# Multi-parameter Model for Layer Jamming Element Performance for Use in Robotic Applications

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# Multi-parameter Model for Layer Jamming Element Performance for Use in Robotic Applications

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***Abstract*—The following paper presents a multi-parameter model for layer jamming mechanisms and its' validation with the experimental data. The proposed analytical model for the layer jamming mechanism can predict the mechanical behavior and helps in improving the controllability of the desired application. Contemporary models are not experimentally validated or are overly complex for use with simple layer jamming elements. Hence, this analytical model for the layer jamming mechanism is developed to account for multiple parameters including the number of layers and layer combinations and is validated with the experimental data. In the experimental study, the tip deflection was measured for four types of layer jamming elements against a given load. Comparison of predicted data with the experimental data shows promising results. Overall results show that the R-Squared for all the combinations is more than 0.8.**

***Index Terms*—Layer jamming, Tunable stiffness, Soft robotics**

## I. Introduction

Soft materials have been used in many robotics applications due to its' inherent advantages over the conventional materials such as safety, adaptability, light weight, and easy human integration. These soft robots are performing impact on wide range of applications such as assistive devices, soft grippers, surgical robots, etc [1] [2] [3]. Soft robotics require stiffening methods with the soft actuation methods to overcome the issues of absorbing vibrations or holding higher loads. Consequently, variable stiffness actuators were proposed which can change its' stiffness. Variable stiffness actuators are made with shape memory polymers and low melting point materials which can be stiffened by stimulating it. But this method got a major drawback of slow response time [4] [5]. As another alternative solution, magneto and electrorheological materials has been proposed which can vary the stiffness by aligning the magnetic particles. However, its' bending and torsion is difficult to control [5].

To overcome such issues, jamming methods such as layer jamming, granular jamming, fiber jamming has become popular. In the jamming methods, stiffness can be changed by applying vacuum pressure. This principle has been used in many applications due to the lightweight and high response time (See Fig.1) [6]. Among these jamming methods, layer jamming mechanism has been integrated with many applications rather than the other jamming mechanisms. Compared to other jamming methods, layer jamming is less bulky, ease of fabrication and higher range of stiffness [5].

Layer jamming mechanism is driven by vacuum pressure. Layer jamming element contains a stack of layers as shown in Fig.2. When the vacuum is applied to the element, the friction between the adjacent layers is increased due to the removal of the air gap between them which lead to increase the stiffness of the element (See Fig.2(b)).

However, layer jamming mechanism has lack of analytical models which lead to major limitations in desired applications. Hence, it creates difficulties in predicting mechanics of the actuators. As a result, this limits the improving the controllability of the desired actuators and the applications. Therefore, this analytical model is developed for optimization of the layer jamming enabled soft orthotic device for hand tremor suppression. Based on this model, the optimum number layers and suitable layer materials can be selected to suppress the hand tremor while optimizing the size of the layer jamming element [1].

The authors propose a multi-parameter analytical model for layer jamming mechanism. The proposed model is designed for multi material layer combinations. This paper demonstrates

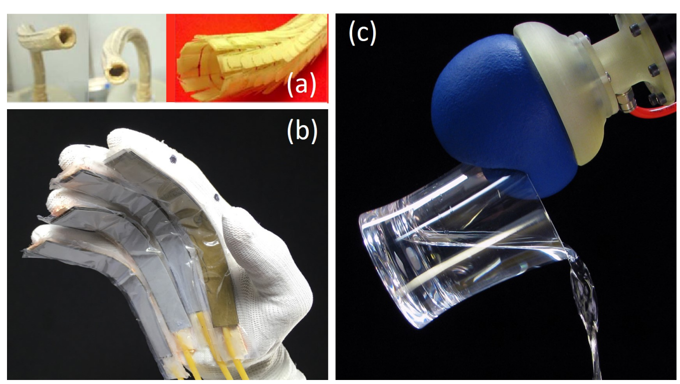


Fig. 1. Soft robotic jamming application (a) Layer jamming enabled surgical robot (b) Hand tremor suppression soft glove [1] (c) Soft granular jamming enabled gripper

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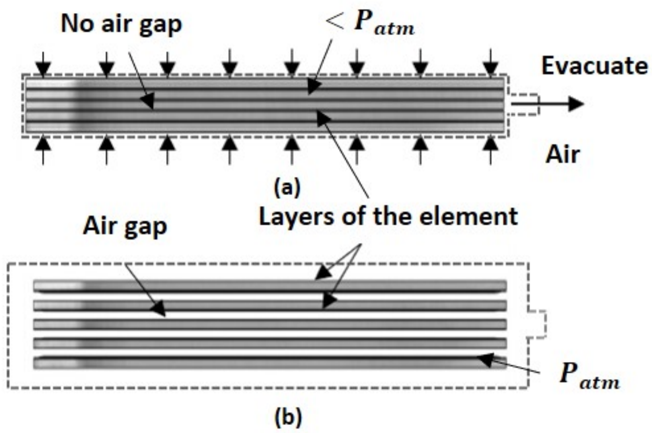


Fig. 2. Layer jamming mechanism (a) Vacuum on state (b) Vacuum off state

the development and validation of a multi-parameter model for layer jamming mechanism. In Section II, related work on analytical models of layer jamming mechanisms is presented. Section III explains the proposed analytical model for multi-layer combination. The fabrication process of the elements is explained in the Section IV. Section V describes the experimental setups and presents the results. Finally, Section VI presents the conclusions, and the future work.

## II. Related Works

Few analytical models were developed for layer jamming mechanism. Narang et al. has proposed an analytical model for cantilevered layer jamming element based on Euler beam theory [7]. Moreover, they assumed that layer slipping initiates from the fixed end and propagates towards the free end of the cantilevered element when increasing the load. However, they validated the mechanical response of the model using a Finite Element Analysis and never validated with the experimental results.

Similarly, Acevedo et al. has proposed another analytical model for the layer jamming material following the same beam theory [8]. They deeply analyzed and tested the layer slipping which occurs between adjacent layers using the Digital Image Correlation (DIC) displacement measurements. The experimental results contradict with the previous assumption of initiation of the layer slipping from the fixed end. But the results conclude that layer slipping propagates towards the free end when increasing the load.

Previously, few analytical models were proposed for the layered media to predict the mechanical response [9]. Furthermore, numerical simulations were stepped forward with Cohesive Zone Models for these layered media [10] [11]. However, comparing all these models, these models are only complaint with layered media and more complex for layer jamming mechanism which can be easily controlled by varying the pressure and the interfacial properties.

## III. Analytical Model

Layer jamming mechanism works with the vacuum pressure and it will remove the air gap between adjacent layers. This increases the frictional force acting on layer surfaces and adjacent layers resist to move relatively. Hence, it creates a resistance on bending the element.

This analytical has been proposed to show the mechanical behavior of the layer jamming element at the vacuumed state and it is based on the Euler beam theory. In the vacuumed state, layer jamming element behaves in 3 regions: Pre slip region, Transition region, Full slip region. Initiation of these regions correlates with the load applying on the layer jamming element.

The pre slip region can be identified during the minor loading on the layer jamming element. In this region, relative motion between two adjacent layers can not be seen. When increasing the load, the layers start to slip if the longitudinal shear stresses on the layer surface exceeds the maximum shear stress at that point. Hence, the transition region begins with initiation of the layer slipping at certain points in the layer jamming element. With increasing loads, the full slip region will begin when the layer slipping can be identified at every point in the layer interface.

The initiation point of the layer slipping has not identified yet. Hence, the transition region and the full slip region has become difficult to verify with the experimental data. For this study, the pre slip region has been deeply analyzed for multi-parameter layer jamming element and will be validated with the experimental data under steady pressure range, ranging from 10 kPa (abs.) to 50 kPa (abs.). This analytical model was developed for the multi-parameters: multiple layer and multiple material combinations. Based on the validation experiment set up, analytical model was derived for the self-weight of the element and the load applied (See Fig.3). The transverse deflection of the cantilevered layer jamming element is given by Eq.1 for the pre slip region. In this equation, E, I, F, w and L denote the Young's modulus, second moment of inertia, applied load, self weight and longitudinal length respectively.

$$Transverse\ Deflection\ (x) = \frac{L^4}{16\,E\,I}\,(F + w) \qquad (1)$$

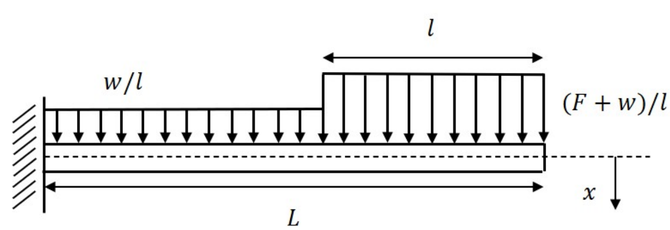


Fig. 3. Free body diagram of the cantilevered layer jamming element

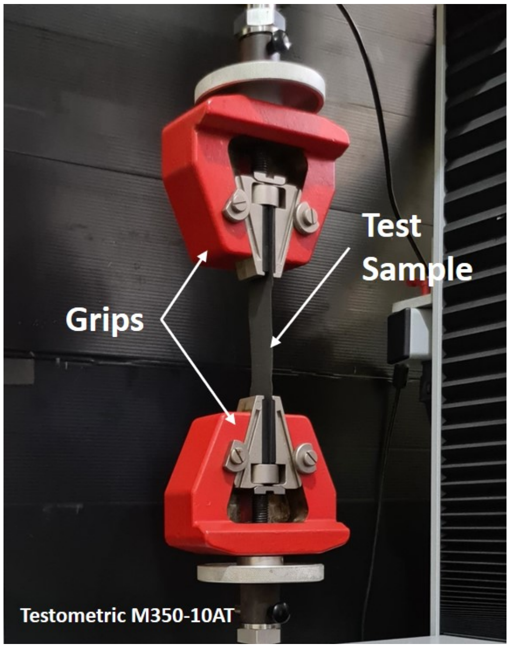


Fig. 4. Tensile testing of layer jamming materials

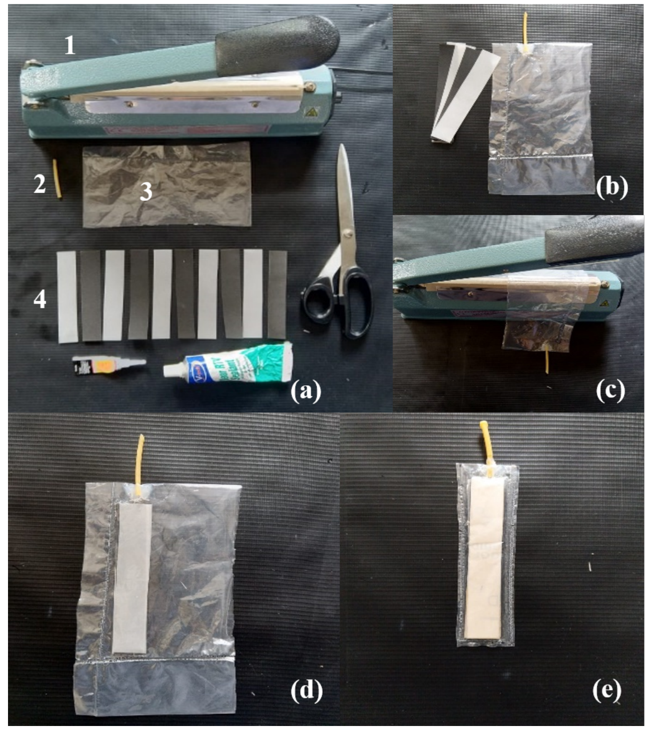


Fig. 5. Layer jamming element fabrication step by step: (a) Components used: 1). Thermal impulse sealer, 2). Latex tubing, 3). Polythene, 4). Stack of layers; (b) Latex tubing attached to polythene with the stack of layers; (c) Sealing the polythene covering; (d) Partially sealed polythene covering with stack of layers; (e) Finished layer jamming element

## IV. Experimental Method

### A. Fabrication of layer jamming element

As mentioned earlier, the analytical model was developed multi-layer and multi material combinations. In case of that, 4 materials were used for the layers as shown in Table I. The Young's Modulus of each material was obtained by conducting the tensile testing for each material in the Testometric M350-10AT tensile testing machine (See Fig.4). Using these materials, 4-layer jamming element types were fabricated by varying the combinations of the layer stack (See Table.II). All the layers were cut with the dimensions of 115 mm x 20 mm (See Fig.5 (a)). Also, each element contains 10-layer stack and sealed them within a polyethylene film (thickness – 0.05 mm). Thermal impulse sealer was used to seal the element as shown in Fig.5 (b)-(d). Latex tubing was attached to element by creating a small hole and fixing it with the super-glue and silicon sealant.

### B. Experimental setup

Experimental setup was designed to measure the tip deflection of the layer jamming elements by varying the loads as shown in Fig.6. A wooden die was used to fold the layer jamming elements by maintaining the overhanging length and

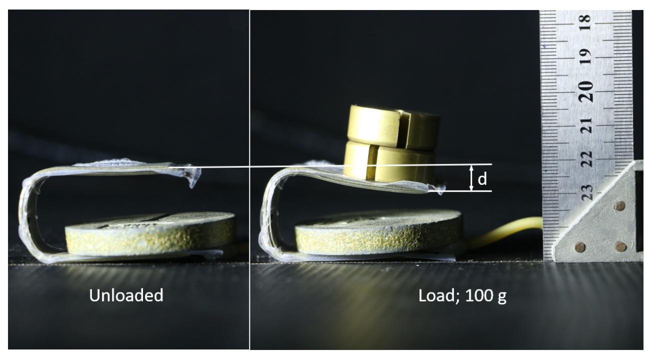


Fig. 6. Experimental set up to evaluate the deflection of the layer jamming element against the load [1]

TABLE I
LAYER MATERIAL PROPERTIES

| Layer material | Young's Modulus (GPa) |
|---|---|
| Sandpaper (120 grade) | 0.435 |
| Sandpaper (320 grade) | 0.484 |
| Tracing Paper | 0.273 |
| Plastic film | 1.325 |

TABLE II
COMBINATIONS OF LAYER JAMMING ELEMENTS TESTED

| Combination | Description |
|---|---|
| A | Sandpapers (320 grade)×10<br>abrasive side facing each other |
| B | Sandpapers (120 grade)×10<br>abrasive side opposing each other |
| C | Tracing papers (0.14mm thickness)×5<br>+ Plastic films (0.15mm thickness)×5<br>(alternative) |
| D | Tracing papers (0.14mm thickness)×10 |

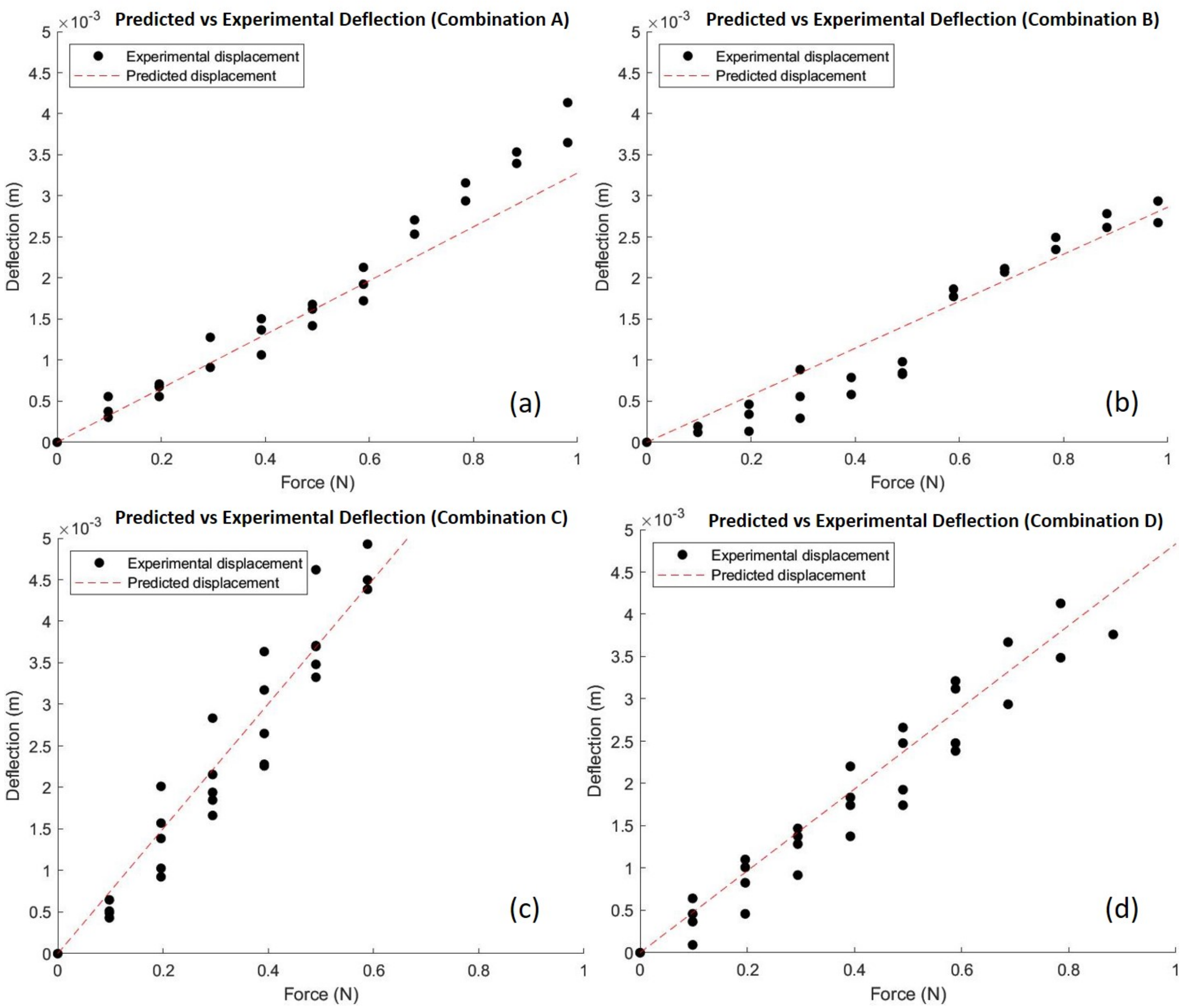


Fig. 7. Comparison of model predicted data for deflection and experimental deflection (a) Combination A (b) Combination B (c) Combination C (d) Combination D

height of the folded element as 50 mm and 22 mm respectively for all the elements. Standard weights were placed on each element when it was in vacuumed state as shown in Fig.6. This experiment was done by varying the loads with 10 g intervals, ranging from 0 g – 150 g. Using a digital camera (Canon EOS 600D), photographs of all folded elements after placing the load were taken to measure deflection (d) of each loading. ImageJ software (Ver. 1.52) was used to measure the transverse deflection at the tip of the element. Similarly, same process was repeated for 5 vacuum pressure, ranging from 10 kPa (abs.) to 50 kPa (abs.) for each layer jamming element type. A large vacuum chamber and a vacuum pump was used to supply and maintain the vacuum pressure consistently.

## V. RESULTS

The proposed analytical model can predict the deflection of the layer jamming element with the loading. Fig.7 (a) - (d) shows the comparison between predicted tip deflection values through the analytical model with the experimental tip deflection for combination A, B, C, and D respectively. To compare the model data with the experimental data, Root Mean Square Error (RMSE) and the R-Squared was calculated for each element. Table III shows the RMSE value and R-Squared value obtained for each layer jamming element type. The stiffness of the each combination was obtained by using the gradient of the model predicted deflection (See Table III).

TABLE III
RMSE AND R-SQUARED OF ALL TESTED COMBINATIONS

| Combination type | RMSE (mm) | R-Squared | Stiffness (N/m) |
|---|---|---|---|
| A | 0.547 | 0.922 | 303.03 |
| B | 0.445 | 0.857 | 344.82 |
| C | 1.25 | 0.801 | 133.33 |
| D | 0.301 | 0.945 | 208.33 |

## VI. Conclusion

The authors presented a development of an analytical model for multi-layer and multi-material layer jamming mechanism and its' validation with the experimental data under steady pressure range, ranging from 10 kPa (abs.) to 50 kPa (abs.). The deflection of the layer jamming element was measured against the load and compared with the predicted data through the model. For this experiment, multi-layer and multi-material jamming elements were fabricated. The results show strong correlations between the predicted data and experimental data of each element. Moreover, R-Squared of 0.922, 0.857, 0.801, and 0.945 can be seen in data sets of layer jamming combinations A (Sandpapers (320 grade) × 10 abrasive side facing each other), B (Sandpapers (120 grade) × 10 abrasive side facing each other), C (Tracing papers (0.14 mm thickness) × 5 + Plastic films (0.15 mm thickness) × 5 (alternative)) and D (Tracing papers (0.14 mm thickness) × 10) respectively. Furthermore, the Root Mean Square Error is 0.547 mm, 0.445 mm, 1.25 mm, and 0.301 mm for combinations A, B, C, and D respectively. The overall results validated this multi-parameter model. This analytical model is developed for optimization of the layer jamming enabled soft orthotic device for hand tremor suppression.

As future work, this multi-parameter analytical model will be validated for all three regions of pre slip, transition, and full slip. Furthermore, layer slipping will be analyzed by identifying the interfacial layer characteristics. This will lead to design layer jamming elements specifically for the application.

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