FE Model of a 3D dielectric elastomer bending actuator

Final project

EM397, Soft Materials

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1. Introduction

This project deals with modeling a planar, dielectric elastomer, bending actuator. The idea came from combining models from [1] and [2]. In [1] they applied voltage and then measured the radius of curvature for a 4-layered actuator, as shown in the next figure:

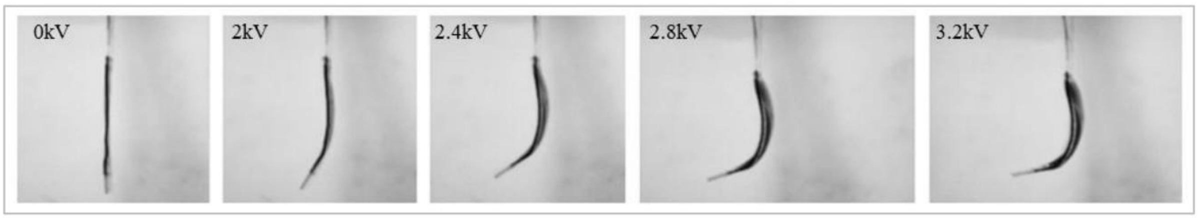


Figure 1: Bending actuator (figure(3) in [1]: Lai, W., Bastawros, A. F., & Hong, W. (2012). Out-of-plane motion of a planar dielectric elastomer actuator with distributed stiffeners. Electroactive Polymer Actuators and Devices (EAPAD) 2012, 8340, 834011. https://doi.org/10.1117/12.917494)

In this project, I basically implement the simplest version of a multi-layered actuator, with only one layer of DE (active region) covered by a stiffer thin layer (passive region).

The actuator is modeled in ABAQUS by implementing the UMAT subroutine provided in class notes. Then, I conduct a (short) sensitivity analysis by examining the effect of stiffness and thickness variations of the thin layer to the overall mechanical response of the actuator. Finally, I model the case of distributed stiffeners along the free surface of the elastomer.

2. Geometry, material parameters

The actuator structure consists of two parts: a) the elastomer and b) a thin (stiff) layer that covers the free surface of the elastomer.

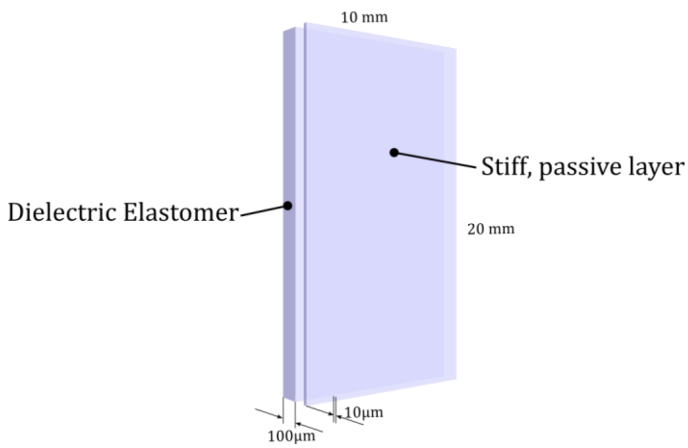


Figure 2 Model geometry

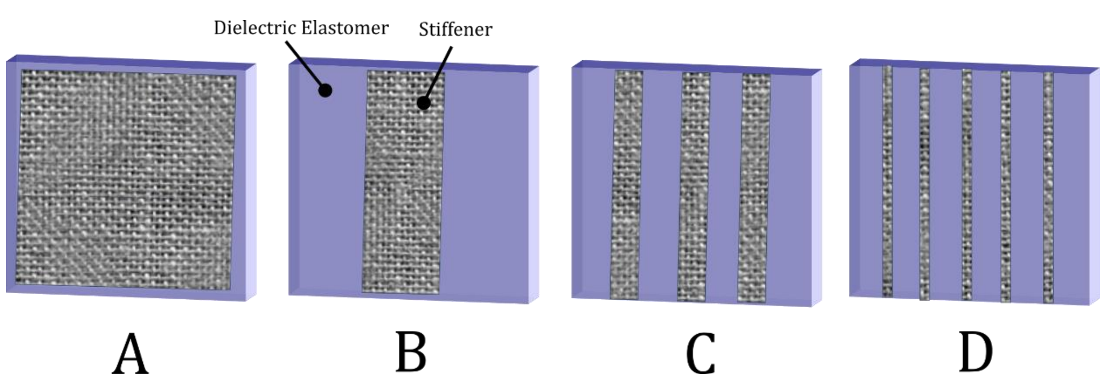
The original structure is supposed to be 20 x 20 mm. Assuming symmetric response with respect to the normal plane in the middle of the square, geometry imported in Abaqus is the one shown in the previous figure.

According to [1] properties for the dielectric elastomer were similar to the 3M VHB (F9460PC) transfer tapes with $C10 = 0.042\ MPa$ and dielectric constant (relative permittivity) $\varepsilon_r = 4.7$. The thickness of the DE is 0.1 mm.

For the stiffener (thin layer, thickness ≈ 0.01 mm) the material parameter is chosen to be at least 2 orders of magnitude greater than μ, for example $C10 = 10\ MPa$.

The following 2 versions of the problem are considered:

1. Stiffener covers the **total area** of the elastomer (Case A)
2. **Distributed Stiffeners**: stiffening tape covers 45% percent of the elastomer surface area (Cases B,C and D)



3. FE model

3.1 Boundary conditions

As presented in the following figure, the top edge of the actuator was fully constrained, all translations and rotations (ENCASTRE). Symmetric boundary conditions were applied at the left long edge (XSYM), whereas the right edge was free.

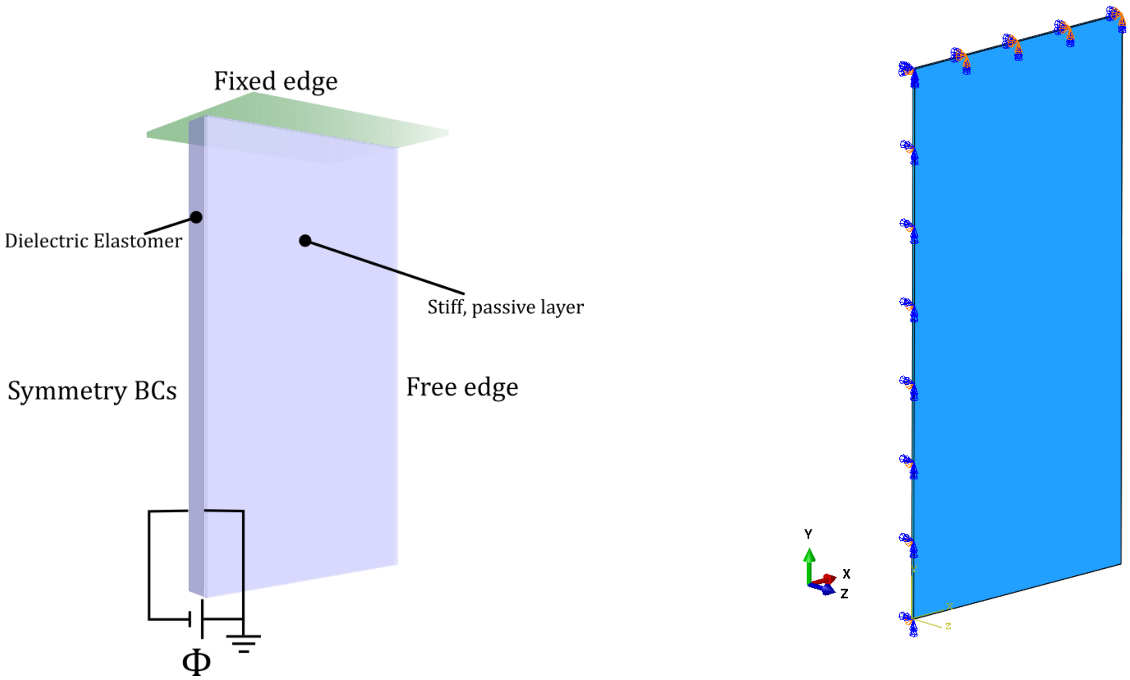


Figure 3: a) Schematic of the actuator model and b) BCs implemented in Abaqus CAE environment

3.2 Material model

In order to model the **dielectric elastomer**, I used the UMAT subroutine, provided in class notes, with the following parameters:

Neo Hookean parameters [MPa , ~]		**Permittivity $[N/V^2]$**	**Nominal electrical field [V/mm]**			**Pre-stretch [~]**		
C_{10}	D	ε	E_{n1}	E_{n2}	E_{n3}	λ_{p1}	λ_{p2}	λ_{p3}
0.042	1e-3	42e-12	0	0	9.5e3	1	1	1

Note that

$$E_{n3} = \frac{\Phi}{L_3}$$

Since the thickness of the elastomer is $t = 0.1\ mm$, the applied voltage range is

$$\Phi = E_{n3}t = 0 \sim 0.95\ kV$$

In order to apply the voltage gradually, a uniform **temperature field** is assigned for the active region. This constant temperature field varies linearly with the pseudo-time of the simulation (static, mechanical analysis), as a ramp function. The magnitude of the ramp function is set to 1, so as to avoid scaling of the imposed electrical field.

In addition, the stiffener layer was modeled by defining a reinforcement skin on active region's face. For this purpose Neo – Hookean material and shell elements (S4R) were used.

Neo Hookean parameters [MPa , ~]	
C_{10}	D
10	1e-4

The volume mesh consists of 20-node quadratic brick elements (C3D20R) in 3 layers.

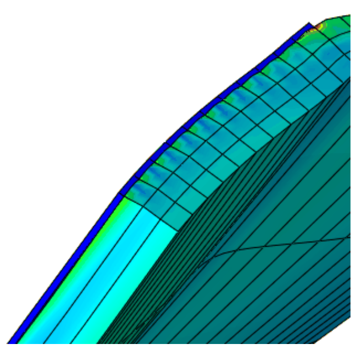


Figure 4: Volume mesh detail (3 layers of C3D20R bricks)

4. Results

4.1 Case A

For Case A, surface area of the DE is completely covered (reinforced) by the stiffening thin layer. In the following figure, the deformed state is shown, after applying voltage, using material parameters as described earlier.

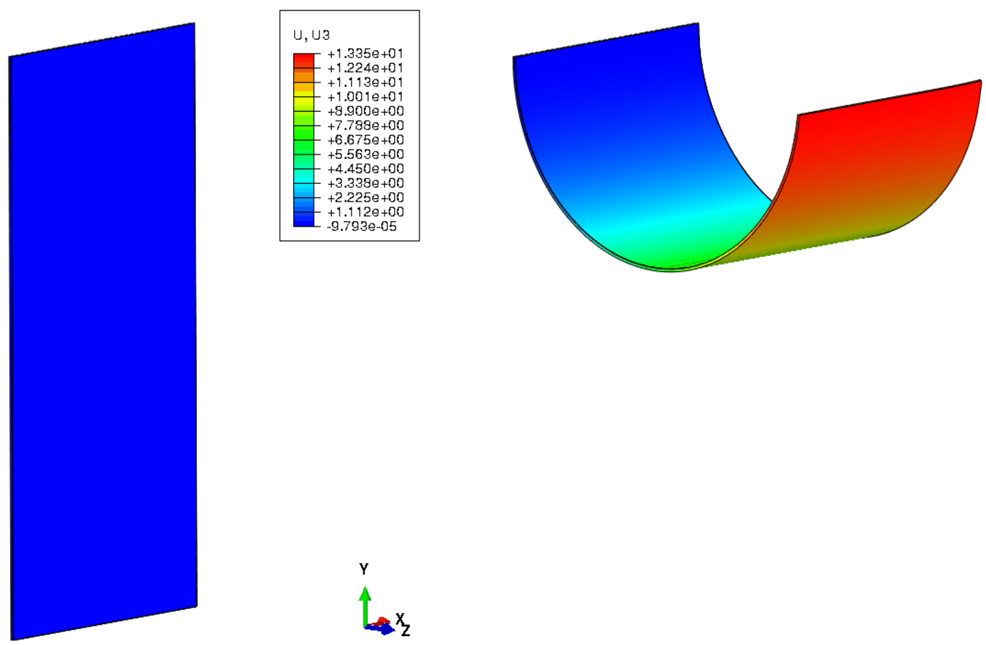


Figure 5 Case A of the bending actuator (colorscale: U3 displacement)

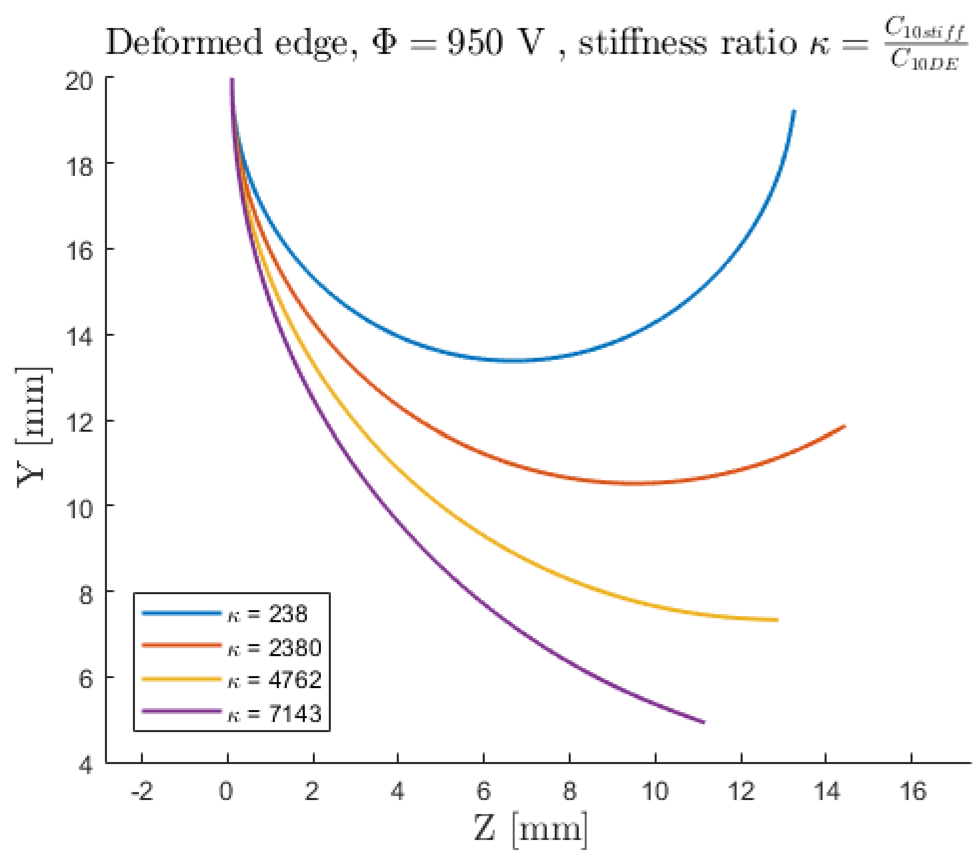
To examine the effect of a) stiffness and b) thickness of the thin layer to the overall performance of the actuator, I tried different combinations of these values and solved again the same problem. The above solution, is considered my reference version of the problem.

4.2 Layer stiffness sensitivity analysis

In this case, the thickness ratio between DE and the thin layer is kept constant, whereas the material parameter of the stiffener is increased according to the next table:

	Reference	1	2	3
C_{10}	10	100	200	300
$\kappa = \frac{C_{10} stiffener}{C_{10}\ DE}$	238	2380	4762	7143

The next plot shows the deformation of the symmetric (middle) edge of the actuator at the maximum value of applied voltage.



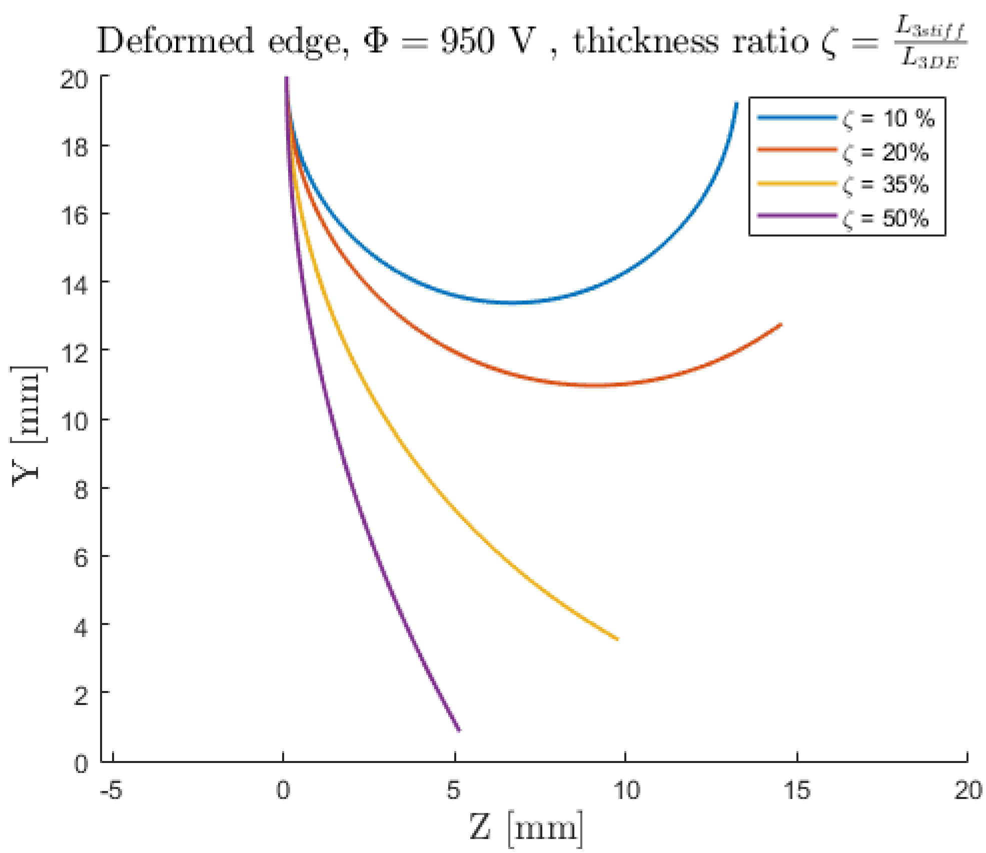
As expected, the radius of curvature is decreased as the C10 of the stiff layer is increased.

4.3 Layer thickness sensitivity analysis

In this case, the stiffness ratio between DE and the thin layer is kept constant, whereas the stiff layer thickness is increased according to the next table:

	Reference	1	2	3
L_3 [mm]	0.01	0.02	0.035	0.05
$\zeta = \frac{L_3\ stiffener}{L_3\ \ DE}$ [%]	10	20	35	50

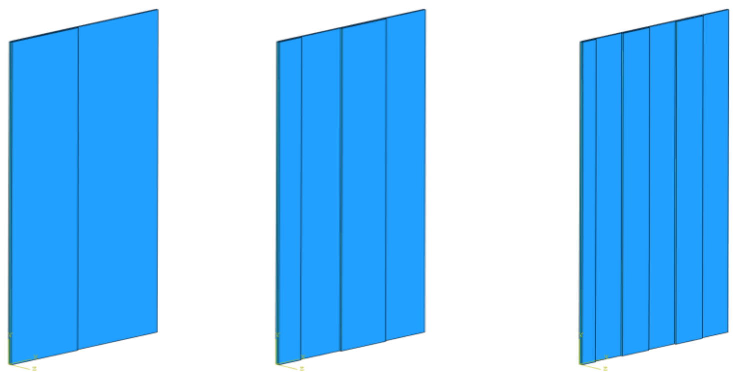
Again, the next plot shows the deformation of the symmetric (middle) edge of the actuator at the maximum value of applied voltage.



Apparently, increasing the layer thickness has the similar effect as in the previous case (increasing C10).

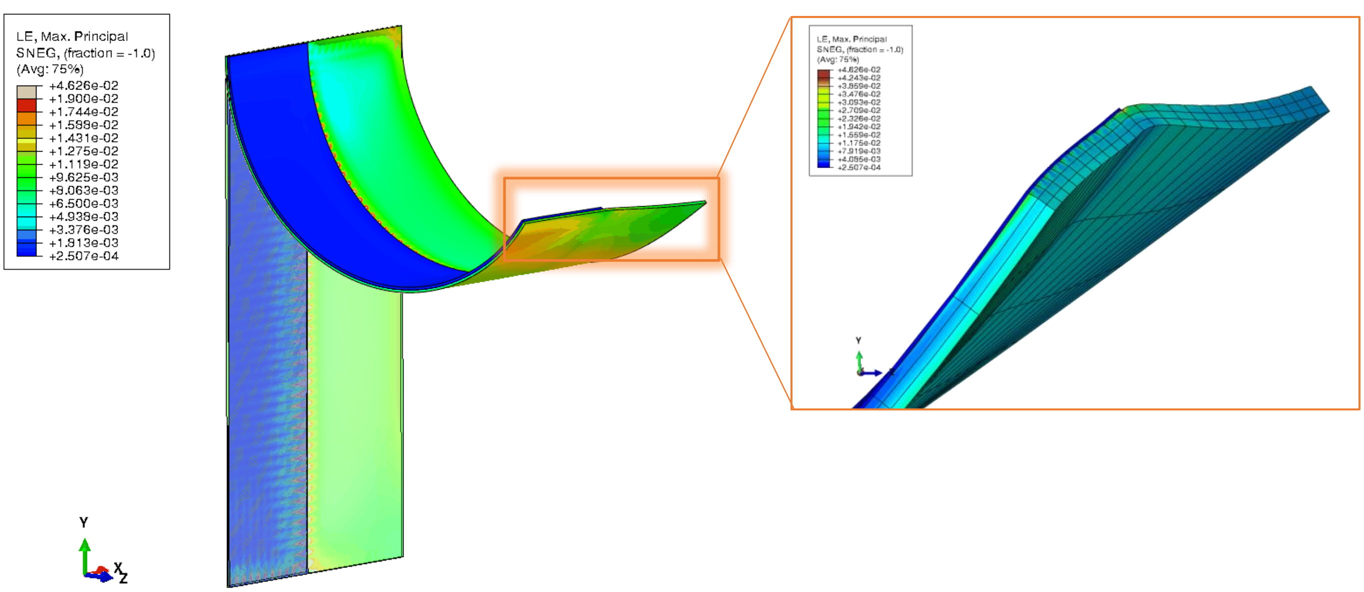
4.4 Distributed stiffeners

The following cases are considered: a) 1 stiffener, b) 3 stiffeners and c) 5 stiffeners. Again, because of the symmetry of the problem I consider only half of the actuator volume.

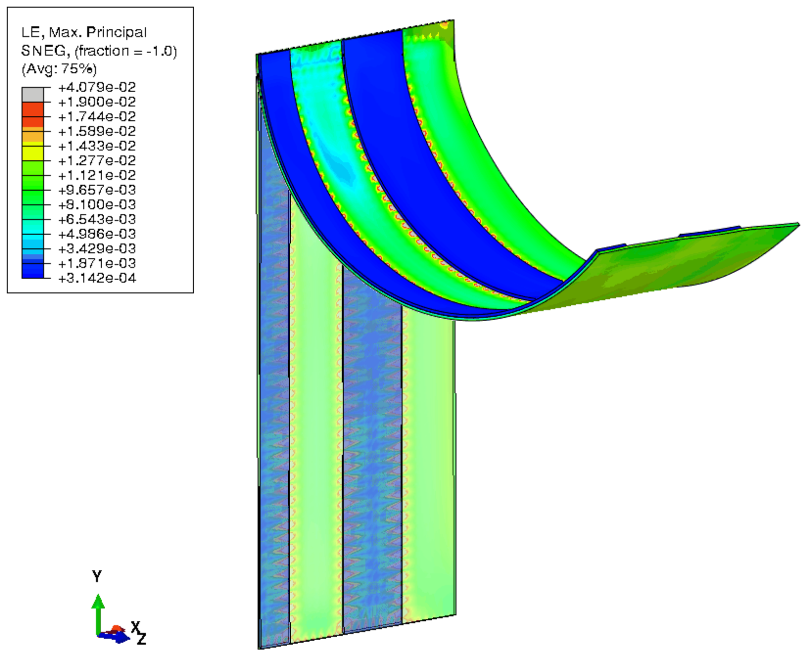


In the following figures, the **logarithmic max principal strain** is presented at the last step of each simulation (voltage Φ = 950 V).

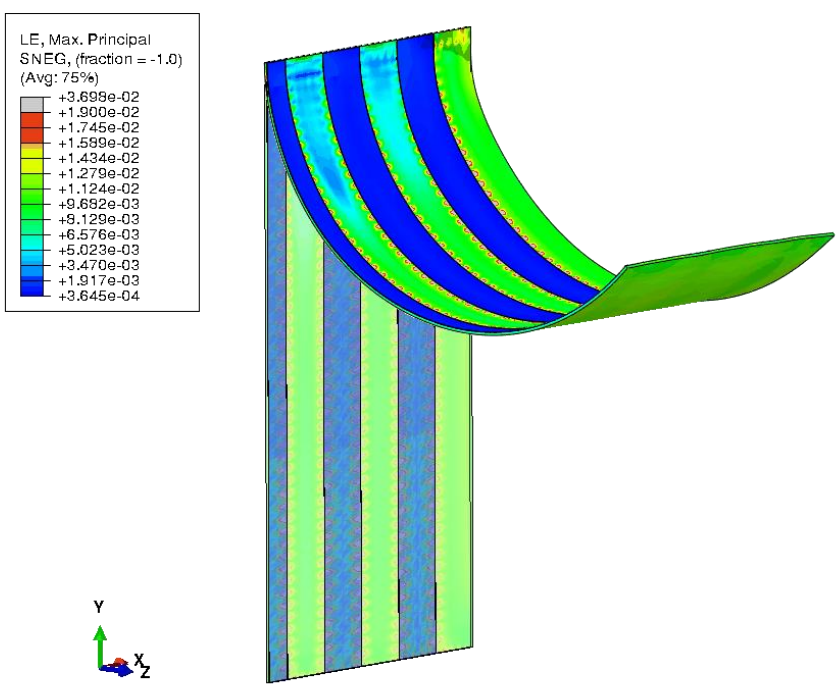
1 stiffener



3 stiffeners



5 stiffeners



Next, I plot the deformed edge and the total strain energy of the system with respect to applied voltage for each case:

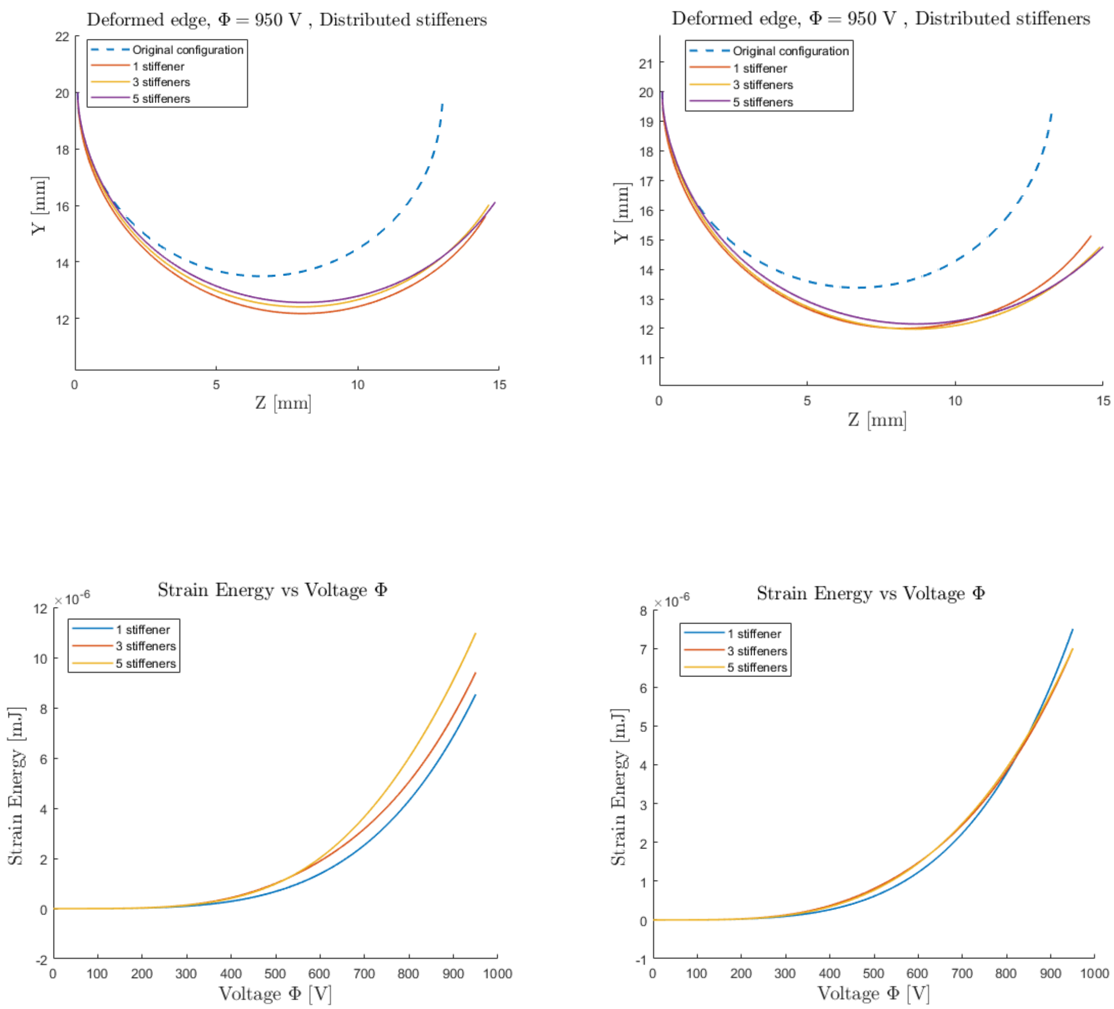
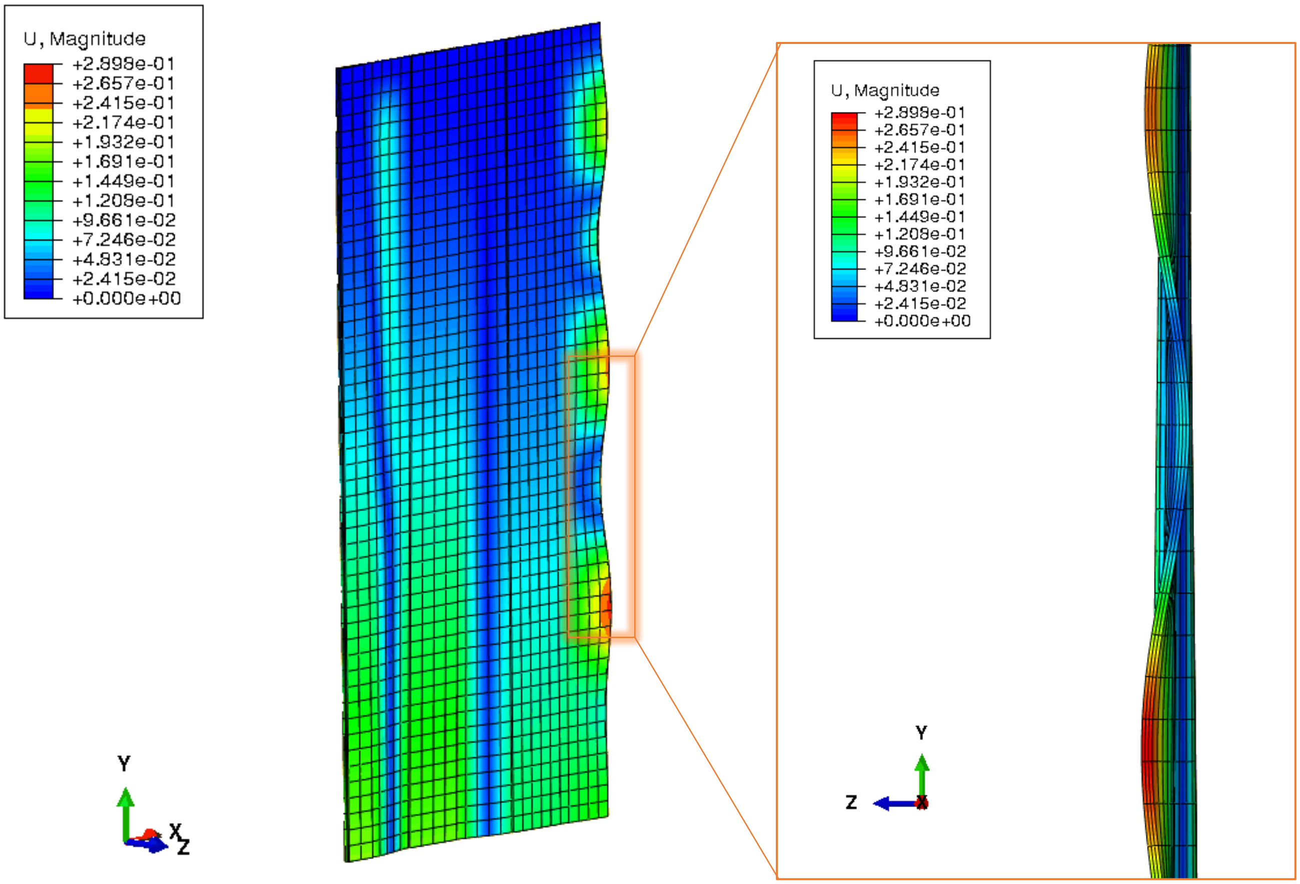


Figure 6: Results for 2 different mesh schemes (a)7400 elements (1 layer of bricks) and b) 4400 elements (3 layers of bricks)

Note that in each case the total **surface area** of the stiffeners is **constant**. According to [1] capability of the actuator to convert applied voltage to elastic potential is improved as the number of distributed stiffeners increases. I was able to reproduce this result with the first mesh scheme and partially, (for voltages<~850V) for the second mesh scheme.

4.5 Instability

For a specific combination of thickness and high enough C10 value for the stiffeners, the actuator does not bend (even for higher voltage Φ =1 kV). Instead, the free surface of the elastomer is wrinkled, as in the following case (5 stiffeners,$C_{10} stiffener = 10^4$,$L_3 = 0.05\ mm$).



REFERENCES

[1] Lai, W., Bastawros, A. F., & Hong, W. (2012). Out-of-plane motion of a planar dielectric elastomer actuator with distributed stiffeners. *Electroactive Polymer Actuators and Devices (EAPAD) 2012*, *8340*, 834011. https://doi.org/10.1117/12.917494

[2] Henann, D. L., Chester, S. A., & Bertoldi, K. (2013). Modeling of dielectric elastomers: Design of actuators and energy harvesting devices. *Journal of the Mechanics and Physics of Solids*, *61*(10), 2047–2066. https://doi.org/10.1016/j.jmps.2013.05.003