Controlling the Bending Response of a Multi-Layer Composite Module

Yixiao Pan, Ming Luo, Erik H. Skorina, and Cagdas D. Onal
Soft Robotics Laboratory
Worcester Polytechnic Institute
Worcester, Massachusetts, 01609, USA
ypan2@wpi.edu, mluo@wpi.edu, ehskorina@wpi.edu, cdonal@wpi.edu

Introduction

Controllable bending stiffness and damping has significant applications in soft robotics, especially for soft slender manipulator arms inspired by octopus tentacles. The bending moment on a solid slender beam is balanced by the sum of moments generated by internal stresses. Resulting stresses are not controllable and decided by the bending curvature, area moment of inertia and elastic modulus of the beam. On the other hand, if a beam is a composite of multiple layers, the internal stresses caused by an external load could be related to the friction force between layers. Thus, the bending response of such a composite beam could be controlled by changing the normal pressure between layers.

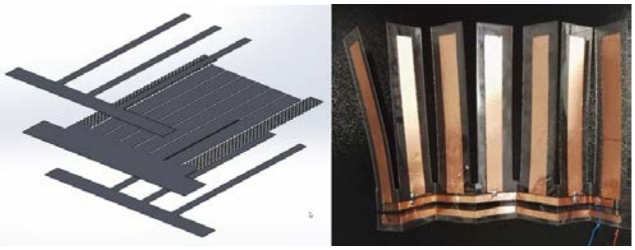
Based on this fundamental concept, we study a multi-layer structure, which is able to achieve variable bending stiffness and damping using several ways to modulate the friction force between layers. We perform static and dynamic tests to determine how normal inter-layer pressure, which can be controlled using various techniques, corresponds to changes in stiffness and damping ratio values. Finally, we describe the design and fabrication of a prototype composite beam comprising multiple thin layers suspended in an elastomeric substrate.

Wall et. al. [1] studied using vacuum pressure to change the bending stiffness of a multilayer structure. In this work, we focus on the application of electrostatic force to modulate the normal pressure between layers by charging flexible electrodes on each sheet and compare our results with the vacuum-driven approach.

Multi-Layer Module Design and Fabrication

The composite multi-layer module is made of two kinds of materials. First is an insulating material used to build the main frame structure and inserted between electrode plates to prevent short circuit. The second kind of material forms flexible electrodes charged with high voltage to generate electrostatic forces.

We first attempted to use ordinary printer paper as the insulator layer to manufacture the composite multi-layer structure. However, the dielectric strength of paper turns out to be too small to sustain a required high voltage. Next, we tried to use polyethylene terephthalate (PET), which has a high dielectric strength to replace paper. However, the bending stiffness of a PET composite module was found to be very large. Finally, we converged on polypropylene, which is used to build thermal lamination sheets. The dielectric strength of polypropylene is similar to PET and it also possesses a desirable flexibility.



(a) Module Design (b) Composite module

Figure 1. The multi-layer composite module comprises a single sheet of polypropylene sandwiched by copper tape electrodes and folded in a zig-zag pattern.

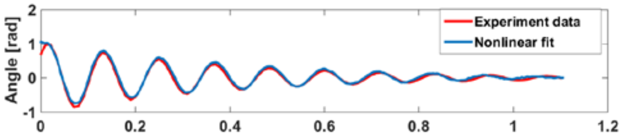
Another problem we have faced early on is the electrical connection of the electrode plates. We first tried to build these layers separately, assemble them together, and connect each plate with wires. However, this method created many points of electrical failure and made the whole system very complicated.

The final design of the main frame is inspired from [2], using an “E” shaped sheet, which integrates the electrode plates and plastic layers in a single unified structure. The electrode plates were also designed in an “E” shape structure and be attached on both sides of the plastic layer. By folding the structure in a zig-zag sequence at one end, the polypropylene sheets attached with copper tape were stacked together nicely and no more connection wires were required.

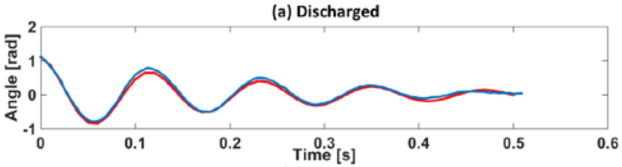
In order to generate a high Coulomb force, we machined the copper tape into 80 mm long and 10 mm wide rectangle pieces and attached them on the sheets as the electrode plates. The final design is shown in Figure 1.

Experimental Results

Controlling Damping Ratio with Electrostatic Force: If the normal pressure exerted between layers is small, then the friction force between sheets would be too weak to prevent the sliding motion among sheets. If a load is applied at the end point of this structure and suddenly removed, then the whole structure will start oscillating and the friction force between sheets will keep consuming the kinetic energy during this process. By changing the friction force, we can change the energy cost ratio of this under-damped system. Our goal is to use the electrostatic force to modulate friction. By measuring the unloaded oscillation response, we are able to determine the relationship between input voltage and damping ratio.



(a) Discharged



(b) Charged

Figure 2. Oscillation response of the composite beam in discharged and charged states indicate a change in damping ratio.

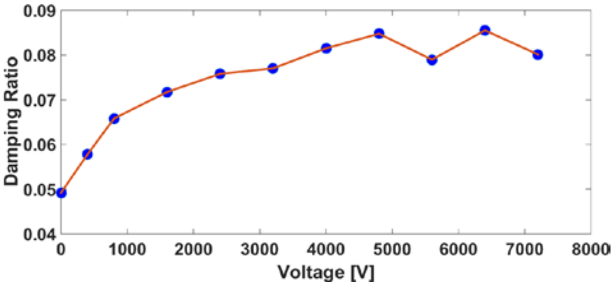


Figure 3. Damping ratio with respect to input voltage.

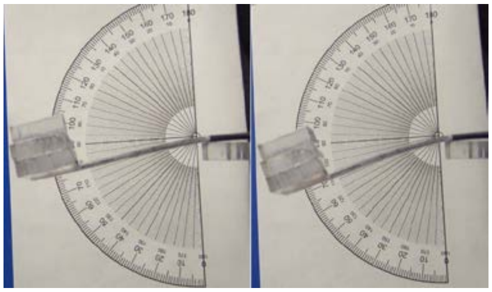
In order to acquire the oscillation response, we used a high-speed camera to track the position of a visual marker at the end of the module. Since this is an under-damped harmonic oscillator, we can calculate the natural frequency and the damping ratio by estimating the fit to the system response curve given as [3]:

$$x = e^{-\gamma t} a \cos\left[\omega_1 t - \phi\right] \tag{1}$$

The γ term in this equation represents the damping coefficient. In this experiment, we built a multilayer beam structure, which is composed of 5 polypropylene sheets and used a high voltage generator module (EMCO Q101) to provide high static voltages. This module is able to generate up to 10,000 V, proportional to an input voltage ranging from 0 to 5 V and uses a power of only 0.5 W. We tracked the position of the end point of the beam and compared the response curve under charged and discharged states. The variation of the damping ratio can be seen in Figure 2.

In order to determine the relationship between charging voltage and damping ratio, we charged the system with different input voltages from 0 to 7200 V and calculated the damping coefficient at each voltage level. We can clearly see the damping ratio is increasing with the input voltage in Figure 3.

Controlling Stiffness with Electrostatic Force: If the normal pressure applied between layers is high enough, then the friction force among layers will prevent the sliding motion between attached sheets and the composite will act as thick solid beam in bending.



(a) 7200 V (b) 0 V

Figure 4. Bending deflection of the multi-layer composite beam in charged (a) and discharged (b) states.

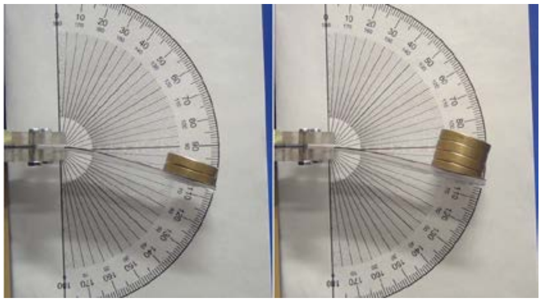
Table 1. Bending stiffness of the multi-layer composite beam in uncharged and charged states.

Voltage (V)	Load (N)	δ (m)	$EI\left(N \cdot m^2\right)$
0	0.09	0.0185	3.43×10^{-4}
7200	0.09	0.0125	5.08×10^{-4}

In this experiment, we fixed one end and applied the same amount of load at the other end of the structure so the entire structure can be described as a classical cantilever beam. The relationship between the end point displacement and applied load at the end point of a cantilever beam could be represented simply as [4]:

$$\delta = \frac{Pl^3}{3EI}, \tag{2}$$

Where P represents the applied load, l represents the beam length, EI represents the bending stiffness. In this experiment, we applied the same amount of load at the end point of the structure, calculated the EI term of the composite beam and compared the stiffness change between charged and discharged states as shown in Figure 4, and tabulated in Table 1.



(a) 2.5 in-Hg (b) 25 in-Hg

Figure 5. Bending deflection under varying air pressure.

Controlling Stiffness with Vacuum Pressure: Since the electrostatic forces are currently not able to generate a high normal pressure to perform a significant stiffness variation, we also tried to use vacuum to control the normal pressure. By integrating the same module in a thermally-laminated airtight flexible cover and using a vacuum pump to evacuate air, we apply variable normal force on the composite beam by controlling the internal pressure of the container (see Figure 5).

Table 2. Bending stiffness at different air pressure

Pressure (in-Hg)	Load (N)	δ (m)	$EI\left(N \cdot m^2\right)$
2.5	0.4	0.02	22.8×10^{-4}
7.5	0.4	0.012	38.1×10^{-4}
10	0.4	0.01	45.7×10^{-4}
25	0.8	0.018	50.8×10^{-4}

In this experiment, we increased the load applied at the end position of the structure and used (2) to describe the relationship between end point displacement and the amount of load. We calculated the structure stiffness at different input air pressure as shown in Table 2.

Discussion

As demonstrated by our results, the bending stiffness of a multi-layer beam is clearly increased by increasing the normal pressure between layers. We can also conclude that using vacuum pressure to increase normal force is currently more effective than using the Coulomb force generated by high voltage potentials. In order to study the differences between these approaches, we calculated the normal pressure generated by the electrostatic method and vacuum method and compared the results.

Since we are charging electrodes in the multi-layered structure, the total electric field between plates can be described as [5]:

$$E = \frac{Q}{A\varepsilon_p\varepsilon_0} \qquad (3)$$

Solving for Q yields $Q = A\varepsilon_p\varepsilon_0\frac{V}{d}$, where *A* is the area of the capacitor plates, which is 8×10^{-4} m^2 in our experimental setup. *V* is the applied voltage, *d* is the distance between two plates. ε_0 ε_0 Stands for the permittivity of air, approximately 8.85×10^{-12} F/m and ε_p represents the relative permittivity of the polypropylene material, approximately 2.2.

Based on Coulomb's law, the attractive force between the two charged plates can be calculated by multiplying the electric field produced by one of the plates times the charge on the other [5]:

$$F = \frac{Q_1Q_2}{2A\varepsilon_p\varepsilon_0} = \frac{\varepsilon_p\varepsilon_0AV^2}{2d^2} \qquad (4)$$

The distance *d* between charging plates is the thickness of the material (0.2 mm). Using these parameters, we calculate the pressure generated by electrostatic force at increasing charging voltage levels as shown in Table 3.

The normal pressure obtained by applying vacuum can be directly read from a pressure gage. We convert the pressure unit from in-Hg into Pa to compare the results as shown in Table 4.

Table 3. Normal pressure at different voltage levels.

Voltage (V)	800	2400	4800	7200
Pressure (Pa)	62.30	560.74	2,242.9	5,046.6

Table 4. Normal pressure at varying levels of vacuum.

Pressure (in-Hg)	2.5	7.5	10	25
Pressure (Pa)	8,466	25,398	33,864	84,660

Conclusions

These initial experiments proved the concept of controlling the bending response of a multi-layer composite module by adjusting the normal pressure between layers. We evaluated two different methods to change the normal pressure and compared experiment results. Though the vacuum method is capable of generating the desired normal pressure, it may not be practical. In order to generate high pressure, it requires a powerful vacuum pump, which will not only take space, but also keep consuming a lot of energy, and require additional valving hardware.

On the other hand, the performance of the electrostatic method highly depends on the high voltage generator module as well as the dielectric strength and thickness of the insulating material between the electrode plates. In our experiment, we use the EMCO Q101 high voltage power supply module, which can generate up to 10 kV. Based on polypropylene's dielectric strength (16.25 kV/mil), our experimental prototype should be able sustain up to 100 kV. Thus, the maximal normal pressure exerted between the layers theoretically could reach nearly 974 kPa. Conversely, if we are able to decrease the material thickness down to 0.05 mm, we can generate a pressure close to 170 kPa at 10 kV. So, as long as we can use a higher voltage input or adjust layer thicknesses to be less than 0.05 mm, we can expect a better performance of using Coulomb forces to control the bending stiffness of a multi-layer beam, which is the focus of current work.

References

1. Vincent Wall, Raphael Deimel and Oliver Brock. Selective Stiffening of Soft Actuators Based on Jamming, 2015, IEEE, ICRA.
2. Yong-Jae Kim, Shanbao Cheng, Sangbae Kim, and Karl Iagnemma. A Novel Layer Jamming Mechanism with Tunable Stiffness Capability for Minimally Invasive Surgery. 2013, IEEE, Transactions on Robotics, Vol. 29, No. 4.
3. Weisstein, Eric W. "Damped Simple Harmonic Motion--Critical Damping." From MathWorld--A Wolfram Web Resource.
4. Gere, James M.; Goodno, Barry J. Mechanics of Materials (Eighth ed.). pp. 1083–1087.
5. Introduction to Electrodynamics (3rd Edition), D.J. Griffiths, Pearson Education, Dorling Kindersley, 2007