Indian Institute of Technology Gandhinagar

Mechanics of Solids
ES 221

Course Project Final Report

Binary Stiffness Mechanism

Group Number: **C1**
Group Name: **Compliant Stiffeners**

20110131 Kush Patel
20110132 Prey Patel
20110133 Shubham Patel
20110161 Rajesh Kumar
20110137 Pearl Khare
20110157 Rahul Raj

April 22, 2022

Abstract

We encounter two completely different types of building blocks that have binary stiffness for mechanical digital machines. The model is a fully compliant mechanism that has rectilinear kinematics. The new V-shaped structure is for negative stiffness which is the uniqueness of the model. By using this, it can achieve two extreme states of stiffness by static balancing and buckling. The binary mechanical switch allows the buckling effect to change the stiffness state and gives access to toggle between nearly equal to zero stiffness and high stiffness. One state has a higher stiffness which resists deformation (or motion) for a high amount of force. The other state has very low stiffness (stiffness reduction of more than 95%). This state should allow a motion for a low amount of force.

In the practical world, miniaturization is needed in all of the mechanisms. It enhances efficiency, and miniaturization in smaller electronic devices enables higher frequency and clock rates. Also, micro-manufactured components are the basic root need for any mechanical mechanism. It could be helpful to increase the accuracy and speed of mechanisms. Generally, to use multiple stiffnesses in the real world, we have to combine multiple mechanisms in a single device to execute our purpose. Instead of using these variable stiffness mechanisms, binary stiffness compliant mechanisms can be used.

Keywords

- Digital Mechanism
- Zero Stiffness
- Static Balancing
- Miniaturization

CONTENTS

1 Introduction

The goal of this project is to design a binary stiffness compliant mechanism that can be used to create more complex mechanisms with the use of a simple machine. The system will be able to balance and sense the level of stiffness in order to adjust its own stiffness accordingly. In order for it to work, the system will need to be able to measure and detect two different levels of stiffness: zero stiffness and maximum stiffness. The first level, zero stiffness, is when the system undergoes the effect of a switch (i.e. when it is being toggled). Maximum stiffness is when the switch is off (i.e. when it is not being toggled). In the real world, digital machines require miniaturization and easily micro-manufactured components. The mechanism should be:

- The two states should be generated by using mechanical logic.
- The mechanism should be made out of only a single material.
- The mechanism should not contain joints or pinned connections. In this way, it is easy to make this on a small scale.
- The mechanism should be planer and monolithic so that it can be miniaturized and also easily micro-manufactured.

The mechanism consists of three components:-

- **Compliant bi-stable switch:** Can be triggered to achieve stability in two different resting positions
- **Two angled blade flexures:** Designed to buckle and curve outward when the switch is pressed inward.
- **Three parallel blade flexures:** These swiftly constrain the shuttle and thus restrict it from moving in any direction except along the direction perpendicular to their flat faces when the bistable switch is in its initial undeformed configuration.

The angled blade flexors are straight and thus similar to a truss, swiftly constraining the shuttle so it cannot move along the direction permitted by the parallel blade flexures. Angled blade flexors buckle(bend) when the bistable switch is pushed inward. Thus, they lose their constraint capabilities so that the shuttle can freely move with the translation in the desired direction. Moreover, the pre-stressed angled blade flexors exhibit negative stiffness in their curved configuration. The negative stiffness cancels out the positive stiffness exhibited by the parallel blade flexors, which results in a mechanism that achieves a near-zero translational stiffness.

2 Model Development

2.1 Development of Experimental Model

First task was to get the 3D CAD model of the desired structure. After that, we used 3D printing technology to fabricate our desired model. The entire model is not just one part. The whole model is divided into various parts like the front plate, middle mechanism, and backend plate. Different parts were 3D printed and then we assembled them together to form the entire structure. It took 12 hours to build the first model. We then started trail experiments on it. Due to constraints like small 3D printer size and tolerance of 3D printers, we had to make structures accordingly. So because of the small size of our model, it was very delicate.

For experimental purposes, we need two parts separately along with the full model. One is parallel flexure and the other is angled flexure. So, we have edited the 3D CAD model in another software, separated it from the original compliant model and then made another CAD model for them as well. Then, we fabricated them separately. We performed some experiments but while performing them, our structure broke. Due to its small size the strength was very low. We then had to make one more structure. But now due to lack of PLA material in Maker Bhavan we had to use ABS 3D printing material. After the structure was printed, we noticed with ABS material that it was not perfectly good for the operation of the binary switch. In ABS material, the switch faced resistance to buckle due to the properties of material and tolerance of 3D printing technology.

One of the major problems due to material property is that the binary switch does not buckle perfectly and due to this, our reading also has little errors. We have encountered those errors later on in our analysis. This is how our model was developed.

2.2 Development of Numerical/Analytical Model

To build the Numerical/Analytical model, we have used ANSYS 2019 R1 and Fusion 360 software. Whatever we want to analyze with the model that facility we could easily get for this software. After we got the CAD model, we imported that full model in ANSYS but according to our procedure, we needed one type of dynamic model because while doing simulation, we needed one of the parts of our model to be rigid and fixed and another part should be movable. So, we could not do this by importing the whole model. Then, we decided to divide our model into some parts in other software like Autodesk Inventor Professional, Fusion 360, etc. We separated our model in such a way that all rigid parts are considered as one portion and the rest of the movable part is the other one. Then, we assembled them to build the modified version of our model that can allow us to do simulations in ANSYS and Fusion software.

There was another issue which is the requirement to develop the two pieces from the whole mechanism. One is parallel flexure and the other is angled flexure. We also needed separated simulations of these two pieces for analyzing force vs displacement phenomena. So, to fulfill this requirement, we have separated these two parts by editing in the main model in another software. After doing this, these pieces were imported into the software.

2.3 Schematics of the Model

Two different configurations of the structure

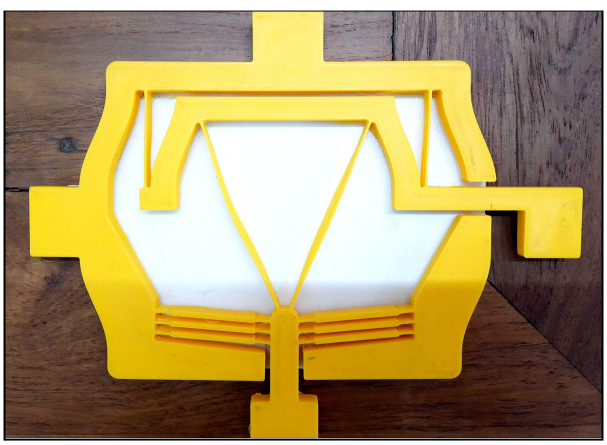
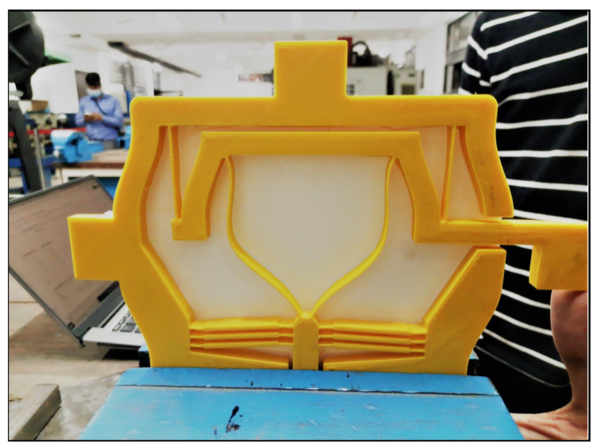
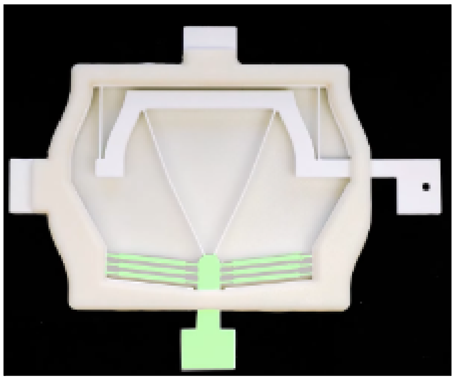
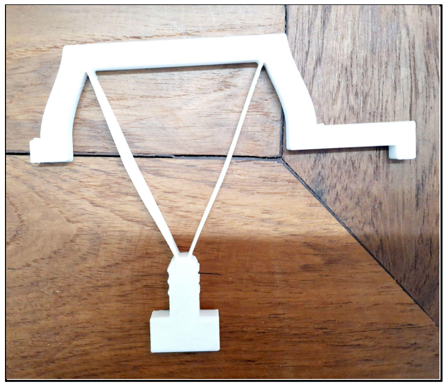
	
Position when the switch is closed.	Position when the switch is open.

Image Source

The three main components of the structure



Bistable Switch



Angled Flexures

Parallel Flexures

Image Source

From the simulations and software perspective, there were various schematics encountered. To get the simulated observation from the software, we need to give some inputs some data related to the model dimensions, types, material properties, etc. We took references from the internet to decide on this quantity.

- ABS Plastic Material
  - Elastic modulus : 2.39E+09 Pa
  - Density : 1.06E-06 kg / mm^3
  - Poisson's Ratio : 0.399
  - Tensile strength : 4.14E+ 07 Pa
  - Yield Strength : 40 MPa
  - Thermal Conductivity : 1.6E-04 W / (mm C)
  - Thermal Expansion Coefficient : 8.57E-05 / C
  - Tensile Ultimate Strength : 4.13E+07 Pa

- Elements in Parallel Flexure Design:
  - Body | Parallel Flexures 1 and 2 | Handle

- Elements in Angular Flexure Design
  - Handle | Angular Flexures (x2) | Switch

3 Experimental Results

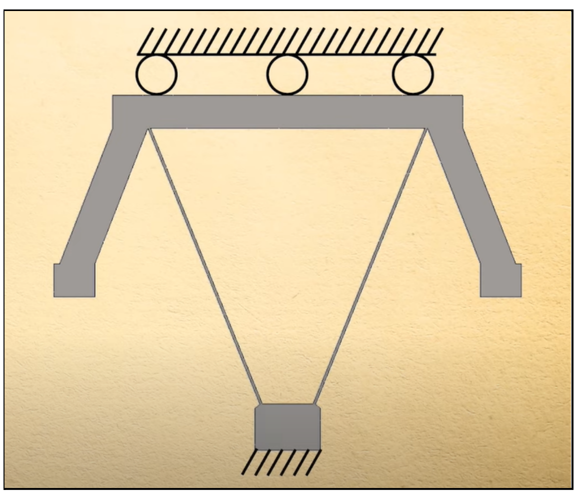
3.1 Experimental Setup

In the experiments, we had to find the deformations for some applied force. We fixed the structure with the use of a bench vise. Force was applied through the spring balance to measure the value of force. Measure scale was used to measure the displacement of the horizontal beam from the original position.

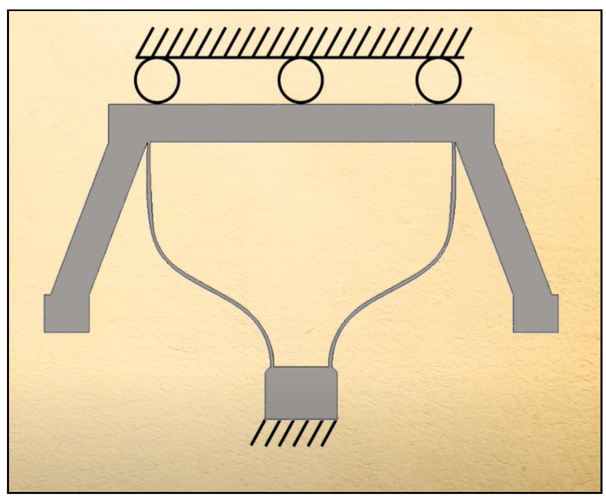
We had to take readings for five situations as follows,

1. For parallel flexures
2. For angled flexures with the bistable switch in on position
3. For angled flexures with the bistable switch in the off position
4. For compliant mechanism with the bistable switch in on position
5. For compliant mechanism with the bistable switch in the off position

For situations of parallel flexures and combined mechanism with structure fixed on a bench vise. The structure was supported at its base. But in the situation of angled flexures, if we fix only the base and apply force then the force becomes momentary and we cannot get the readings of deformations. So we had to also set roller supports on the top part of the structure.



Angled flexure with bistable switch on



Angled flexure with bistable switch off

3.2 Key Results and Findings

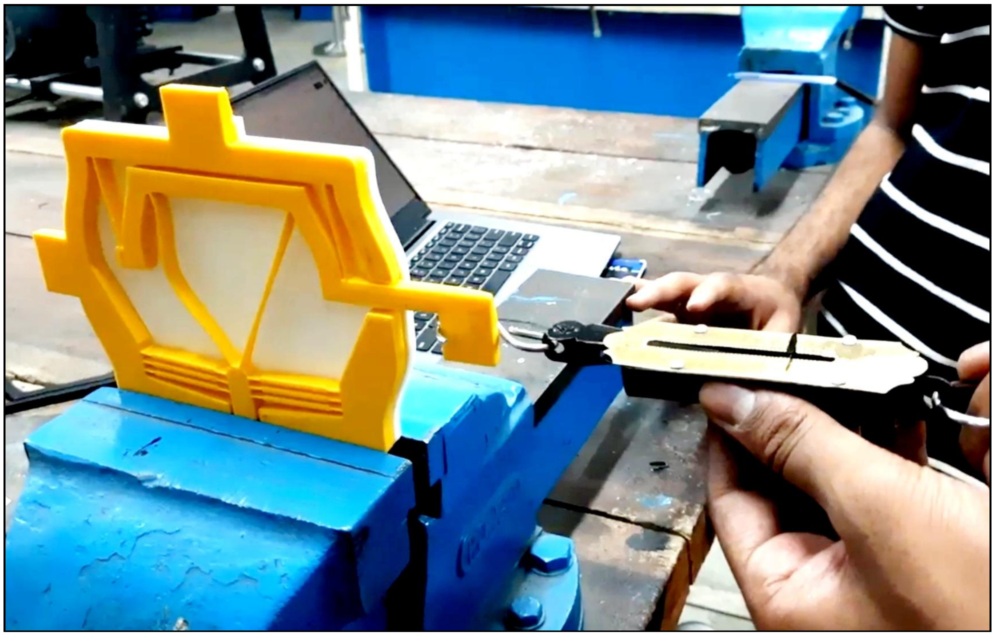
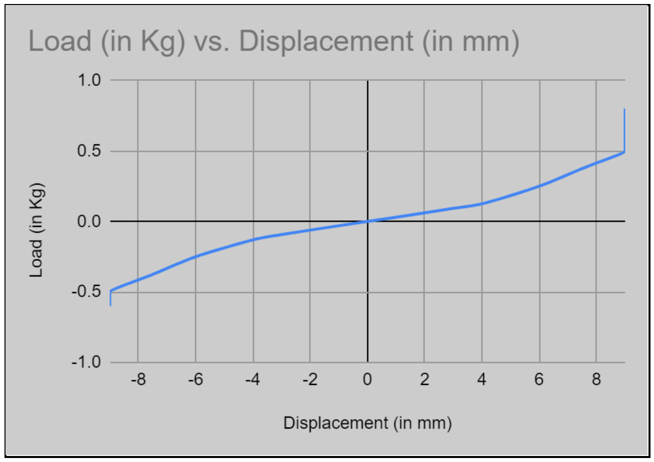


Figure: Experimental analysis

1. For parallel flexures

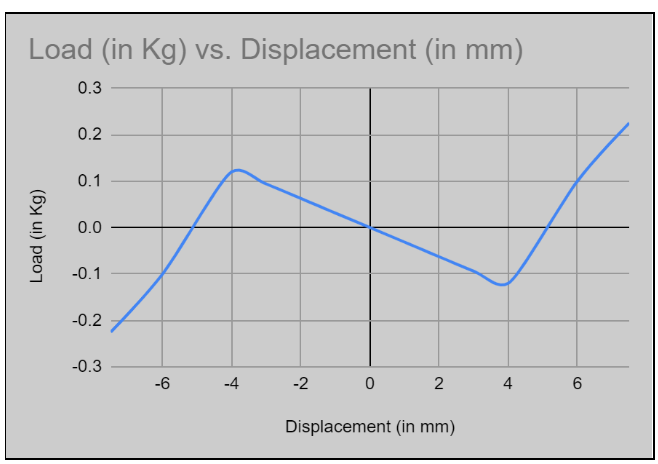
Displacement (in mm)	Load (in Kg)
-9	-0.6
-9	-0.5
-7.5	-0.375
-6	-0.25
-3.9	-0.125
-3	-0.093
-1	-0.03
1	0.03
3	0.093
4	0.125
6	0.25
7.5	0.375
9	0.5
9	0.6
9	0.7
9	0.8



Here, we can see that our graph has linearity which is expected because parallel flexure gives us positive stiffness and here the slope of the curve is nearly equal to a constant which is nothing but the stiffness.

2. For angled flexures with the bistable switch in on position

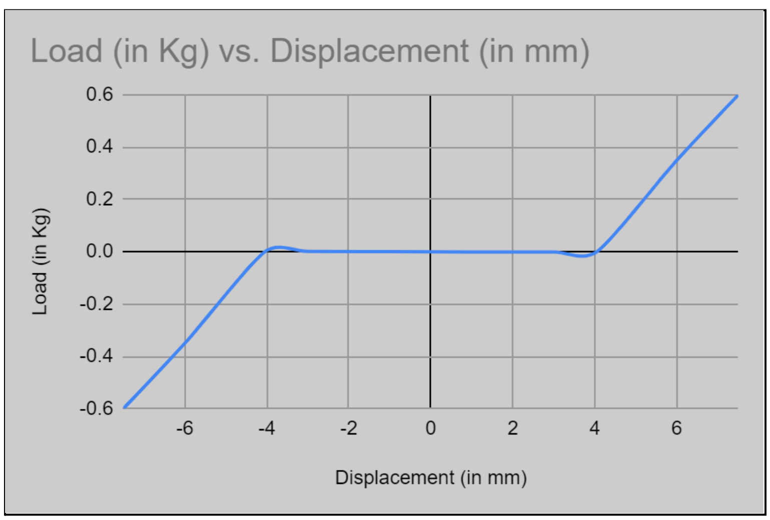
Displacement (in mm)	Load (in Kg)
-7.5	-0.225
-6	-0.1
-4	0.12
-3	0.09375
-1	0.03125
1	-0.03125
3	-0.09375
4	-0.12
6	0.1
7.5	0.225



Here, we can observe that for a middle region(-4 mm to 4 mm) the graph becomes negative. It means the slope of the graph is negative which is nothing but the negative stiffness while the binary switch is toggled.

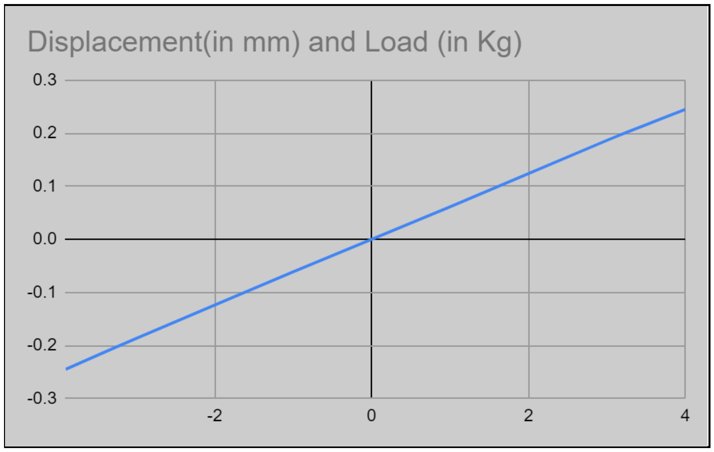
3. For Compliant Mechanism

Displacement (in mm)	Load (in Kg)
-7.5	-0.6
-6	-0.35
-4	0.005
-3	0.001
-1	0.0009
1	-0.0009
3	-0.001
4	-0.005
6	0.35
7.5	0.6



- Maximum load(for Parallel Flexure) = 0.5 kg & Stiffness = 0.32 N/m
- Maximum load(for Angled Flexure) = 0.12 kg & Stiffness = -0.31 N/m
- Load Range (for Compliant Mechanism) = 0 - 0.005 kg & Stiffness = 0.01 N/m

4. Compliant mechanism with bistable switch in off position



Now for the full mechanism when the bistable switch is off we get a linear graph for the load vs deformation. In this normal situation, we get the slope of 0.6125. Which shows that the stiffness of the mechanism when the switch is off is 0.6125 N/m.

While analyzing experimental data points, some values could not be calculated due to limitations of the scale of the device. That is why we used an interpolation method to determine the observation at small scales.

4 Simulated Results

4.1 Analysis Procedure

We have used Autodesk Inventor and Autodesk Fusion 360 to obtain the analytical data of the binary stiffness mechanism.

First we obtained the configuration of our mechanism in the OFF condition, over here we apply the force (F=4N) in the +x direction and obtain the corresponding value of displacement, which comes out to be very less. (as the angular flexures and the parallel flexures tend to keep it stationery)

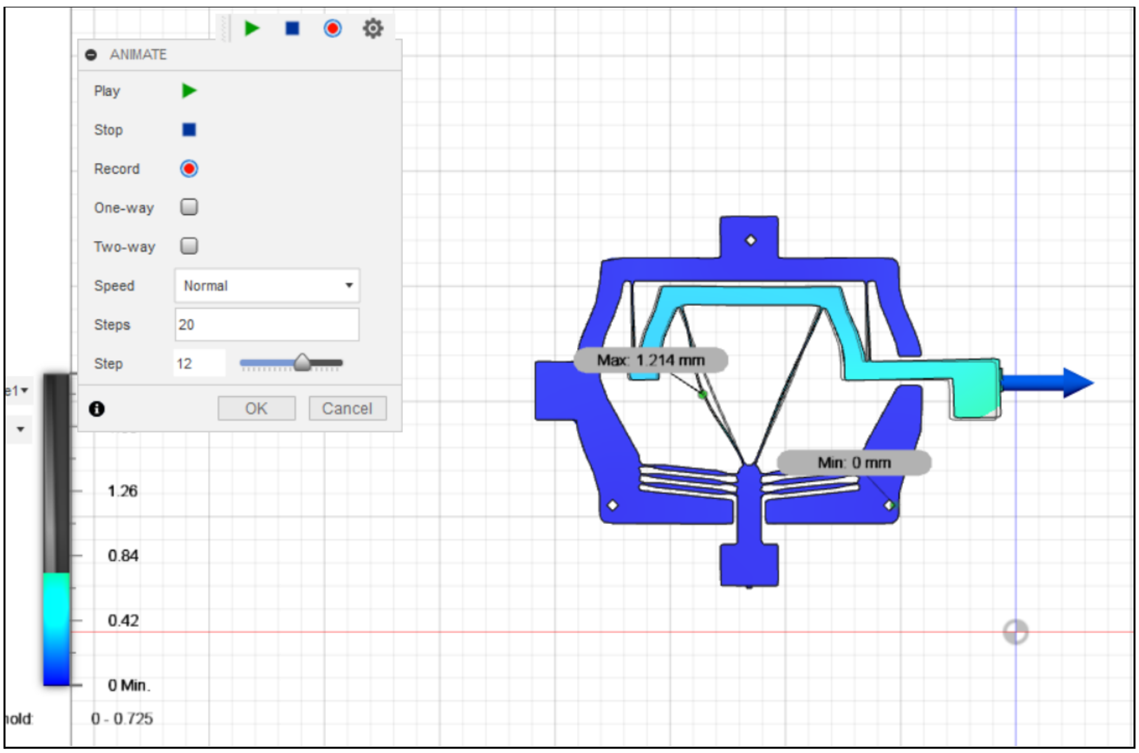


Fig1: Force = +4N ; Displacement of handle = +0.6mm (both in same direction, +stiffness)

After that we make the configuration in the ON state, by displacing the switch above (5mm). And we applied a force of -5.8N perpendicular to the area of the handle, and obtained the displacement of -7.5mm. For obtaining the displacement we have used the Nonlinear Static Stress "Study" of the Fusion 360, and we have used the transient function to obtain the displacement caused by different forces at different times.

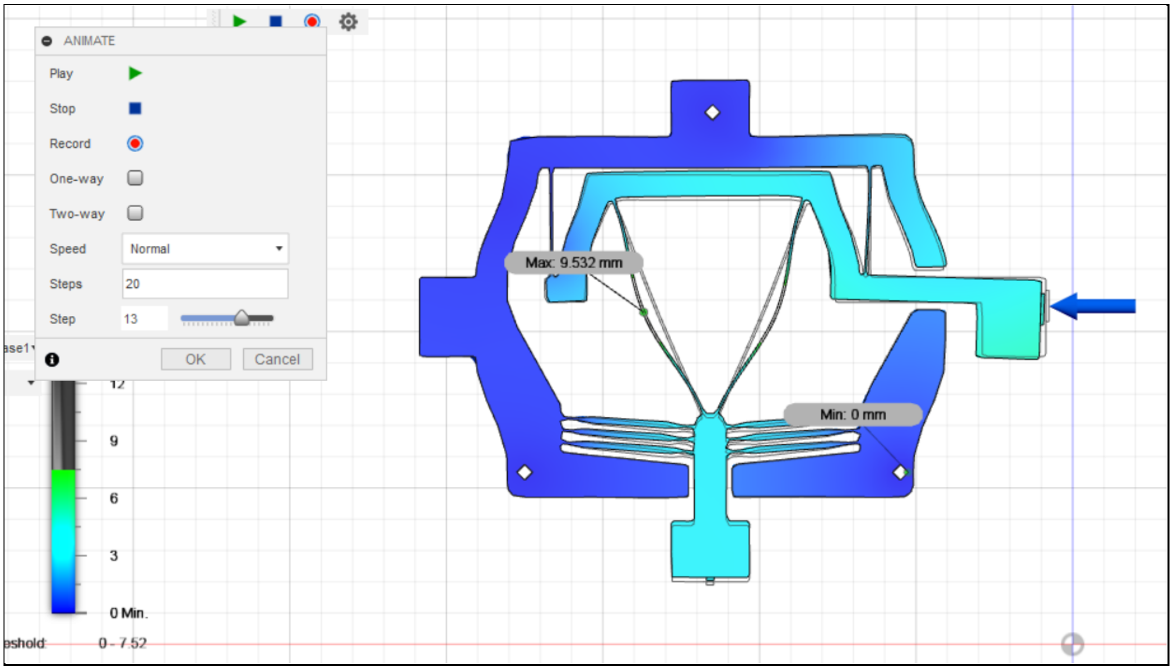
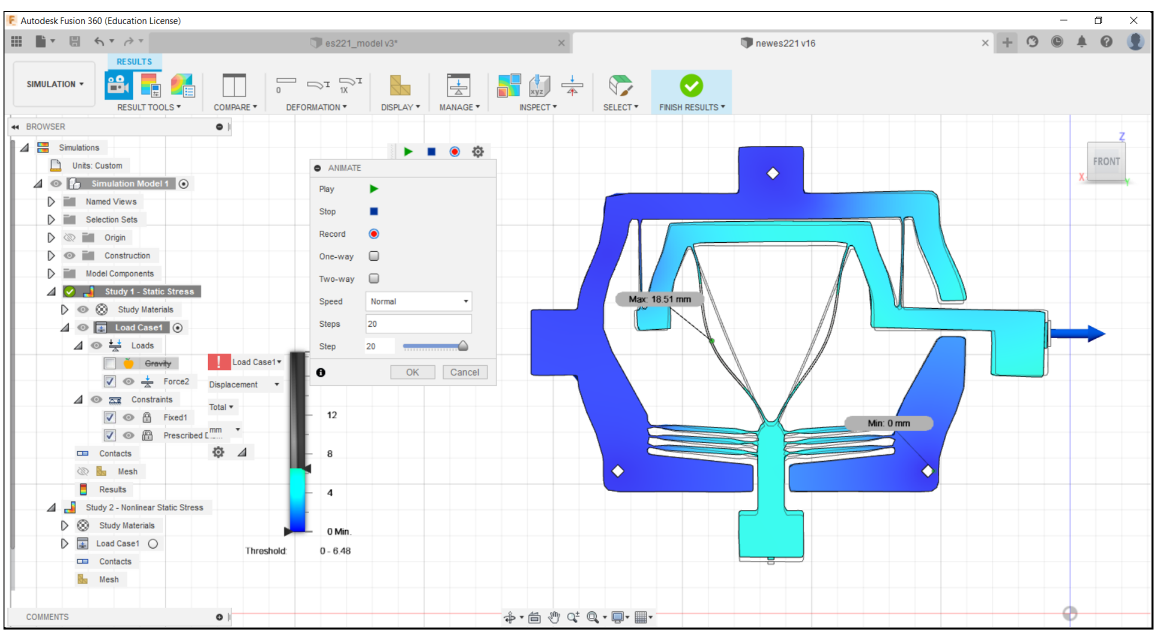


Fig1: Force = -5.8N ; Displacement of handle = -7.5mm ; ON condition ; positive stiffness

We find the special case of the mechanism that is "negative stiffness". Due to the **buckling effect** being generated in the angular flexures despite a force of 0.1N being applied in the positive direction, we are getting a negative displacement of 5.8mm.



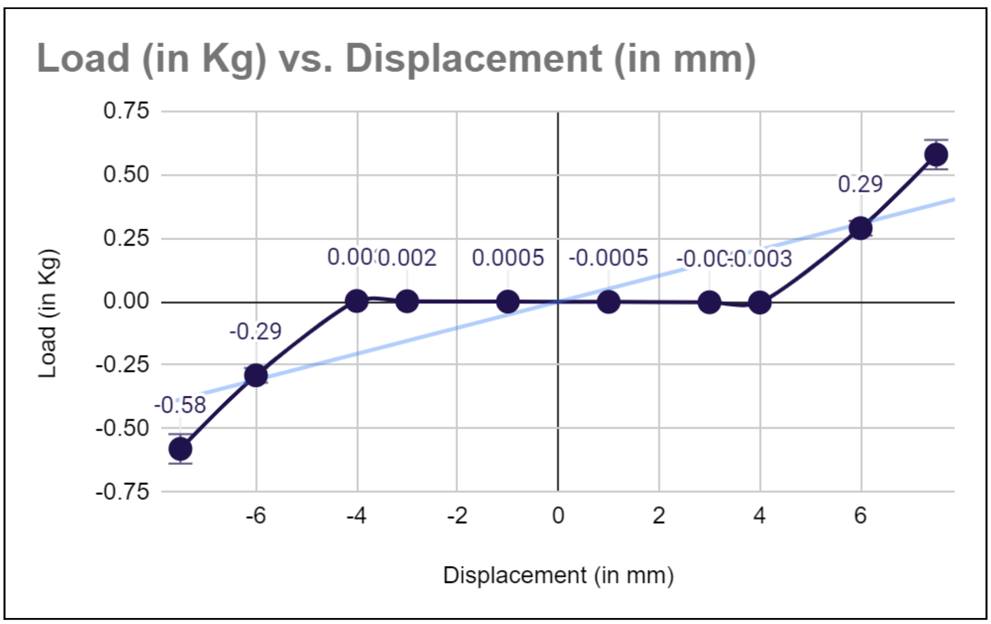
Force = +0.1N ; Displacement of handle = -5.8mm ; ON condition ; negative stiffness

4.2 Key Results and Findings

We obtain the following result analytically using the Transient Function in the Nonlinear Static Stress Study.

Displacement (in mm)	Load (in Kg)
-7.5	-0.58
-6	-0.29
-4	0.003
-3	0.002
-1	0.0005
1	-0.0005
3	-0.002
4	-0.003
6	0.29
7.5	0.58

Also, the above data is represented graphically as follows:



We see from the above graph that a region of nearly zero stiffness occurs between -4mm and +4mm displacement. This is due to combined effect of angled blade flexures (having positive stiffness in this region) and parallel blade flexures (have negative stiffness in this region)

5 Comparison and Results

There are some deviations between the results obtained from the experimental data and the analytical results via Fusion 360. This can be due to many factors, some of which are:

- Accuracy of force:
- Random error:
- Numerical error and Least count of the devices used in the experiment
- The maximum force of 7.5N yields more displacement for experimental outcome as compared to the analytical result, this may be attributed to the instability of the switch
- Interpolation has been used while plotting the graph of the experimental data, and this is one factor that can lead to variations between the results

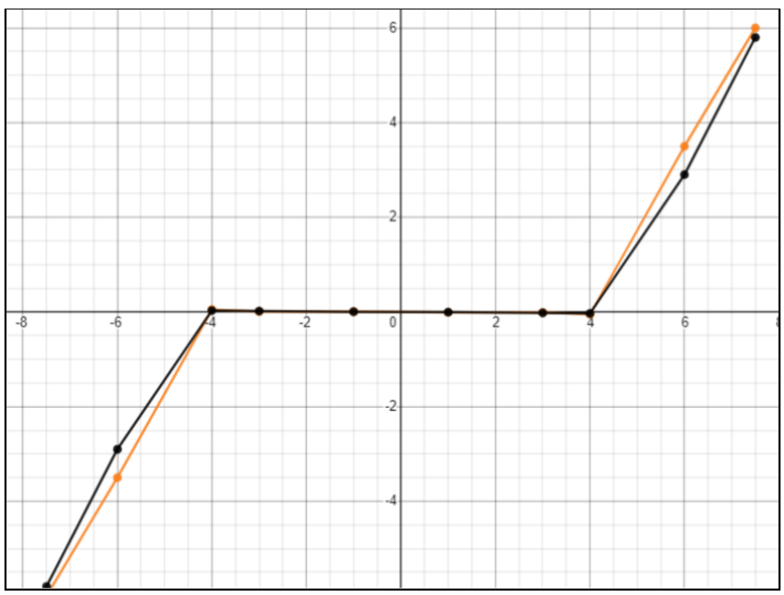


Figure: Comparison of experimental and analytical results

We can observe from the both graphs that they are overlapping to each other that means our experimental results match with analytical data. For a certain region, stiffness is nearly equal to zero. We can notice that the difference between experimental results and analytical results are very small which are quite good and as expected. Apart from that certain region, both data are mismatching. The main reason for little mismatching is uncontrolled condition and natural error. While measuring the displacement, there might be some error of 0.0001 - 0.001 mm due to tolerance of scale. While applying the force by spring balance, there is a natural tolerance present in spring because it is not perfectly elastic.

6 Summary and Conclusion

As shown in the results in the point 3.2.3 and 3.2.4 we got,
Stiffness of the compliant mechanism when the binary switch is on is 0.01 N/m.
Stiffness of the compliant mechanism when the binary switch is on is 0.6125 N/m.

Stiffness reduction:

$$stiffness\ reduction = \frac{stiffness\ when\ switch\ is\ off - stiffness\ when\ switch\ is\ on}{stiffness\ when\ switch\ is\ off}$$

$$stiffness\ reduction = \frac{0.6125-0.01}{0.6125} = 0.9837 = 98.37\%$$

As we can see above, this mechanism allows us to reduce the stiffness by a larger amount. By using such a system, we can use two states of stiffness at the same time. This phenomenon is very unique and used in the practical world. It might be very useful and give substantial results in future mechanisms.

7 Brief of other Projects

Group B7:

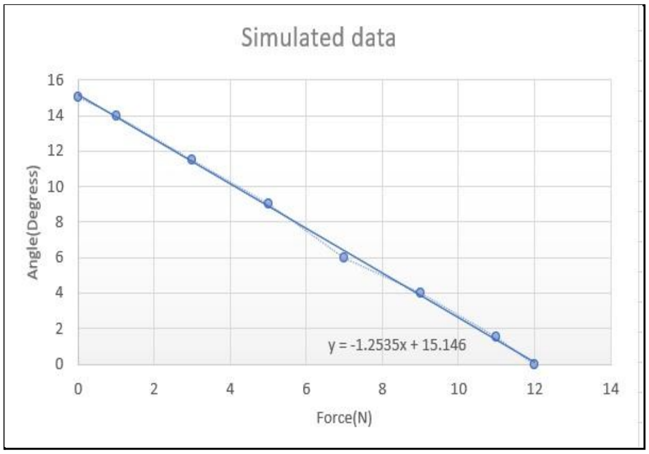
Introduction:

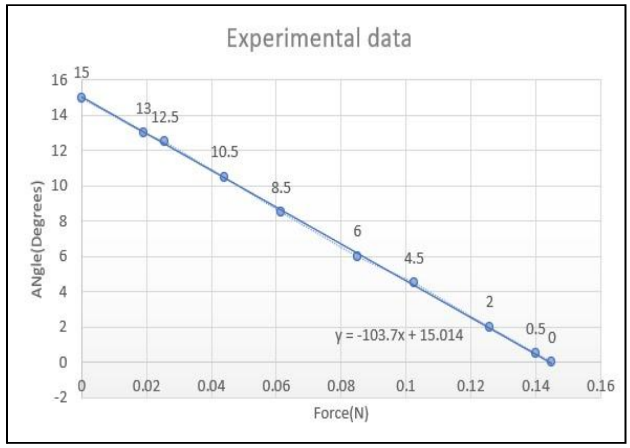
Our friends from the group B7 tried to simulate and experimented with the landing gears that are used by the SpaceX company. For this they had created a set of four landing gears and a rocket over which they gradually increased the load and measured the angle that the landing gears made with the ground.

Experimental Setup

Measuring criteria to obtain the result for their experiment is basically the angle that the landing gears make upon loading

Experimental Details:





For measuring the load they placed the setup on the weighing machine, and plotted the corresponding graph which is shown above.

Simulation Details:

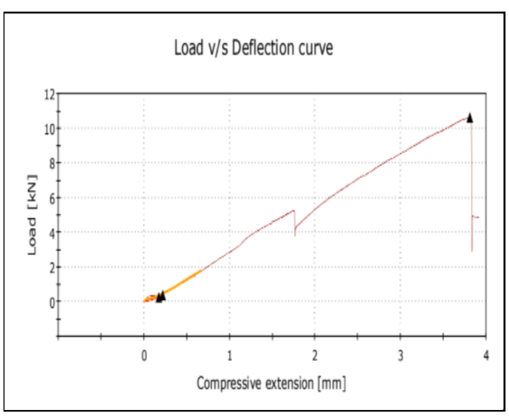
The model was considered to have failed if the landing gears almost touched the ground, and for this they had equipped the boundary condition that the tips of the landing gear were fixed in the ground. Also, they had chosen ABS plastic instead of PLA.

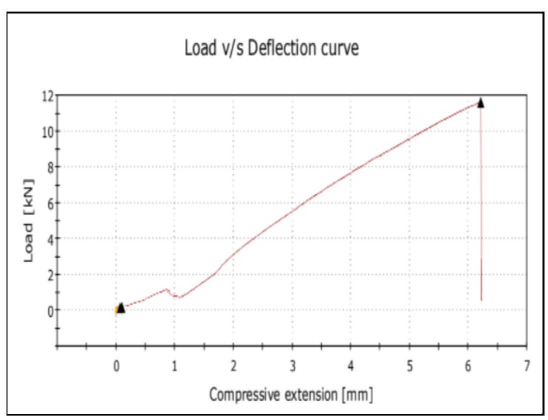
Group A5:

Introduction:

Our friends from group A5 have created a non prismatic beam that effectively uses the material, that is more material is placed at places of high bending stress. For this they have used the following result, that is the equation of non-prismatic beam

$$h^2 = \left(\frac{2h_0^2}{L}\right)x$$





Experimental Setup:

They have used a jigsaw machine to obtain the wood beam, and this beam has been obtained from the equation above. Their prismatic beam failed at 10.6kN and non prismatic beam failed at 11.6kN.

ANSYS Analytical Result:

They have taken the assumption that the sudden decrement in the material at the supporting end is not causing any severe change in the analysis. Upon feeding their design in the ANSYS they found out that the non prismatic beam failed at 14.56kN.

Findings:

They had assumed the model as elastic, while doing simulation and numerical calculations but actually, most of the experiments took place in plastic regions that's why the deformation is coming slightly high in numerical calculation.

8 Contribution

Prey Patel:- Experimental Analysis, Modeling and Experimental Designing, Documentation

Kush Patel:- Project Proposal, Experimental Analysis, Modeling and Experimental Designing, Documentation, Data analysis(Graphs)

Shubham Patel:- Experimental Analysis, Modeling and Experimental Designing, Documentation

Rajesh Kumar:- Software Analysis, Documentation, Experimental Analysis

Pearl Khare:- Project Proposal, Software Analysis, Documentation, Experimental Analysis

Rahul Raj:- Documentation, Data analysis(Graphs)

9 References

[1] https://www.youtube.com/watch?v=X2tRcEME14w

[2]https://www.researchgate.net/publication/347705766_Monolithic_binary_stiffness_building_blocks_for_mechanical_digital_machines

[3]https://www.sciencedirect.com/science/article/pii/S0094114X10000042?via%3dIhub

[4]https://asmedigitalcollection.asme.org/IDETC-CIE/proceedings-abstract/IDETC-CIE2009/49040/313/342222

10 Acknowledgement

In the accomplishment of completion of our project on **'Binary Stiffness Mechanism'** we would like to convey our special gratitude to Mr. Manish Kumar, Associate Professor at IIT Gandhinagar. Your valuable guidance and suggestions helped us in various phases of the completion of the project. We will always be thankful to you in this regard.