Chapter 7
Design, Fabrication and Characterization of Layered Jamming Bistable Composite Structures for Assistive Robotics

Hugh A. Bruck, Supriya Shastry, and Oliver J. Myers

Abstract There is growing interest in developing assistive robotic structures, such as exoskeletons, for a variety of potential applications, such as rehabilitation robotics. Advanced structural and material concepts, such as layered jamming and bistable composites, are providing new opportunities to engineer assistive robotic structures that can employ mechanics principles that allow for new approaches to controlling these structures to achieve better outcomes than conventional robotic platforms employing traditional machine components (e.g., servo motors, linear actuators, etc.). New manufacturing and design processes employing 3d printing, digital twins, and Artificial Intelligence are also providing new opportunities to rapidly realize new systems that employ advanced structures and materials. We have recently investigated the fabrication, design, and characterization of a model assistive robotic structures employing advanced structural and material concepts to achieve novel control of the robot's mechanical behavior relative to the plant's behavior.

Keywords Bistable composites · Layered jamming · Hysteresis · Morphing · Vacuum pressure

Introduction

There is increasing interest in creating lightweight morphing structures that can be deployed in a variety of applications, including soft robotics, vibration control, medical devices, material handling, and aerospace. One approach we have recently pursued for realizing morphing structures, primarily for robotic platforms, is layered jamming [1–4]. This technique involves stacking multiple material layers and using differential pressure to modulate the friction between them, thereby enabling real-time control over the mechanical properties of a structure. There have been a variety of techniques developed for controlling properties of materials in situ, including electro-programming, thermal actuation, and magnetic fields. The ability to vary properties in situ has become crucial in the field of soft robotics, where both flexibility and stiffness are required in applications such as grippers, exoskeletons, and aerospace [5, 6]. However, layered jamming offers several advantages over alternative approaches, including variable stiffness through rapid transitions between flexible and rigid states, minimal volumetric change, simple fabrication, and a high strength-to-weight ratio. These properties make it particularly well-suited for applications requiring tunable stiffness.

In parallel, recent advancements in bistable structures, such as those composed of asymmetric layups of laaminated carbon fiber composites, have enabled the development of structures capable of maintaining two distinct equilibrium states for applications, such as robotics, including bistable structures with a tunable response and Kirigami bistable composites [7, 8]. Bistable structures have been widely studied for their ability to achieve rapid energy release and force amplification. For carbon fiber composites, the bistability arises from an orthogonal and asymmetric curing configuration of unidirectional carbon fiber layers, which induces an internal bending moment due to the residual stress distribution that can last for millions of cycles [9]. However, traditional bistable composites typically operate between two fixed states, limiting their adaptability. Recent work has shown that intermediate states with tunable energy barriers can significantly expand their

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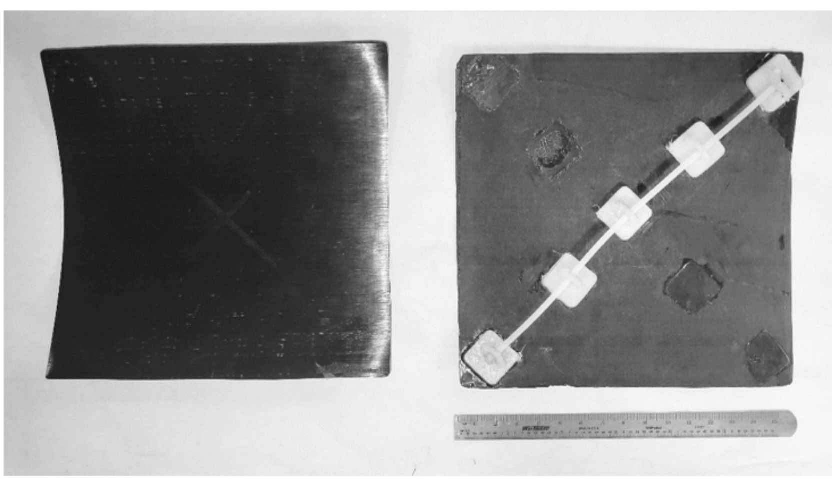
functionality, enabling more precise control over deformation and response. Additionally, bistable structures are inherently energy efficient, as they rely on stored elastic energy rather than continuous actuation, making them promising candidates for applications requiring low-power operation. While actuation methods such as magnetic fields, thermal activation, and electroactive materials have been explored, vacuum-based control provides a highly efficient and reversible approach for modulating mechanical properties in real time. Despite these advantages, relatively few studies have explored how integrating bistability with passive material systems—such as layered jamming—could enable reconfigurable structures with tunable mechanical properties for applications, such as exoskeletons for assistive robotics.

To address this gap, we investigate the integration of layered jamming with bistable laminated composites and examine how the mechanical interaction between the two layers is influenced by vacuum pressure when they are jammed. Two bistable composite plates, one with a 3D printed mechanism to induce a biasing force to allow recovery between the two stable states, were stacked on top of each other in the stable state with maximum curvature and with the axes of curvature collinear and the curved surfaces facing in the same direction. The specimens were placed in a bag and tested in three-point bending with the vacuum pressure being varied up until a full vacuum. The resulting data was compared with a model we previously developed for layered jamming composites.

Experimental Method

Layered jamming structure with bistable composites.

For this investigation, we fabricated structures using two bistable composite plates made from unidirectional carbon fiber lamina. The plates were 150 mm × 150 mm in-plane, and had a $0_2/90_2$ and the other a 0/90 ply layup for thicknesses of 0.8 mm and 0.4 mm respectively. A mechanism was designed to be 3-D printed and attached to the bottom of the $0_2/90_2$ plate to constrain it from deforming, and enabling it to reverse from the deformed to the initiate stable state through the biasing moment. The two bistable composite plates can be seen in *Figure 1* from the bottom surface of the plates, with the thicker plate inverted to display the 3D printed biasing mechanism. The curvature can be seen in the side view in Figure 1. It is



Top View

Side View

Fig. 1 Two bistable composite plates that were used for layered jamming experiments (biased plate with biasing mechanism is on the right).

clear that the curvature for the 0/90 plate results in a height that is twice that of the $0_2/90_2$ plate. To fabricate the jammed structures, we placed the plates in the stable state with maximum curvature on top of each other with the axis of curvature collinear and the curvature facing in the same direction. The plates were then placed inside a vacuum bag for testing.

Three-point bend mechanical testing

To characterize the effects of vacuum pressure and cyclic loading, we performed three point bend tests with just two opposing corners of the plate specimen pinned and the central load applied to the center of the surface of the plate using a Bose Electroforce test frame. The degree of deformation exhibited by a bistable laminated composite is very sensitive to boundary conditions, therefore we built a three point-bending test rig that would enable us to control the distribution of the clamping force in order to characterize the mechanical behavior of the layered jamming structure using conditions that range from clamped to pinned (*Figure 2*). A vacuum is drawn inside the bag by using a electric vacuum pump at a rate of 1.6 L/sec with the vacuum pressure measured using a Hardware Factory Store 8542039686 vacuum gauge. A valve was used to control the vacuum pressure from -3 kPa to a full vacuum. shown in Figure 2. The displacement and load data were obtained at a sampling rate of 1000 Hz. Experiments were conducted from vertical displacements of 0 mm at the unloaded state to -21 mm of displacement over 10 cycles at 1 Hz.

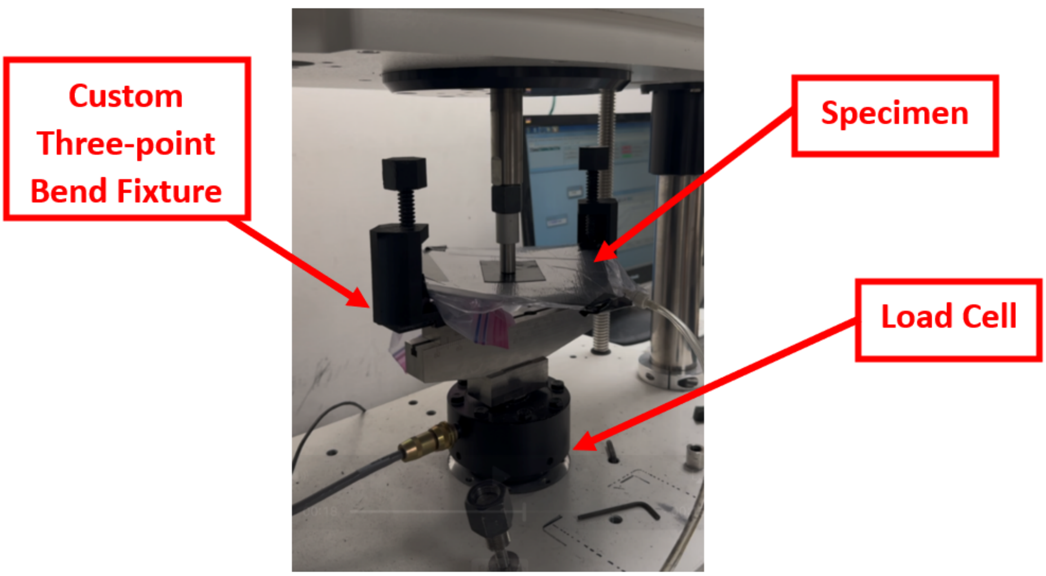


Fig. 2 Three-point bending test with layer jamming bistable composite specimen.

Modeling Mechanical Behavior in Three-point Bending

Previously, we developed the following model based on Euler-Bernoulli equations to predict the mechanical behavior of a layered jamming structure. First, we relate the change in strains, ε_i, between layers to the displacement discontinuity at the interface due to slip, du_i, along the axial location, x.

$$\varepsilon_{o,i} + kt_i - \varepsilon_{o,i+1} = \frac{du_i(x)}{x}$$

We can then determine the strain at the bottom of the first layer from the slip and the curvature of the structure, k, and thickness of each layer t_i, as follows:

$$\varepsilon_{o,1}h = -\sum_{i=1}^{N}\left[\frac{k(x)t_i^2}{2}\right] - \sum_{i=2}^{N}\sum_{j=2}^{i} t_i\left[kt_{j-1} - \frac{du_{j-1}(x)}{x}\right]$$

To achieve equilibrium, we relate the corresponding internal stress distribution to the applied bending moment, *M*, and the internal balance of force from the transverse location of each interface, h_i, as follows:

$$M(x) = Eb\sum_{i=1}^{N}\left[-\frac{k(x)}{3}\left({h_{i+1}}^3-{h_i}^3\right)+\frac{(k(x)h_i+\varepsilon_{o,i})}{2}\left({h_{i+1}}^2-{h_i}^2\right)\right]$$

$$0 = \sum_{i=1}^{N}\left[-\frac{k(x)}{2}\left({h_{i+1}}^2-{h_i}^2\right)+\left(k(x)h_i+\varepsilon_{o,i}\right)\left(h_{i+1}-h_i\right)\right]$$

From the Euler-Bernoulli model, the maximum shear stress occurs in the center of the cross section of the beam and is given by:

$$\tau_{max}= 1.5\frac{\mathrm{V}}{\mathrm{A}}$$

where V is the shear force and A is the cross-sectional area. Interlayer shear stress, τ_{inter} is given by:

$$\tau_{\text{inter },i}=\frac{3V}{2A}\left[1-\left(\frac{2y_i}{h}-1\right)^2\right]$$

Where h is the total thickness of the layer jamming specimen. The maximum interlayer shear stress that can be sustained by jamming layers with surface friction coefficient, under a vacuum pressure is given by:

$$\tau_{\text{inter }\_max}=\mu\Delta P$$

Therefore, the maximum load, V_{max}, before slip occurs at an interface located at y_i:

$$V_{\text{max}}=\frac{2A\mu\Delta P}{3\left[1-\left(\frac{2y_i}{h}-1\right)^2\right]}$$

For our experiments, one of the specimens was biased by a mechanism to induces a constraint on the lower surface that prevents it from stretching, and imposes a bending moment opposing the loading so that the lower surface of the structure has zero strain. The resulting biased bistable composite plate has an impact on the resulting stiffness reduction for the layered jamming bistable composite structure when slip occurs at the interface between the bistable composite plates. We again can look at this from a 1-D perspective using the previous Euler-Bernoulli beam theory, where for the two layer jammed bistable composite structure with plate thickness h_1 and h_2, respectively, the bending stiffness, $(EI)_{c,jam,}$ is related to the bending stiffnes of each layer, $(EI)_1$ and $(EI)_1$, as follows:

$$(EI)_{c,jam}= (EI)_1+4E{h_1}^3/b+(E1)_2+E(h_1+ 0.5h_2)^2\ h_2b$$

When there is slip at the interface, their stiffness becomes:

$$(EI)_{c,jam}= (EI)_1+4E{h_1}^3/b+(E1)_2$$

Since the constraint is applied on the first plate to create the biased response. Thus, the resulting stiffness reduction ratio, $(EI)_{c,ratio,}$ can be determined as follows:

$$(EI)_{c,ratio}= [(EI)_1+0.25E{h_1}^3/b+(E1)_2]/[(EI)_1+E{h_1}^3/(4b)+(E1)_2+E(h_1+ 0.5h_2)^2\ h_2b]$$

For our specimens, $h_1 = 2\ h_2$, therefore, the stiffness reduction ratio should be 3.3.

Experimental Results

Three-point bending of layered jamming bistable composites

For the initial set of experiments, we used three-point bending to characterize the behavior of the two bistable composite plates stacked on top of each other in the stable state with maximum curvature with the directions of curvature collinear. The inherent load-displacement behavior for the biased bistable composite plate can be seen in *Figure 3* (seen in wide black in the figure, we only tested the biased plate, since it maintains contact during the entire compressive displacement range that we tested through the bistable response region. The response of the two jammed bistable composite plates can also be seen in Figure 3 with vacuum pressures as low as -3 kPa all the way (designated in wide red) to a full vacuum. It can be seen that at -3 kPa, the response represents the combination of the two bistable composite plates. As the vacuum pressure increases, the hysteresis loop expands as the jammed bistable composite plates stiffen by increasing the energy level associated with the instability to make it more difficult to initiate the plate buckling response.

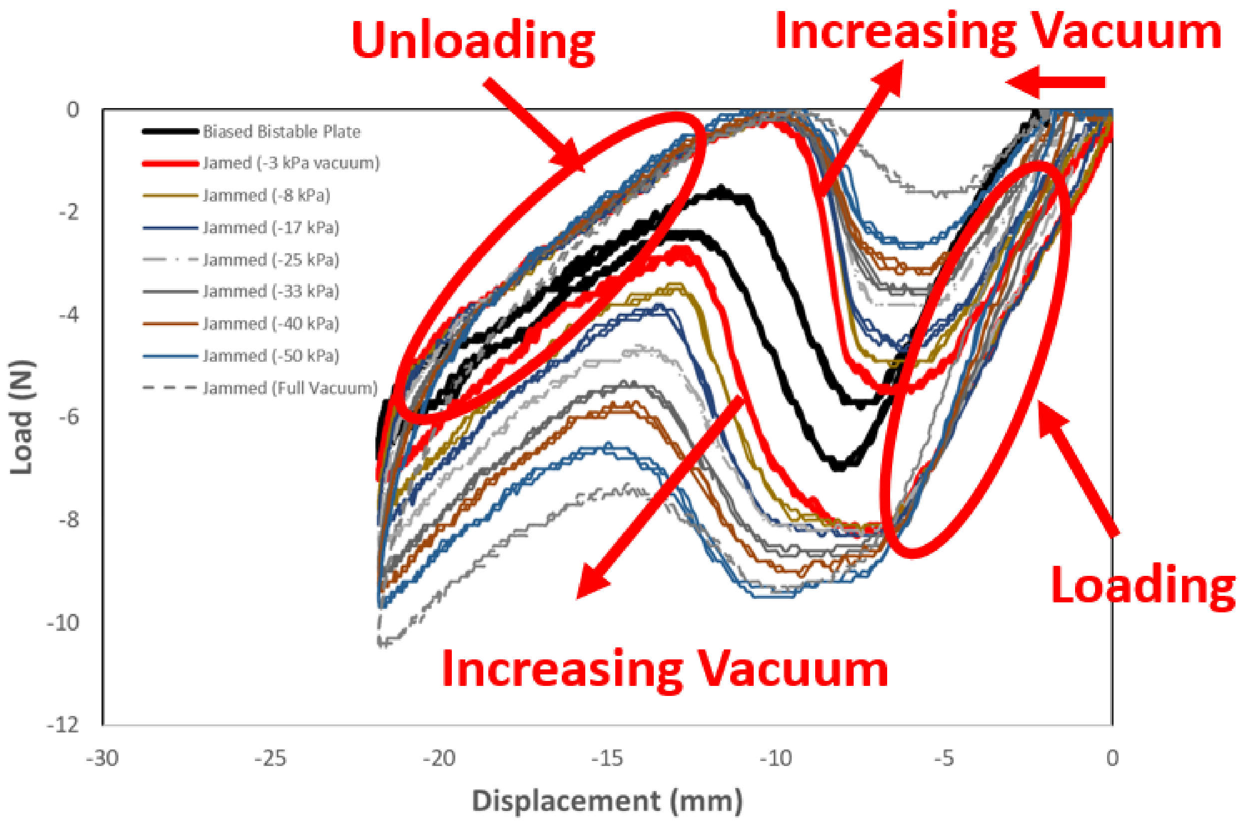


Fig. 3 Experimental results obtained in three-point bending for two jammed layered bistable composite plates starting at -3 kPa of vacuum pressure (wide red) all the way to a full vacuum, as compared to the biased bistable composite plate.

The increase in hysteresis with vacuum pressure can be attributed to the maximum shear force that was expected at the interface. It can be seen that the minimum load after the buckling instability is initiated upon loading goes from near the response of the biased bistable composite plate at -2.9 N when there is -3 kPa of vacuum pressure all the way to -7.4 N at full vacuum. From the model, the expected shear load resistance at full vacuum pressure would be increasing from 0 N up to 4.5 N for a coefficient of friction of 0.24 at the interface between the bistable composite plates. Thus, it appears the vacuum pressure is controlling that dip in load based on the vacuum pressure. Thus, it is possible to control the bistable response to adjust to the desired needs of the patients. At higher pressures, there is a much lower negative stiffness, which increases the interaction distance with patients.

It was also noted that as the vacuum pressure increased, the load approached 0 before the buckling instability initiated when the jammed plates were unloaded. Initially, the adhesion of the two plates induced by layer jamming is sufficient to treat the structures as one continuous structure with stiffness associated with the combined thicknesses. This “tightening up” of the structure can also be seen as the initial displacement for three-point bend loading decreases with increasing vacuum pressure, which decreases to -2.19 mm. That stiffened response was maintained until a level of -6 N was reached. At that point, the response separates with increasing take-off stiffness with increasing vacuum pressure. The same tightening effect can also be seen as the plates are unloaded, until they approach 0 N at approximately -12 mm, at which point the take-off response upon buckling becomes more compliant with increasing vacuum pressure until the specimen is fully unloaded. Clearly, this indicates that the specimen is starting to approach a state where there is residual energy left to initiate reverse buckling and allow the plates to deform. In fact, the plates tended to stay deformed after 10 cycles at a displacement of approximately -12 mm as the vacuum pressure increased, as seen in Figure 4. The unloading and loading bath had an initial slope similar to the slope upon initial loading during the first cycle. At -4.5 N of loading, the specimen exhibits a reduction in stiffness of 2.6X, which is close to what was expected based on the modeling prediction without the instability, which is also shown in *Figure 4*. This slope is also slightly greater than the slope observed after the instability is initiated upon loading and unloading. For applications such as exoskeletons for assistive robotics, this would equate to a time-dependent response that would initiate under the right cyclic loading condition to activate either a permanent decoupling of the structure from the patient, or a permanent grasping force.

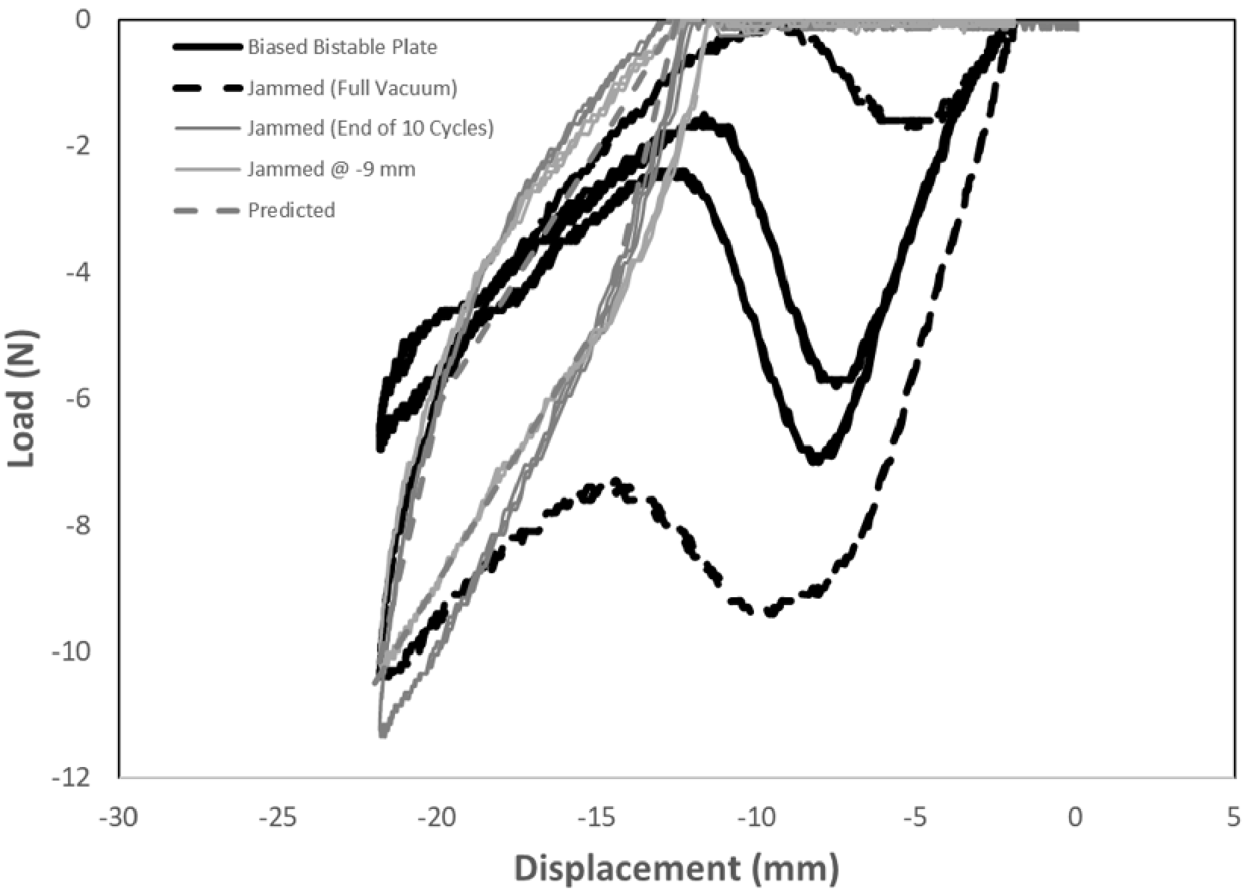


Fig. 4 Experimental results obtained in three-point bending for two layered bistable composite plates jammed at full vacuum pressure initially and after 10 cycles of loading. The resulting response of the specimen with vacuum pressure applied at -12 mm to jam it is nearly identical, as is the predicted response from the modeling.

Morphing behavior of layered jamming bistable laminated composites

One of the interesting aspects of the layered jamming bistable laminated composites was the ability to retain plastic deformation at elevated vacuum pressures to “lock in” a deformed state at -12 mm of displacement when activated by cycling loading, as seen in *Figure 5*. Of course, upon reducing the vacuum pressure, the specimen would initiate recovery to the original undeformed state at a vacuum pressure of approximately -25 kPa. This also correlated to when the load upon unloading reached 0 with increasing vacuum pressure to this level, as seen previously in Figure 3. This morphing behavior can be seen below in Figure 5. It also provides another mechanism for controlling the interaction of a structure with the patient, allowing the deformed response to be initiated upon cycling loading, and then deactivated upon reducing the vacuum pressure. This ability to reverse plastic deformation is very similar to a shape memory material, where the mechanism in this case is vacuum pressure.

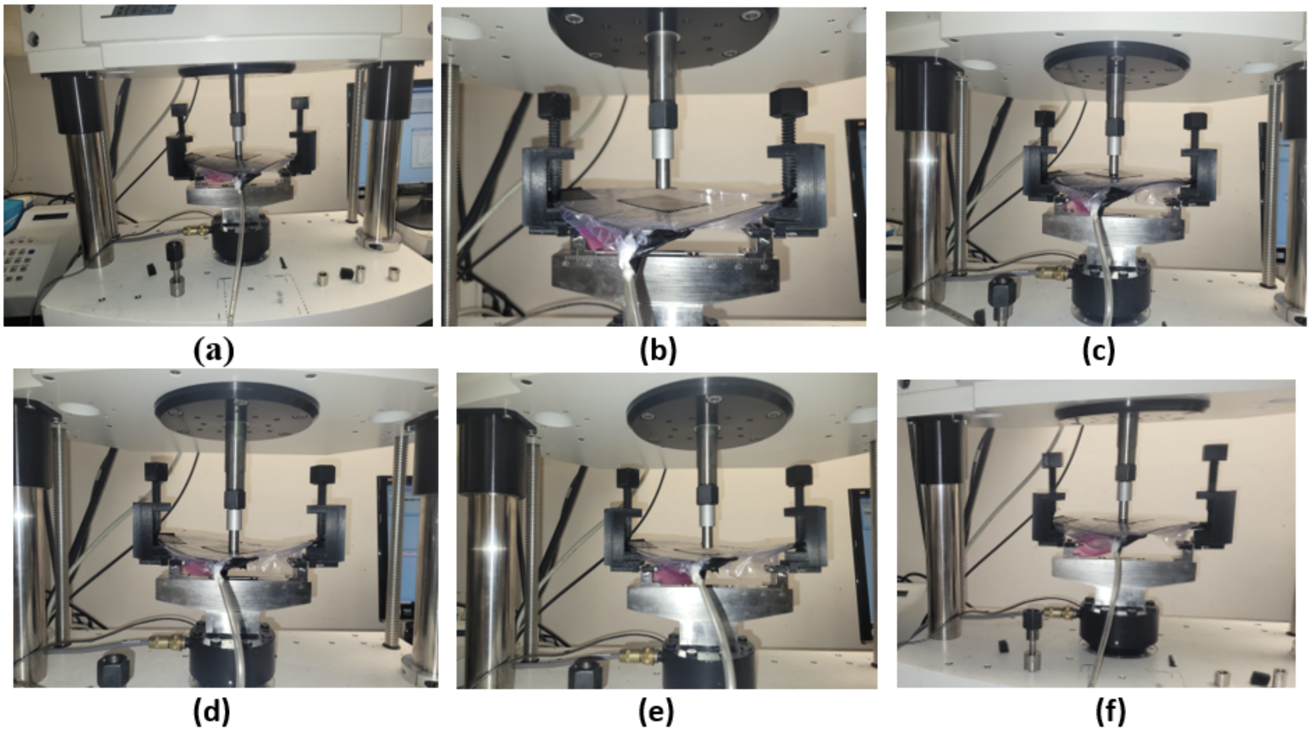


Fig. 5 Morphing behavior of two layered bistable composite structure jammed at full vacuum pressure: (a) before cycling loading, (a) after cycling at 1 Hz for 10 cycles., (c) after reducing vacuum to below -25 kPa, (d) deforming the specimen to -12 mm and drawing a full vacuum, (e) after unloading, (f) after reducing the vacuum to below -25 kPa.

Conclusions

We have recently characterized layered jamming structures consisting of layered bistable laminated composites, in order to understand how layered jamming can be used to create novel lightweight morphing structures for various applications, such as assistive robotics. The bistable laminated composite is capable of transitioning between two stable shapes and can be combined together or with passive elements through layered jamming, the bistable behavior can be controlled using vacuum pressure, resulting in morphing behavior that is similar to a shape memory material. Specimens were fabricate from two composite bistable plates made from carbon fiber/epoxy lamina, with two different layups to induce different levels of curvature. A stiff 3D printed structure was attached to one side of the plate with the lower curvature in order to prevent the surface from deforming and therefore inducing a reverse bending moment that could reverse the structure from the second stable state back to the original stable state upon unloading. It was observed that as the vacuum pressure increased, the hysteresis increased, as stiffness after the instability initiated due to slip at the interface. A similar trend was observed upon unloading. However, as the pressure increased to full vacuum, the load would reach 0 N upon unloading, and the specimen would stay in a permanently deformed state at the end of 10 cycles. The specimen would then exhibit similar cycling behavior without the instability as it would if the specimen had the vacuum drawn after it had been deformed to -12 mm without a vacuum. The change in the minimum load observed after the instability is initiated upon loading and unloading correlated to the increase in loading that would be required to overcome the frictional force, which is proportional to the vacuum pressure, at the interface between the plates. This vacuum-controlled stiffness allows for novel implementation for impedance control of assistive robotics, where itis possible to control the bistable response to adjust to the desired needs of a patient. The cyclic behavior in the permanently deformed state also correlated to model predictions without the instability. The permanently deformation could be recovered by reducing the vacuum pressure below -25 kPa. This enabled the structure to exhibit morphing behavior similar to a shape memory material, where it could be used to control the interactions with a patient for assistive robotic applications, such as exoskeletons, where it can activate either a permanent decoupling of the structure from the patient, or a permanent grasping force.

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