it was a prepreg. The material was stored in a contaminate-free container and placed in a freezer at a constant temperature of 0 °F. At least 20 hours prior to use, it was necessary to cut the appropriate amount of material needed
for use and wrap it in nonporous Teflon sheets to be left out at room temperature for stabilization. The Teflon sheets prevented moisture from condensing on the prepreg while it was exposed to the room temperature environment prior to usage. Once the 20 hours have elapsed, the prepreg along with the Teflon sheets were placed in a hot press at 250 °F and 50 psi of pressure for a one hour curing cycle.

Upon completion of the curing cycle, the prepreg was left to cool and then cut to size. Since the fibers laid in the longitudinal direction, it was more difficult to cut the prepreg horizontally to the appropriate size, so instead of using a table saw, scissors deemed more appropriate. The specimen was cut into two pieces that had a length of 200 mm, width of 40 mm and had a thickness of 1mm. In order to have a single lap joint, it was determined to have the joint length be 100 mm. M-Bond 200 adhesive purchased from Vishay Micro-Measurements was used to bond the two pieces together to make the single lap joint. A schematic of the beam configuration can be seen in Figure 2.9.

A tensile test of the glass epoxy prepreg was performed using a MTS QTest/150 Elite Controller, which has an operating capacity of 150 kN, maximum testing speed of 508 mm/min and a minimum testing speed of 0.005 mm/min. The tensile test was performed in order to determine the actual Young’s Modulus of the material. For the actual tensile test, a test speed of 1.3 mm/min and data acquisition rate of 2 Hz were used. Since the prepreg was very thin (1 mm), the top and bottom of the specimen were glued to a thicker piece of material in order for the MTS crosshead to get a better grip of the material for the test.
**Figure 2.7 Glass epoxy prepreg on teflon sheet**

**Table 2.3 Prepreg properties**  
(Date Source: http://www.prepregs.com)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.011 inches</td>
</tr>
<tr>
<td>Weight</td>
<td>0.083 lbs/sqft</td>
</tr>
<tr>
<td>Resin Content</td>
<td>38% by weight</td>
</tr>
<tr>
<td>Flexural Strength (ASTM D790)</td>
<td>@75° 112 x 10^6 psi</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>@75° 4.1 x 10^6 psi</td>
</tr>
<tr>
<td>Tensile Strength (ASTM D 3039)</td>
<td>@75° 81 x 10^6 psi</td>
</tr>
<tr>
<td>Standard Roll</td>
<td>12 inches wide by 120 yards long</td>
</tr>
</tbody>
</table>

**Figure 2.8 Hot press**
A tensile test of the glass epoxy prepreg was performed using a MTS QTest/150 Elite Controller which has an operating capacity of 150 kN, maximum testing speed of 508 mm/min and a minimum testing speed of 0.005 mm/min. The tensile test was performed in order to determine the actual Young’s Modulus of the material. For the actual tensile test, a test speed of 1.3 mm/min and data acquisition rate of 2 Hz were used. Since the prepreg was very thin (1 mm), the top and bottom of the specimen were glued to a thicker piece of material in order for the MTS crosshead to get a better grip of the material for the test.
Tensile tests were performed on five samples and the average Young’s Modulus and Ultimate Tensile Strength were taken in order to determine the specimen’s properties.

Table 2.4 Results from specimen tensile test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Young's Modulus (GPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.21</td>
<td>585</td>
</tr>
<tr>
<td>2</td>
<td>16.81</td>
<td>574</td>
</tr>
<tr>
<td>3</td>
<td>17.13</td>
<td>577</td>
</tr>
<tr>
<td>4</td>
<td>16.02</td>
<td>564</td>
</tr>
<tr>
<td>5</td>
<td>16.13</td>
<td>551</td>
</tr>
<tr>
<td>Average</td>
<td>16.66</td>
<td>570.2</td>
</tr>
</tbody>
</table>
The Young’s modulus for the glass epoxy prepreg was determined to be 16.66 GPa. The ultimate tensile stress was 570 MPa. The various reductions in stress seen in the stress strain curve for the glass epoxy prepreg was due to the fibers breaking in the longitudinal direction as the load increased. This can be see in Figures 2.11 and 2.12 above.

### 2.6 SINGLE LAP JOINT EXPERIMENTATION

For the first experiment, the goal was to observe the actuator’s performance when the composite beam is subjected to tensile loading. A bending test was also conducted to investigate the piezoelectric actuator’s ability to recover strain when an external load is applied to the beam’s free end.

Upon receiving voltage, the piezoelectric actuator produces a pair of equal and opposite forces located at the left and right ends as seen in Figure 2.14. For this particular case, the forces are shown in compression since the actuator produces a bending moment in the positive y-
direction. This bending moment is what forces the beam to act in the opposite direction of the applied load. The actuator can also produce a bending moment in the negative $y$-direction depending on how the terminals of the connector pins are attached to the amplifier.

![Figure 2.14 Piezoelectric actuator forces](image)

Once the specimen was configured, strain gages and the piezoelectric actuators were surface bonded to the beam at three discreet locations. By placing the piezoelectric actuator in various locations, it will assist in determining which location produces the most strain recovery and compare the strain to other locations. The first location, region 1, is closest to the clamp of the beam. Region 2 is located at the middle of the joint, while region 3 is near the free end of the beam. The strain gages were placed directly in line with the middle of the piezoelectric actuator but on the opposite side of the beam, which will enable the strain gage to receive accurate piezoelectric response. For the bending experiment, the piezoelectric actuator was placed on the bottom of the beam in order to counterbalance the load on the beam’s free end. Since the beam is relatively thin, 1 mm, the thickness of the joint area is 2 mm.
In order to apply the strain gage to each beam, a solution of 200 Catalyst, purchased from MIDE Technology, was used to clean both the strain gage and the material. M-bond 200 adhesive was then applied to the entire area of the strain gage and placed on the beam. The piezoelectric actuator was surface bonded with the same cleaning solution and the adhesive was applied across the entire area of the actuator in order for it to be completely bonded to the
prepreg. It was very important that the beam laid on a flat surface when applying both the piezoelectric actuator and the strain gage in order for both materials to get a good firm bond.

For the bending experiment, four different weights were chosen arbitrarily, 0.1 N, 0.3 N, 0.5 N and 1 N in order to apply bending at the free end of the beam. For each weight, two different trials were run. The first trial consisted of a Pre-load, in which the piezoelectric actuator was actuated at 200 volts and the load was applied there after. The second trial was Post-load in which the load was applied first and the actuation proceeded. By performing two different trials, it can be determined which process would be more effective at reducing strain in the beam. For each trial, the experiment was performed three times and the average was calculated for the results. As seen in Figure 2.17, a stool held additional weights in order for the beam to be zeroed with the DAQ when the weight is attached before each experiment began.

![Figure 2.17 Bending actuation in initial position](image)

Once the strain gages were zeroed, the cylinder was removed to allow the load to be applied and hence bend the beam. The strain gage data was recorded directly from the DAQ for
each designated region. The same beam was used for both the tensile and bending test. The only variation was the load being applied.

2.7 SINGLE LAP JOINT ACTUATION RESULTS

The results from both the tensile and bending load configuration is presented in this section.

2.7.1 TENSILE TEST ACUATION RESULTS

There was only one actuator, QP20w, used for the tensile test and only the joint location is represented in Figure 2.18. It is seen that once the load is applied, the strain becomes negative but once voltage is applied, the beam is able to act like a smart material and correct itself to counterbalance the applied load. When the actuator is located at the joint region with a tensile load of 1 N, the strain went from -24 microns to a positive 5 microns after piezoelectric actuation.

2.7.2 BENDING TEST ACUATION RESULTS

A Pre-load and Post-load trial was performed. Pre-load allows the beam to induce deflection prior to applying the external load. It is intended that by actuating the piezoelectric actuator prior to the load being applied, the overall strain will be reduced. The results shown here reflect the ability of the actuator to reduce strain at the various regions with various weights applied to the beam’s free end. Both QP20w and QP20n piezoelectric actuators were compared. The Pre-load data for each region is shown first, starting with Figure 2.19, followed by the Post-load data and a Pre-load vs. Post-load comparison.
Figure 2.18 Stress vs. time graph for tensile loading

For region 1, the clamped end, it can be seen in Figure 2.19 that less strain is produced when the piezoelectric actuator is located at region 1. As the actuator is moved along the beam, the strain near the clamp is increased. This is due to the additional weight caused by the actuator in addition to the applied load. It can be seen that the piezoelectric actuator QP20w is more effective and reduces more strain than QP20n. This may be due to the additional surface area QP20w is able to cover since its width is larger than that of QP20n.

Figure 2.19 QP20w Pre-load effect on region 1
Figure 2.20 QP20n Pre-load effect on Region 1

Figure 2.21 QP20w Pre-load effect on region 2
Figure 2.22 QP20n Pre-load effect on region 2

Figure 2.23 QP20w Pre-load effect on region 3
When the actuator was placed at region 3 with 1N applied, the DAQ was unable to read the strain so no results are seen on the graph for “piezo at free end” for 1N. Region 2, the joint area, saw the least amount of overall strain no matter where the piezoelectric actuator was located. Region 2 was least effected when the actuator was located at region 3. Although the strain levels in region 2 are close when the actuator is at the clamp and the joint, the strain was reduced when the actuator was placed at the joint. This is due to the localized strain produced by the piezoelectric actuator. As seen in Figure 2.23 and Figure 2.24, region 3 saw minimized strain when the actuator was placed at the free end. Region 3’s strain level was nearly unchanged when the actuator is placed at region 1 or region 2.

For the Post-load experiment, the load was applied first and the actuation followed. By comparing the Pre-load data with the Post-load data, the most effective way to reduce strain in the beam can be determined. The Post-load experiment did not see any induced deformation prior to the load being applied. Since the strain is linear to the voltage being applied, the strain was recorded at 100V and 200V. One the graphs below, the left side of the black line indicate
the load being applied and the right side of the black line represents the actuation of the piezoelectric actuator.

![QP20w at Region 1 PostLoad](image)

**Figure 2.25 QP20w Post-load effect on region 1**

Figure 2.25 shows the effect of piezoelectric actuation after the load is applied. Each load reduced strain once the voltage was applied. Figure 2.27 shows the amount of strain recovered by the actuator when the load is applied, which is the difference between the final position and the initial applied load position. It can be seen that when the piezoelectric actuator was placed at region 1, the strain recovery increased as the load increased. QP20w was able to recovery much more strain than QP20n. Again, this is due to QP20w being able to cover more surface area on the beam.

When the actuator is placed at region 2, the amount of strain recovered decreased as the load increased. This can be seen in Figures 2.29 and 2.30 for both the QP20w and QP20n actuators respectively.

Region 3 saw the least amount of strain recovery. This was expected since the Pre-load data showed very minimal effect when the actuator was at region 3. Placing the actuator at region 3 would definitely not be the ideal case in order to reduce strain across the beam.
Figure 2.26 QP20n Post-load effect on region 1

Figure 2.27 QP20w region 1 Post-load strain recovery
Figure 2.28 QP20n region 1 Post-load strain recovery

Figure 2.29 QP20w Post-load effect on region 2
Figure 2.30 QP20n Post-load effect on region 2

Figure 2.31 QP20w region 2 Post-load strain recovery
Figure 2.32 QP20n region 2 Post-load strain recovery

Figure 2.33 QP20w Post-load effect on region 3
Figure 2.34 QP20n Post-load effect on region 3

Figure 2.35 QP20w region 3 Post-load strain recovery
To evaluate the effectiveness of Pre-load versus Post-load, the strain of the Pre-load is compared to the final Post-load strain. Results comparing the two can be seen in the graphs below.

**Figure 2.36 QP20n region 3 Post-load strain recovery**

**Figure 2.37 QP20w Pre-load vs. Post-load in region 1**
Figure 2.38 QP20n Pre-load vs. Post-load in region 1

Figure 2.39 QP20w Pre-load vs. Post-load in region 2
Figure 2.40 QP20n Pre-load vs. Post-load in region 2

Figure 2.41 QP20w Pre-load vs. Post-load in region 3
For both piezoelectric actuators and for each load, it can be seen that the Pre-load actuation reduces more strain than postload actuation. Again, this is due to the induced deflection of the Pre-load prior to applying the external force.

2.8 CONCLUSION

This chapter focused on the piezoelectric actuator’s effect on the composite single lap joint. Three discreet locations were chosen for the actuator and both tensile loading and bending were applied to the beam. It was shown that when the piezoelectric actuator is placed at the joint, region 2, it is more effective under tensile loading rather than bending. When a tensile load was applied, Figure 2.18 shows how the actuator was able to counterbalance the load and act as a smart material by correcting the beam. When subjected to bending, the amount of strain which was recovered decreased as the load was increased. Therefore, with a tensile load configuration more weight can be applied and the actuator will be more effective. It was also shown that Pre-load actuation reduces more strain than Post-load actuation. The next chapter will discuss the piezoelectric actuator’s performance on the curved beam.
CHAPTER 3: SMALL BEAM CURVATURE ACTUATION

Many of the existing piezoelectric actuation studies focus on the straight beam actuation with surface bonded or embedded piezoelectric actuators so there has been limited research conducted on the actuator’s performance on curved beam. The next part of this thesis focuses on the actuator’s effect on the curved beam when various system parameters are changed. Previous studies have looked at the effect of actuator thickness, beam thickness, beam radius and bonding layer thickness. In the present study we will focus on the composite beam, actuator length, actuator location and curve fitting of the deformed beam.

3.1 CURVED BEAM EXPERIMENTATION

The material used for this experiment was a thin walled four inch PVC pipe. In order to get a small curved beam, it was necessary to cut a section of the pipe into fourths as seen in Figure 3.1 below. Since the piezoelectric actuator was too rigid to be placed on the inside of the beam due to the beam’s curvature, it was placed on top. With this configuration, the actuator will eventually “pull” the pipe instead of “push” the pipe to counterbalance the load. The curved beam had a length of 85 mm, a width of 91 mm and a thickness of 2 mm. A small hole was drilled in the center of the beam’s free end in order for a load of 16 N to be applied. Two C clamps were used to hold the pipe in place during the experiment. A strain gage was placed on the inside of the pipe directly opposite of the middle of the piezoelectric actuator in order to receive an accurate piezoelectric response.
3.2 ANALYTICAL REVIEW

As with the straight beam actuation, a Pre-load and Post-load experiment was performed with three trials for each and the average was calculated for the results. Unlike the straight beam actuation, the curved beam causes the piezoelectric forces to no longer act in the purely axial

![Figure 3.1 Pipe cut into fourths for small curve beam](image1)

![Figure 3.2 Thin walled 4in PVC pipe](image2)
Figure 3.3 Curved beam

Figure 3.4 Strain gage on curved beam

Figure 3.5 Piezoelectric actuator on curved beam
Figure 3.6 Curved beam experimental set up

Figure 3.7 Schematic of curved beam experiment

position as shown in Figure 3.8. Thus, forces are acting at a 45° angle, with respect to the x-axis, when the actuator is placed in the middle of the beam. The angles for various piezoelectric placements along the beam can be calculated by performing fundamental trigonometry. No matter where the actuator is located on the curved beam, the left and right ends will have both an
\( x \)-direction force, as well as, a \( y \)-direction force component. The forces can be calculated based on the angle the actuator is located, as well as, how much voltage is applied to the actuator. The strain gauge sees no effect when placed at various locations along the beam due to its flexibility.

![Figure 3.8 Piezoelectric actuator forces on small curved beam](Picture Source: Ryan Meyer Thesis, 2010)

For the curved beam data, several different parameters were varied using the noncommercial finite element software ANSYS, in order to determine the piezoelectric actuator’s response. Since the deflection of the beam was not measured experimentally, it was calculated in ANSYS as the various parameters changed. These parameters included measuring the deflection as the actuator’s location along the beam varied, deflection vs. force applied, deflection as the actuator length varied, and deflection of beam with the piezoelectric actuator surface bonded to different materials, as well as, comparing the deflection with various shapes such as an ellipse or parabola when the load is applied. By comparing the deflection with different shapes, it will be possible to predict the shape of the beam when a certain load is applied and a known voltage can be applied to the actuator in order for it to be able to bring the beam back to its initial position. This idea can be used in various applications where it is necessary for a curved member to be in contact with another material in order to perform
properly. When the curved structure is deformed and disconnected from another material, piezoelectric actuation will be able to reconnect the two and the device can begin to work again.

In order to verify the simulation is correct, an analytical derivation for the deflection of a curved beam was used. It starts out with the strain energy stored in a beam by bending as seen in Figure 3.9.

![Figure 3.9 Beam bending element](image)

In Figure 3.9, segment $AB$ is a section of the curve of length $ds$ and has a radius of curvature $\rho$. The strain energy stored in this element of the beam is

$$dU = \frac{M ds}{2\rho}$$  \hspace{1cm} (3-1)

with $M$ being the bending moment. The curvature of a beam subjected to a bending moment $M$ is given by
\[ \frac{1}{\rho} = \frac{M}{EI} \quad (3-2) \]

From there we can solve for \( \rho \) and eliminate it completely to get the strain energy.

\[ \rho = \frac{EI}{M} \quad (3-3) \]

\[ dU = \frac{Mds}{2\left(\frac{EI}{M}\right)} \quad (3-4) \]

\[ dU = \frac{M^2 ds}{2EI} \quad (3-5) \]

When \( M \) is not a constant, such as the case for this particular curved beam, the integral form becomes

\[ U = \int \frac{M^2}{2EI} \, ds \quad (3-6) \]

One unique way of analyzing deflection in beams is by using an energy method call Castigliano’s Theorem. The theorem states that “when forces act on elastic systems subject to small displacements, the displacement corresponding to any force, in the direction of the force, is equal to the partial derivative of the total strain energy with respect to that force.” Castigliano’s theorem is seen in Eq. (3-7).

\[ \delta = \frac{\partial U}{\partial F} \quad (3-7) \]

For curved beams in which the radius is significantly larger than the thickness, \( \frac{R}{h} > 10 \) which is the case, only the strain energy due to bending needs to be considered (i.e., strain energy due to shear can be neglected). The strain energy becomes

\[ U = \int \frac{M^2}{2EI} R \, d\theta \quad (3-8) \]
From here, Castigliano’s theorem can be used to obtain a result for the deflection.

\[
\delta = \frac{\partial U}{\partial F} = \int \frac{1}{EI} \left( M \frac{\partial U}{\partial F} \right) Rd\theta \tag{3-9}
\]

In order to determine the bending moment \( M \) and the deflection produced by the force \( F \), Figure 3.10 was used.

![Curved Beam Evaluation](image)

**Figure 3.10: Curved Beam Evaluation**

Substituting \( M \) and \( F \) into Eq. (3-9), an approximate result of the deflection of a thin curved beam with an applied load and no piezoelectric actuation can be obtained as seen in Eq. (3-12).

\[
\delta = \int \frac{1}{EI} \left[ FR(1 - \cos \theta) \right] \left[ R(1 - \cos \theta) \right] Rd\theta \tag{3-10}
\]

\[
\delta = \frac{FR^3}{EI} \int_0^{\pi/2} [(1 - 2\cos \theta) + (\cos \theta)^2]d\theta \tag{3-11}
\]
This equation was used to verify the ANSYS simulation deflection.

\[ \delta = \frac{FR^3}{EI} \left( \frac{3\pi}{4} - 2 \right) \]  

\( \text{(3-12)} \)

The equation for the \( x \)- and \( y \)-component of the deflection for the piezoelectric actuator only, was also derived. This equation does not consider any external load applied.

According to figure 3.11, for \( 0 \leq \theta \leq \beta_1 \), the moment \( M = FR(1-\cos\theta) \). For \( \beta_1 \leq \theta \leq \beta_1 + \beta_2 \), \( M = [FR(1-\cos\theta) + F_p(R_o-R\cos(\theta-\beta_1))] \), where \( R_o \) is the outer radius and \( R \) is the middle radius. When \( \beta_1+\beta_2 \leq \theta \leq \frac{\pi}{2} \), \( M = FR(1-\cos\theta) + F_pR[\cos(\theta-\beta_1-\beta_2) - \cos(\theta-\beta_1)] \). The derivation for the deflection in the \( y \)-direction is as follows,

\[ \delta_y = \int \frac{1}{EI} \left( M \frac{\partial M}{\partial F} \right) R \, d\theta \]  

\( \text{(3-13)} \)
Of course $F = 0$ after the partial derivative with respect to $F$ was taken. Now we have,

$$
\delta_y = \frac{1}{EI} \int_{\beta_1}^{\beta_1 + \beta_2} F_p [R_o - R\cos(\theta - \beta_1)][R(1 - \cos\theta)] R \, d\theta
$$

$$
+ \frac{1}{EI} \int_{\beta_1 + \beta_2}^{\frac{\pi}{2}} F_p R[\cos(\theta - \beta_1 - \beta_2) - \cos(\theta - \beta_1)] R(1 - \cos\theta) R \, d\theta
$$

Simplifying we have,

$$
\delta_y = \frac{F_p R^2}{EI} \int_{\beta_1}^{\beta_1 + \beta_2} [R_o (1 - \cos\theta) + R(1 - \cos\theta) \cos(\theta - \beta_1)] \, d\theta
$$

$$
+ \frac{F_p R^3}{EI} \int_{\beta_1 + \beta_2}^{\frac{\pi}{2}} (1 - \cos\theta) + (1 - \cos\theta)[\cos(\theta - \beta_1 - \beta_2) - \cos(\theta - \beta_1)] \, d\theta
$$

Figure 3.12 Curved beam schematic with piezo only (x-direction derivation)
According to figure 3.12, the deflection in the x-direction, $0 \leq \theta \leq \beta_1$, the moment $M = QR \sin \theta$. For $\beta_1 \leq \theta \leq \beta_1 + \beta_2$, $M = QR \sin \theta + F_p [R_o - R \cos(\theta - \beta_1)]$ and when $\beta_1 + \beta_2 \leq \theta \leq \frac{\pi}{2}$, $M = QR \sin \theta + F_p R [\cos(\theta - \beta_1 - \beta_2) - \cos(\theta - \beta_1)]$. The derivation for the deflection in the x-direction is similar to that of y-direction by replacing $F$ with $Q$, and the result is:

$$
\delta_x = \frac{F_p R^2}{EI} \int_{\beta_1}^{\beta_1 + \beta_2} [R_o \sin \theta + R \sin(\theta - \beta_1)] \, d\theta
$$

$$
+ \frac{F_p R^3}{EI} \int_{\beta_1 + \beta_2}^{\pi/2} [\sin \theta + \sin(\theta - \beta_1 - \beta_2) - \cos(\theta - \beta_1)] \, d\theta
$$

(3-16)

The total deflection can be obtained through

$$
\delta = \sqrt{\delta_x^2 + \delta_y^2}
$$

(3-17)

### 3.3 SMALL BEAM CURVATURE RESULTS

Again, PVC pipe was used for the curve beam experiment. Only the QP20w actuator was used for this experiment and only one region and one weight were investigated experimentally. As in the straight beam actuation, both Pre-load and Post-load experiments were performed and compared. The experimental results can be seen in the graphs below.

As we have seen in the straight beam actuation, Pre-load is the best option to minimize strain. The strain recovery was approximately 50 microns. Since the deflection was not measured experimentally, ANSYS software was used to observe the deflection when various system parameters were altered.
Figure 3.13 Curved beam Pre-load

Figure 3.14 Curved beam Post-load
Figure 3.16 shows the deflection of the beam against the undeformed model when only the load is applied. The deflection was calculated to be 4.26 mm which was verified by performing an analytical derivation as seen in section 3.2. A fixed boundary condition is imposed on the left end of the beam and a solid 4 node 182 element type was used during the beams construction. The Young’s Modulus of the PVC pipe was 2.89 GPa and the poisson’s ratio was 0.41. The inner and outer radius of the beam was deemed to be 0.0498 m and 0.0518 m respectively. For the modeling, a partial annulus was used to create the beam’s configuration for \( \theta \) two equals 90º. A 16N load was applied to the last center node on the beam’s free end. Figure 3.17 is an experimental image of the difference in deflection when the beam is in its initial position and when the load is applied, as seen in ANSYS.
Figure 3.16 Deflection of curved beam with applied load only

Figure 3.17 Experimental view of deflection, no load vs. load
The next model created in ANSYS was that of the beam and only the piezoelectric actuator. As mentioned in the previous chapter, the left and right ends of the actuator have both an $x$-direction and $y$-direction force component. The amount of the forces are dependent upon the angle at which the piezoelectric actuator is placed along the beam. When the forces are extended facing away from the actuator, the movement of the actuator is downward and vice versa. For this case, since the actuator was placed on top of the beam, the forces are in compression in order to move the beam in the positive $y$-direction. This movement can be seen in Figure 3.18 below.

![Figure 3.18 Curved beam with piezo actuator only (200V)](image)

In Figure 3.18, the actuator is assumed to be 10 mm in length. The deflection calculated for the beam when actuation is applied was found to be 20 mm.
Figure 3.20 shows the deflection of the beam as a function of the actuator length. It was assumed that the center of the actuator is placed at the middle of the beam as shown in Figure 3.19.

![Figure 3.19 Schematic of actuator on curved beam](image)

As the length of the actuator is increased, the same follows for the deflection. It can also be seen that for every 5 mm of additional actuator length, the deflection of the beam is increased by 12 mm. Another parameter that was investigated was the deflection as a function of actuator location along the beam, as shown in Figure 3.22.

![Figure 3.20 Deflection vs. actuator length graph](image)
There is an increase in deflection as the actuator is moved closer to the free end. The 15 mm actuator produces the most deflection amongst the other two sizes. This may vary
depending on the beam’s configuration but for this particular beam, selecting a 15 mm actuator would be the best choice.

The deflection for various materials was also investigated and the results can be seen in Figure 3.23. It was assumed that the actuator would be placed at the center of the beam and the length was 10 mm. The results are based on the QP20w piezoelectric actuator with 200 volts applied.

![Figure 3.23 Deflection vs. material graph](image)

Another item investigated was deflection vs. shape. The idea was to see if the deflection of the beam conformed to any particular shape such as an ellipse or parabola. If so, it can be determined that if the external force applied is known, the shape of the curve will also be known and the actuation can be provided accordingly. An ellipse curve was formed and plotted against an ANSYS simulation with an applied load of 10N for comparison.

Several trials were ran to vary the load but the ellipse curve was not able to conform to any of them. A parabola curve was also created and plotted against the ANSYS model but the ellipse curve proved to be a closer match.
3.4 CONCLUSION

This chapter introduced the curved beam actuation. Experimental, as well as, an ANSYS simulation was investigated. Like the single lap joint, Pre-load actuation reduced more strain than Post-load actuation. An actuator of length 15 mm proved to produce the most deflection among the 10 mm and 20 mm lengths. The most optimal placement to receive the most deflection is closest to the free end. The deflection of various materials were also observed and an ellipse was plotted against the deformed shape in order to see if a known shape can be predetermined. Unfortunately, no matter how large the load was, the ellipse did not form a perfect match but it was close enough to get an idea of the ultimate goal of would be.

Figure 3.24 Ellipse curve fitted to deflected beam
CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

Composite materials have gained popularity for various applications that need to be lightweight, yet strong enough to counterbalance external loading conditions. Such applications may include airplane wings, propellers, fishing rods, light poles and bicycle frames. In the present study, experimental and finite element models were investigated to observe the behavior of piezoelectric actuators when subjected to various configurations and system parameters. Piezoelectric materials are used in a wide variety of industries and applications including but not limited to the aerospace industry, medical devices, energy harvesters and ink jet printers. Piezoelectric materials are also used in the smart joint/ smart structure applications in order to protect the structural integrity of the entire system. The results shown here can be used in many applications that are exposed to external loads and/or require curved structures. They are discussed in the preceding sections.

4.1 SINGLE LAP JOINT

When the piezoelectric actuator was surface bonded to region 2, the joint, on the composite beam, it performed better when tensile loading occurred rather than a bending load. The tensile load configuration will allow the beam to see higher loads than the bending configuration. The piezoelectric actuator was the most efficient when it was placed at region 1, the clamped end for the bending configuration. QP20w was more effective than QP20n due to its additional surface area. It was shown that Pre-load actuation was more effective at reducing the overall strain of the beam instead of using Post-load actuation. This was due to the induced deformation of the beam once the actuation occurs. The joint area, region 2, saw the least amount of strain when compared with the other two regions in the bending configuration.
Placing the actuator at the free end of the beam is almost negligible since it hardly had an effect on the rest of the beam. This experimental study proved that piezoelectric actuators have the capability to minimize strain and counterbalance the forces caused by external loading.

4.2 CURVED BEAM ACTUATION

An analytical model, FEM and experimental results were obtained for the curved beam. The analytical model provided the total deflection, including the x and y component, which can be calculated by knowing $F_p$, $\beta_1$, $\beta_2$, and $\beta_3$ respectively. The location of the actuator, as well as its size can be changed with $\beta_1$ and $\beta_2$. By altering the system parameters, parametric studies can be conducted to find the optimal location and size of the actuator that will provide the greatest deflection and find the minimal voltage required by the actuator. The finite element software ANSYS was used to verify the analytical model and the deflection of the curved beam. Experimental results were also able to demonstrate the actuator’s ability to perform as the analytical model and FEM proposed. Therefore by performing the parametric studies, optimization can be obtained by using the piezoelectric actuator to counterbalance the external force and return the free end to its initial position. If multiple actuators are available, this study will not only be able to return the free end to its initial position but multiple actuators can be placed along the beam in order to bring multiple points back to its initial position. The external load does not necessarily have to be at the free end but anywhere along the length of the beam. This study will be very beneficial to many applications such as o-rings and preventing leakages in pipe joint structures. Applications that require precise motion and force control such as micro switches or for example, a circuit that needs to be kept in contact but may disconnect due to vibration of an external load, would also benefit from this study. When there is a known external
load or if a small gap forms within the curved structure, the piezoelectric actuator can be actuated in order to close the gap and bring the materials back together.

4.3 LIMITATIONS

Even with the work done in the present study, as well as, existing studies, there are still many limitations when considering the use of piezoelectric actuators. One limitation of using piezoelectric actuators is since the actuators produce a localized strain, many actuators need to be used at one time in order to see significant results. There is also a maximum voltage at which the actuators can be excited, which limits the maximum force that the actuators can produce. Piezoelectric actuators are not compatible with all materials, thus the material needs to be soft and not too thick or rigid. Finally, an on-site external power supply must be used to provide voltage to the piezoelectric actuators, which may be very expensive or inconvenient due to space limitations.

4.4 RECOMMENDATIONS FOR FUTURE WORK

Future work for this present study includes using multiple piezoelectric actuators to return two or more points to their initial position. This should be done through modeling, as well as, experimentally. The actuators can either be placed all on one side or bonded to both sides of the beam to determine its effect. The same work can be done on different shapes other than the quarter circle beam used in this study to analyze the results of the beam and actuator. Different materials can also be used, as well as, various types of piezoelectric actuators. Different external loading positions should also be considered.
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VITA

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