BISTABLE COMPOSITE LAMINATES FOR DIRECT AND ACTUATED DEFORMATION

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ABSTRACT

Bistable composites are unsymmetric laminated carbon fiber reinforced polymers (CFRPs) that exhibit stability in two shapes because of the unsymmetric laminate stacking sequence about the middle surface. A sequential modeling and experimental effort for bistable composite laminates for direct physical loading and piezoelectric morphing structures is presented. The methodology explores tessellated geometries and several iterations are carried out to find the combination of symmetric and unsymmetric laminates for which the desired shapes are achievable. The experimental setup was developed to measure the snap through and snap back loads. The loading and boundary conditions used in the simulation were replicated. The laminate was loaded in discrete steps by adding physical weights in a slotted weight hanger, and the load at which the laminate changed shape gave the measure of the critical loadBoth the snap through and snap back loads were measured in a single setup, just by changing the location where the weights were hanged and not disturbing the laminate. Experimentation was done with an MFC actuator. Tests were run by applying a voltage to the MFC actuator where voltage loads were adjusted by increments of . 02VDC from an initial input of 0VDC magnitude. This was done until snap through to cylindrical (post-load) shape was observed. The voltage load was then removed to test the stability of the laminates.

1 INTRODUCTION

Bi-stability of the composite laminate is achieved during fabrication. After the cure process, multiple deformation shapes can be observed based on the ply orientation and material and thickness of the laminate [1]. This deformation is due to the thermal strain gradient between the layers of the laminate and cure shrinkage during the cure process [2]. As an essential part of the smart material morphing system, the cure process and the resulting post-cure deformation shapes are heavily investigated. Thin unsymmetric cross- ply composite laminates will deform to a uniform circular cylindrical shape, with the shape in between these two cylindrical shapes being unstable and called the saddle shape. Applying a force to the deformed composite laminate will cause it to snap through to the other cylindrical shape. The laminate is scheduled to be loaded in discrete steps by adding physical weights in a slotted weight hanger, and the load at which the laminate changed shape gave the measure of the critical load. Contrary to established literature, the bistable laminates will be supported by suspended boundary conditions rather than floating and movable boundary conditions [3].

Piezoelectricity is the snap through force studied here and the piezoelectric effects are generated by bonding an macro-fiber composite (MFC) patch, or actuator, to the post-cure deformed laminate. Piezoelectricity exhibits electro-mechanic coupling making it very useful for sensing and actuation in smart material systems. Actuation in this research is established by using the converse piezoelectric effect. For the converse piezoelectric effect, an electric field is applied to the piezoelectric crystal causing strain in the crystal [4]. Applying a voltage to the MFC actuator induces this mechanical strain in the patch which is then transferred from the actuator to the composite laminate causing it to snap through to an orthogonal cylindrical shape, cylindrical shape II. With removal of the applied voltage, stable composite laminates will continue to stay in cylindrical shape II. This study applies experimentation and numerical models to compare post-cure deformation shapes and actuated deformation of the composite laminates.

2 FABRICATION OF THE UNSYMMETRIC LAMINATES

The unsymmetric laminates were fabricated from the unidirectional prepreg DA 409U / G35 150 material using an aluminum mold in a WABASH PC hot press. Prepregs are pre-impregnated fibres, where the matrix material is already present. Prepregs generally come in the form of unidirectional fibres, and the matrix generally epoxy resin is present in the B stage condition. Using prepregs is one of the fastest way of composite fabrication and however, it is also costlier than other methods. The prepreg used in this research is made of unidirectional carbon fibres and epoxy matrix.

2.1 Mold and Prepreg

The mold consisted of a top plate, a bottom plate and four side plates, assembled together by using ten bolts. The mold dimension is 7 in x 4 in and the maximum dimension of a laminate that can be fabricated using this mold is 5 in x 2.5 in (approx. 12mm x 63 mm). In the current research, a hot press is used for the fabrication, the heat transfer is through conduction. To prevent the bolts from bending and from becoming non-reusable, the top and bottom plates were countersunk such that the two plate surfaces comes in direct contact with the platens. The mold is shown in Fig.1.

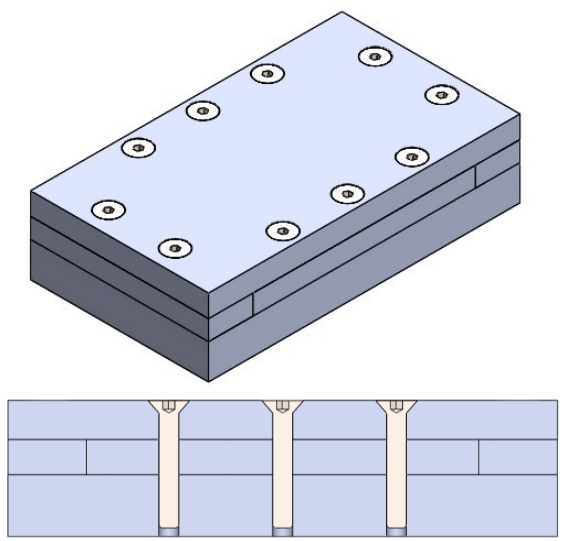


Figure 1: Isometric and sectional front view of the corrected mold

2.2 Fabrication process

The first step in the fabrication process is the mold preparation. The mold is prepared by applying three different coatings: sealant, mold release agent and quick skin agent. Sealant is applied to prevent the epoxy from flowing outside of the mold, as the epoxy becomes liquid, when it is raised to the curing temperature. The mold release agent is applied for easy removal of the laminate from the mold, once the fabrication process is done. The quick skin agent is applied to improve the surface finish of the laminate. The second step is cutting the prepreg for required dimensions and orientation of fibres. Since it is a unidirectional prepreg, by default all the fibres are oriented in a single direction. Appropriate cutting needs to be done, to obtain fibres oriented in other directions as needed in the laminate stacking sequence. The third step is laying up each individual prepreg, one above the other in the mold bottom plate, according to the laminate stacking sequence. Since epoxy has a very good adhesive property, all layers stick to each other firmly. The fourth step is closing the mold. All the side plates are kept in place, the top plate is closed and all the ten bolts are fastened. Since hardened steel fasteners are screwed into aluminum threads (comparatively softer material), proper anti-seize is used to prevent threads from binding. The fifth step is the curing process, where

the closed mold with the prepreg inside, is kept in a hot press and cured at 250°F and 80 psi for 1 hour. The final step is removing the cured laminate from the mold. Once the curing process is done, the mold is allowed to cool down to the room temperature, the mold is opened and the cured laminate is taken out.

3. EXPERIMENTAL SETUP AND RESULTS (STATIC)

A simple experimental setup of applying load by means of adding physical weights is used in this experimental setup. The boundary conditions used in the simulations are replicated. Also the setup is designed in such a way that, both the snap through and snap back loads can be measured just by changing the location of the weights and not disturbing the laminate.

3.1 Description of the experimental setup

The 3D CAD model of the experimental setup is as shown in Fig.2. The main framework is a simple construction that consists of a top plate, bottom plate and four columns, the overall dimension of the setup is 1ft x 1ft x 2 ft. The laminate is held in the middle of the framework, by means of strings attached to 2 eyebolts in the top plate and 2 eyebolts in the bottom plate. The setup also has a three pulley arrangement on the bottom side to pull the laminate downwards and a two pulley arrangement on the top side to pull the laminate upwards. The weights are added by using a slotted weight hanger system as shown in Fig.3.14, hence the weights can only be increased in discrete steps.

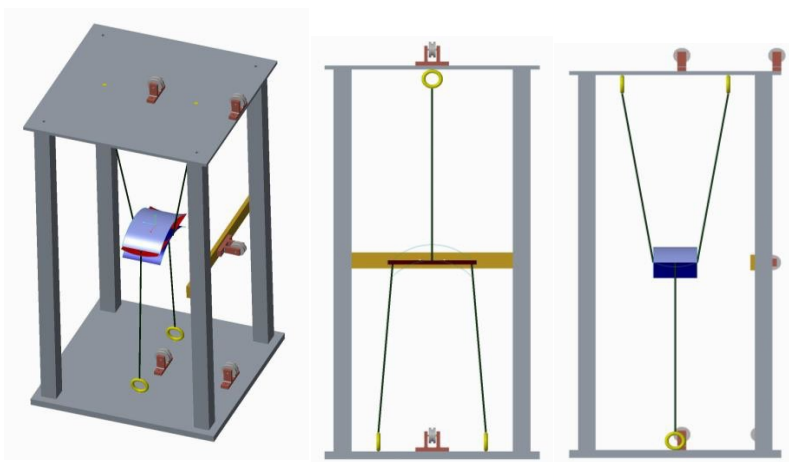


Figure 2: Isometric, front and side views of the experimental setup

Figure 3: Slotted weight hanger system (image courtesy – science lab supplies)

An enlarged image of the laminate portion in Fig.2 is as shown in Fig.4. It appears, as if there are three different laminates present, but they are actually the three different positions of a single laminate. Dark blue is the first position, red is the second position and light blue is the third position.

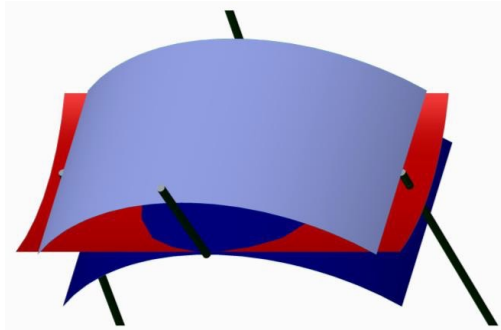


Figure 4: Laminate portion in the experimental setup

The working principle is as follows:

1. In the first position, the laminate is in its post fab shape. The top two strings are in their fully extended position, and the bottom two strings are loose. When the load is applied in the geometric center of the laminate in such a manner that the laminate is pulled downwards, the top two strings constrains the mid-point of the two horizontal edges from moving in the z direction, and all four strings restricts the load application point to move only in the z direction. Once the critical load is reached, the shape changes and the laminate goes to the second position. After this, when the load is removed, the laminate retains the post load shape and remains in the second position.
2. In the second position, the laminate is in its post load shape. The top two strings and the bottom two strings are in their fully extended position. When the load is applied in the geometric center of the laminate in such a manner that the laminate is pulled upwards, the bottom two strings constrains the mid-point of the two vertical edges from moving in the z direction, and all four strings restricts the load application point to move only in the z direction. Once the critical load is reached, the shape changes and the laminate goes to the third position.
3. In the third position, the laminate is back in its post fab shape. The bottom two strings are in their fully extended position, and the top two strings are loose. This is an intermediate position because only till the load is present, the laminate stays in this position. Once the load is removed, the laminate goes back to the first position.

When the laminate is in its post fab shape (first position), the weights are added in the location as shown in Fig.5 (a). This pulls the laminate downwards and the weight at which the shape changes to the post load shape (second position), gives the measure of the snap through load of the laminate. After measurement, when the weights are removed, the post load shape is retained as per the bistable characteristics. When the laminate is in its post load shape (second position), the weights are added in the location as shown in Fig5 (b). This pulls the laminate upwards and the weight at which the shape goes back to the post fab shape (third position), gives the measure of the snap back load of the laminate. After measurement, when the weights are removed, the post fab shape is retained but the laminate goes back to the first position.

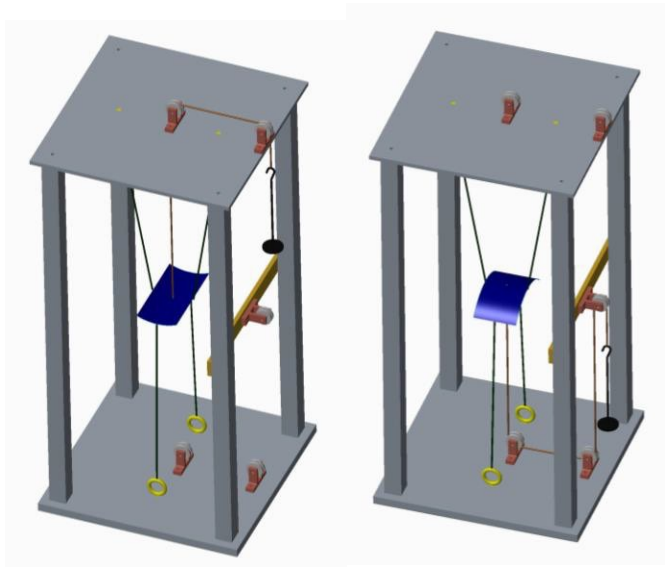
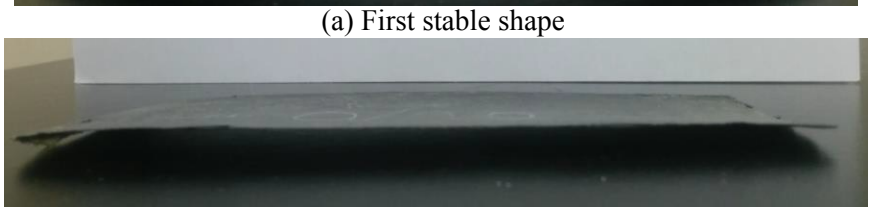


Figure 5: (a) Snap through loading position, (b) Snap back loading position

The two stable shapes of the unsymmetric laminate fabricated using the fabrication process explained above are shown in Fig. 6 (a) & (b). It is a rectangular laminate of dimension 5 X 2.5 in, the unidirectional prepreg used is DA 409U / G35 150, the laminate stacking sequence is [0/90] and the lamina thickness is 0.15 mm. The first stable shape has a curvature about y-axis and the second stable shape has a curvature about x-axis.

(a) First stable shape



(b) Second stable shape

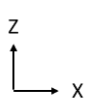


Figure 6: Stable shapes of rectangular unsymmetric laminate [0/90]

4. EXPERIMENTAL SETUP AND RESULTS (PIEZOELECTRIC ACTUATION)

The snap through and snap back loads measured using the experimental setup for three samples 2 and are given in Table 1.

Table 1: Snap through and snap back loads from experiments

S. No.	Laminate sample	Description	Snap through load range	Snap back load range

1	Sample 2	Half geometry working	240 to 250 g (2.35 to 2.45 N)	20 to 30 g (0.20 to 0.29 N)
2	Sample 3	Half geometry working	210 to 220 g (2.06 to 2.16 N)	30 to 40 g (0.29 to 0.39 N)
3	Sample 6	Full geometry working	390 to 400 g (3.82 to 3.93 N)	15 to 20 g (0.15 to 0.20 N)

Among the first two samples, sample 2 has higher snap through load and lower snap back load compared to the loads of sample 3. In sample 2, half of the geometry which does not has bistability stays in the first shape, and during load application for snap through, since the entire geometry is in the first shape, it provides more resistance for shape change, thereby the snap through load is higher. In sample 3, the half of the geometry which does not has bistability stays in the second shape, and during load application for snap through, since only half of the geometry is in the second shape, it provides comparatively less resistance for shape change, thereby the snap through load is lower. The same explanations would hold good for the opposite effect on snap back loads. The snap through and snap back loads for the same laminate from FEA simulations are given in Table 2.

Table 2: Snap through and snap back loads from simulation

S.	Laminate	Snap through	Snap back
1	Simulation	4.57 N	3.32 N

In all three samples of the experiments, the snap back load is much lower than the snap through load. In sample 6, the snap back load is only 5% of the snap through load. In simulation, both the snap through and snap back loads are very close to each other, the snap back load is almost 73% of the snap through load. The curvature results were consistent for all the fabricated samples. There is a curvature reduction as the number of plies increases which matches with the simulation results. To correct the snap back loads discrepancy, suitable corrections need to be carried out in the simulation as well as the experimental setup. After cooling for more than twenty-four hours, the MFC actuator from Smart Material Corp was bonded to the laminate. First, wires were soldered to the MFC piezoelectric electrodes for ease of voltage application. This was done before bonding due to the high temperatures while soldering. The MFC actuator used here from Smart Material Corp already comes polarized, therefore the poling process is not needed.

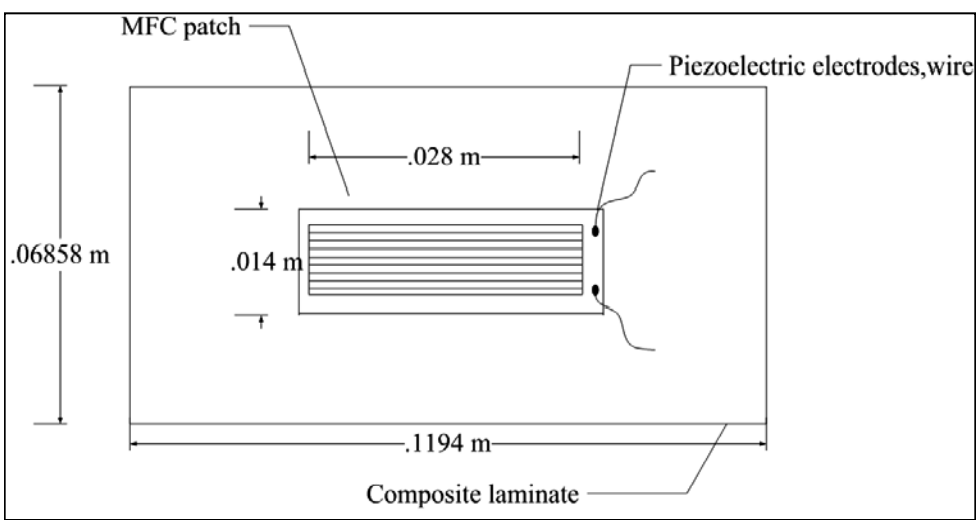


Figure 7: Piezoelectric patch applied to bistable laminate

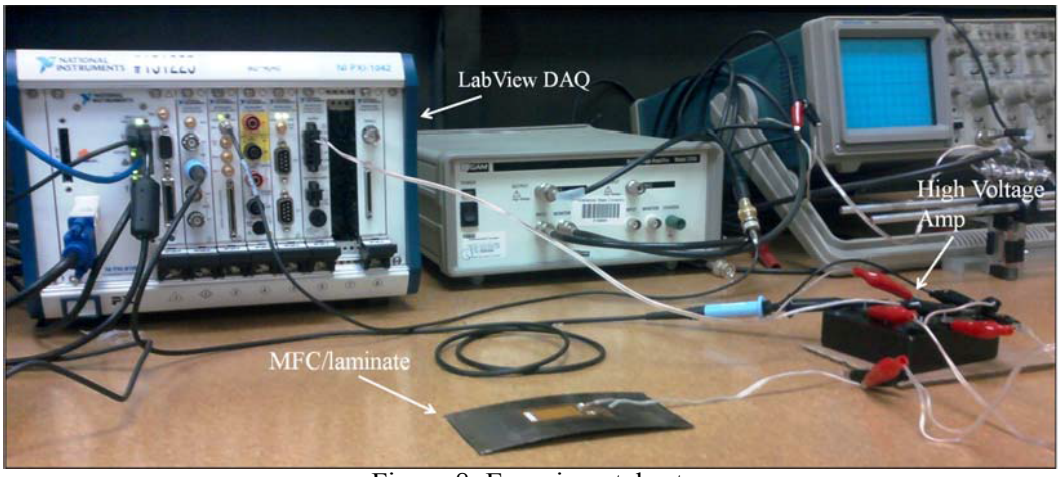


Figure 8: Experimental setup

A Loctite two-part epoxy was used for the adhesive of the MFC actuator. The epoxy was applied to the bottom surface of the MFC actuator then attached to the de- formed post-cure shape laminate. The bond is then clamped together over night to secure adhesion. Figure 7 shows a drawing of the smart material system with the experimental setup shown in Figure 8. A LabView chassis was used to control the system. The LabView system also provided a programming voltage needed for a high voltage amplifier. A high voltage amplifier, which was distributed by EMCO, was used due to the low output voltage of the LabView chassis(max output of 5V DC). The high voltage amplifier. LabView data acquisition system, input and output voltages were supplied and monitored. The high voltage amplifier was controlled by the programming voltage in the LabView system. The input voltage for the amplifier ranges from 0-5V DC, which is the magnitude of the programming voltage controlled by LabView input. There is a linear relationship between the input voltage (programming voltage) and the output voltage of the amplifier. The maximum output of the voltage amplifier is 6000V DC. Therefore since the relationship is linear, if the programming voltage was set at 5V DC, the output would be 6000V DC. The first stacking sequence experimented with was the [0/90] rectangular laminate. Using the monitor voltage from the amplifier and linearity from the relationship of the programming voltage and output voltage, an estimated voltage can be calculated at the time of snap through. For experimentation, the programming voltage was increased from zero by .02V DC per 45 seconds until snap through was observed. After snap through of the laminate to the orthogonal cylindrical shape II, the voltage load is removed to assure the cylindrical shape II is stable. If the shape was unstable, removing the load (voltage) would cause the laminate to snap back to cylindrical shape. In Figure 9, the transverse actuated displacement in the second picture.

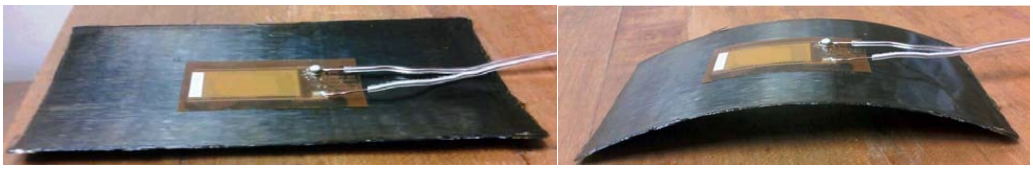


Figure 9: Cylindrical shapes I,II of the rectangular[0/90] laminate

It was observed for the rectangular [0/90] laminate, the experimental voltage at snap through was 391V DC. The post-cure deformation shape and the piezoelectric actuated shape are similar. Therefore the numerical model (briefly discussed below) proved as a reasonable prediction for the actuated displacement of the rectangular [0/90] laminate. This voltage magnitude was then used in the numerical model to get better results for comparisons. The same procedure was done with the square [0/90] laminate, seen in Figure 10. The estimated voltage at snap through was 951.45V DC, which was close to three times more than the snap through voltage for the rectangular laminate.

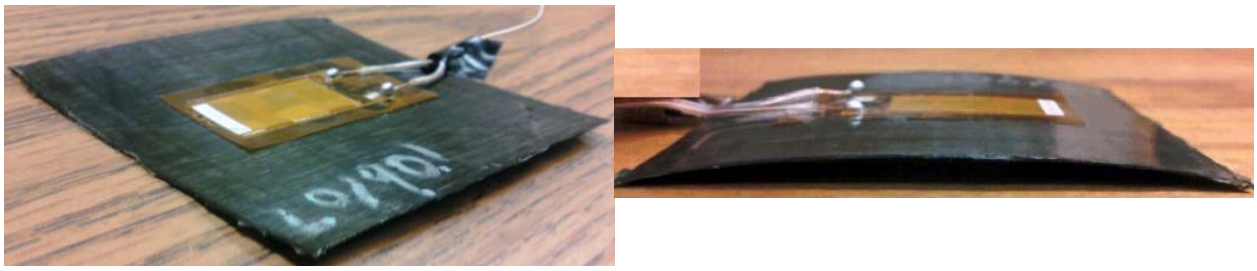


Figure 10: Cylindrical shapes I,II of the square [0/90] laminate

The actuated displacement curvature is predicted by the analytical and numercical models. These predictions are then compared to the experimental results. The rectangular [0/90] laminate comparisons of the numerical and experimental results are reasonably accurate. As expected, the actuated snap through curvature of the rectangular [0/90] laminate is along the y-axis, which is the orthogonal cylindrical shape II. This proves the numerical and analytical models are reasonable prediction models for actuation.

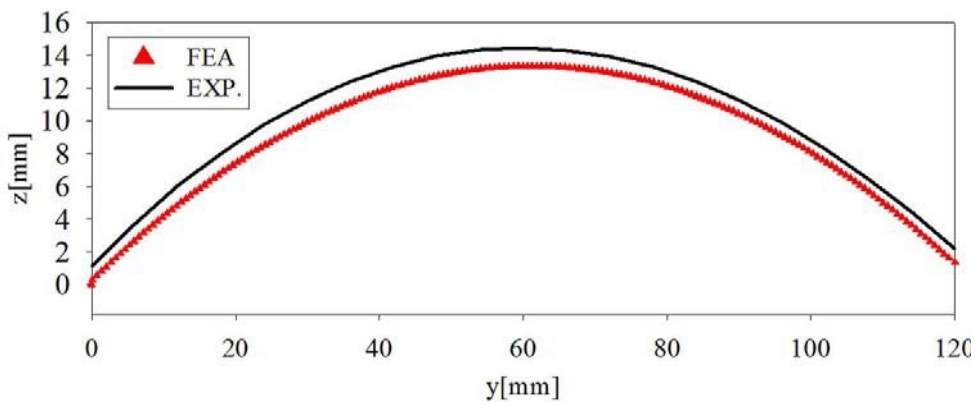


Figure 11: Rectangular [0/90] laminate actuated displacement

The same actuated snap through curvature is expected for the square [0/90] laminate shown below in Figure 12. It can be seen that with the same actuation voltage used, the numerical model for the rectangular [0/90] laminate are reasonably close to the experi- mental result. For the square [0/90] laminate, the error in the comparison for the actuated displacement is more evident here. The numerical model of the square [0/90] laminate exhibits a more symmetric curvature of the actuated displacement. The numerical model consist of ideal parameters. When conducting the experimentation for the cross-ply lami- nates, the situations weren't as ideal. Due to the size and flexibility of the laminate, when using the FARO gage CMM to obtain data points the laminate will tend to move. The data obtained from the experimental actuation therefore will not be as precise as the numerical ideal models. When comparing the actual experimental result to the numerical model, this error can be seen.

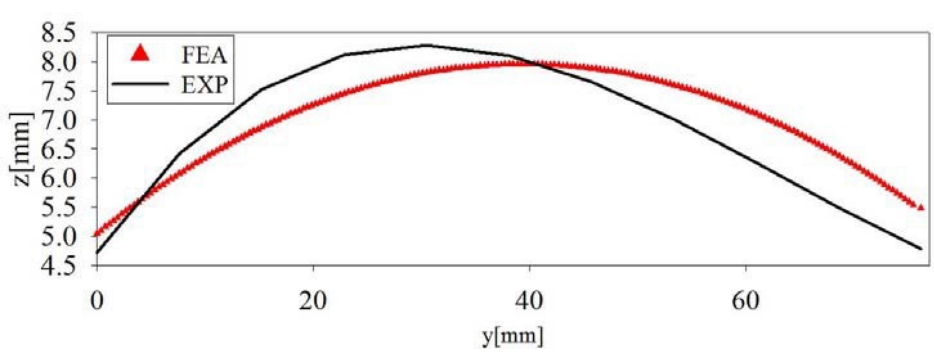


Figure 12: Square [0/90] laminate actuated displacement

Table 3 represents the maximum snap through displacement of the laminates. The actuated displacement is measured as an new shape, therefore the measurements shown are not the displacement difference between cylindrical shape I and II. For the thicker $[0_2/90_2]$ laminates, piezoelectric actuation was done analytically and numerically. Due to the thickness and increased stiffness of the $[0_2/90_2]$, these laminates were not stable and could not snap through. The laminates not classified as simple cross-ply laminates were investigated analytically, numerically, and experimentally. For piezoelectric actuation, test were done on these laminates to assure that the laminates were unstable and that they would snap back to its original post-cure shape after the actuation voltage is removed.

Table 3: Actuated Displacement (mm) and Snap-through Voltages

	[0/90] rt. Voltage: +391.10 DC	**[0/90] square Voltage: +953.45 DC**	**[0/45] rt.**	**[0/45] sq.**
Experiment	13.97	8.54	Voltage: +354.65 DC	Voltage: +586.27 DC
Numerical	13.12	7.89		

5. CONCLUSIONS

This paper addresses three areas of simulation, fabrication of unsymmetric laminates and experimental setup for critical load measurement and piezoelectric actuation. The simulation process was standardized in finite element analysis software. To understand the overall behavior of the unsymmetric laminates, all three stages such as curing, snap through and snap back were simulated. The experimental setup was developed to measure the snap through and snap back loads. The loading and boundary conditions used in the simulation were replicated. The laminate was loaded in discrete steps by adding physical weights in a slotted weight hanger, and the load at which the laminate changed shape gave the measure of the critical load. An operating procedure was established for the load measurement. Result: Both the snap through and snap back loads were measured in a single setup, just by changing the location where the weights were hanged and not disturbing the laminate. Piezoelectric actuation was then investigated numerically, and experimentally. Numerical models were implemented to observe actuation results. Experimentation was done next with an MFC actuator from Smart Material Corp. The MFC actuator was bonded to the deformed thin laminates and clamped over night to as- sure bondage. Test were ran by applying a voltage to the MFC actuator. Voltage loads were made by increments of .02V DC from an input of 0 magnitude. This was done until snap through to cylindrical shape II was observed. The voltage load was then removed to test the stability of the laminates.

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