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CONTROLLING THE ROTATIONAL DOF OF LAMINAR JAMMING STRUCTURES WITH END CLAMPING MECHANISM

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ABSTRACT

Variable stiffness structures lie at the nexus of soft robots and traditional robots as they enable the execution of both high-force tasks and delicate manipulations. Laminar jamming structures, which consist of thin flexible sheets encased in a sealed chamber, can alternate between a rigid state when a vacuum is applied and a flexible state when the layers are allowed to slide in the absence of a pressure gradient. In this work, an additional mode of controllability is added by clamping and unclamping the ends of a simple laminar jamming beam structure. Previous works have focused on the translational degree of freedom that may be controlled via vacuum pressure; here we introduce a rotational degree of freedom that may be independently controlled with a clamping mechanism. Preliminary results demonstrate the ability to switch between three states: high stiffness (under vacuum), translational freedom (with clamped ends, no vacuum), and rotational freedom (with ends free to slide, no vacuum).

INTRODUCTION

Variable stiffness structures are of particular interest for soft robotics as they can offer both strong and compliant behavior. These structures can be programmed to exert substantial forces when needed to perform rigorous tasks, yet collapse upon impact with fragile objects. As reviewed by Manti, several different strategies have been employed to produce variable stiffness structures for soft robots [1]. These methods fall under two broad categories shown in Fig. 1: antagonistic actuation and intrinsic tunable stiffness. The former utilizes antagonistic arrangements of soft actuators to realize high stiffness when opposing actuators are activated as in [2, 3, 4, 5, 6, 7]; the latter focuses on modifying the mechanical properties of the underlying materials themselves via phase transformation [8], shape memory effect [9], chemical reaction [10], or other means of mechanics modification [11, 12, 13].

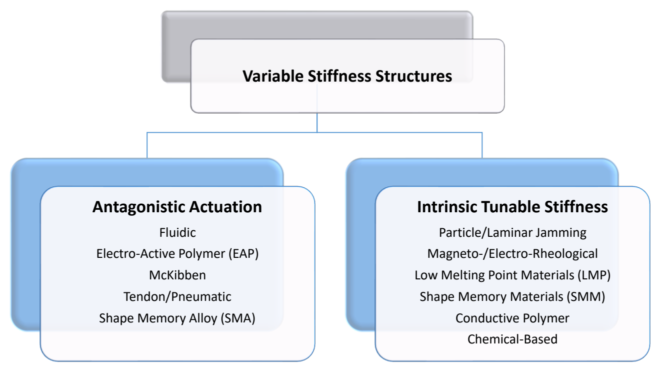

FIGURE 1. CLASSIFICATION OF VARIABLE STIFFNESS STRUCTURES.

While the intrinsic tunable stiffness approach offers uniform, compact variable stiffness with minimal complexity, these

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FIGURE 2. PRIMITIVE 3-POINT BEND TEST OF LAMINAR BEAM IN 3 DIFFERENT STATES.

materials often involve thermal systems encased in insulative soft materials. Thermally-activated shape memory materials, low melting point materials, and conductive polymers demonstrate remarkable intrinsic stiffness variability, but require heating and cooling of substantial thermal mass [8, 14, 15, 16, 17, 18]. Chemical based reactions which involve hydro-absorption to instigate stiffness change also require long absorption and drying phases [10, 1]. As a result, slow cycling time is a persistent challenge among these materials [19].

Particle and laminar jamming structures offer instrinsic variable stiffness without the drawback of slow thermal cycling. Unrestrained relative sliding of particles or layers in these structures enables flexible characteristics whereas application of a vacuum immediately jams the particles or layers together causing an increase in stiffness. These structures have gained popularity in recent years as they lend themselves well to soft robotics applications such as grippers and simple joints [20, 21].

Narang et al. characterizes the stiffness of laminar jamming structures and proposes usage in a 2-fingered soft gripper. The shape-locking feature of these structures is also suggested to maintain a pose after the actuation is removed [22]. In [23], a similar laminar jamming structure is proposed for shock absorption since the high friction between layers absorbs energy rapidly. A laminar jamming sandwich structure is proposed in [24] to maximize the performance-to-mass ratio in these variable stiffness members. A tunable impedance robot wrist is proposed by Aktas and Howe in [25] where two jamming structures are placed in series with a 90° offset to control the flexural stiffness in two directions. By modulating the stiffness in each direction, the wrist can perform precise tasks in the high stiffness state or avoid transmitting large contact forces by switching to the compliant state if positioning uncertainties are present [25].

While the variable impedance robot wrist proposed by Aktas and Howe focuses on controlling the translational degree of freedom (DOF) in two directions using traditional laminar jamming structures, the work in this paper proposes a method of controlling the rotational DOF's as well. The concept of end-clamping is proposed to enable control of the rotational DOF in laminar jamming structures. The constraints applied to the ends of laminar jamming structures play a critical role in determining the types of motion that are allowed. When the ends of a laminar jamming beam are clamped as in [25], relative rotation of the ends of the beam is prohibited as the layers are prevented from sliding at the ends of the beam; thus, only translation is allowed. Conversely, when the ends of the beam are free to slide, the beam can deform freely and the ends may rotate relative to each other. The vacuumed state remains unaffected, producing a high stiffness state regardless of the end restraints. These attributes are evidenced in Fig. 2. Applying this concept to a variable impedance wrist design could improve the mobility and controllability of the design.

Humans and many other animals possess different types of joints including synarthrosis and amphiarthroses which allow little to no movement, gliding synovial joints which allow translation but very little rotation, and angular synovial joints which allow bending [26]. Each of these joint types can be enacted by the 3 different stiffness states of the laminar jamming beam with end clamping. Thus, a single device can perform three different types of biologically inspired movements. The highly controllable degrees of freedom offered by laminar jamming structures with end clamping could enable soft robot joints matching the capabilities of these three different classes of human joints, enabling adept movements and stiffness control of soft robots.

METHOD

Physical Design, Fabrication, and Test Setup

To demonstrate the controllable DOF's of the proposed element, a physical test piece is constructed using 64 layers of 20 lb printer paper cut to 1 inch x 5.5 inches. The laminar beam is then placed on a 3-point bend test stand with a support span of 2.5 inches. The beam is then loaded with a 0.36 lb weight at the center to compare the shape and maximum deflection of the beam in each of the 3 states. For the free-ends test, the papers are simply stacked and placed on the test stand. For the clamped-ends test, small clamps are placed on the ends of the stacked papers to prevent sliding of the sheets at the ends of the beam. For the vacuum test, the stacked papers are sealed in a plastic bag with a vacuum applied through a small tube attached to the bag.

Finite Element Analysis

A representative model is also developed in Solidworks to evaluate the behavior of the beam using FEA in a cantilevered mounting with a load applied at the free end of the beam. This setup is representative of the type of loading that would be seen in a wrist, where one end of the joint is fixed to the arm while a load is applied to the opposite side of the joint at the hand.

The FEA model is simplified to include only 10 laminae with increased thickness (0.15 mm) to make the study feasible. The 10 sheets are encased in 0.3 mm thick silicone material. The ends of the beam are encased in 0.3 mm thick alloy steel which holds the beam in place but does not exert any clamping force. As shown in Fig. 3, the steel end casings cover 5 mm of the laminae at each end of the 40 mm sheets. The properties of the 3 encompassed materials treated as linear elastic isotropic materials are shown in Tab. 1.

TABLE 1. MATERIAL PROPERTIES INCLUDED IN FEA STUDY.

Material Name	Elastic Modulus	Poisson's Ratio	Mass Density
Alloy steel	210 GPa	0.28	7700 kg/m^3
Silicone rubber	0.11 GPa	0.49	2330 kg/m^3
Paper laminae	5.0 GPa	0.00	156 kg/m^3

Since there are no significant forces acting transverse to the beam, the linear static study is set up with the plane strain simplification using a section depth of 20 mm. A global no penetration contact set is established with a global friction coefficient of 0.4. The end faces of the silicone casing are bonded to the inside ends of the steel end casings. For all 3 states, the steel end casing on the left end is fixed while a 1.5 N downward force is applied to the steel casing on the right end.

For the free-ends study, the simulation is run on this basic assembly. For the clamped-ends study, the 5 mm end segments of the papers are bonded together and to the inside of the silicone casing. This prevents slippage at the ends of the beam but allow the papers to slide and bend freely in the center region of the beam. For the vacuum study, a 500 kPa uniform pressure is applied inwardly on the outside layers of paper and on the inner

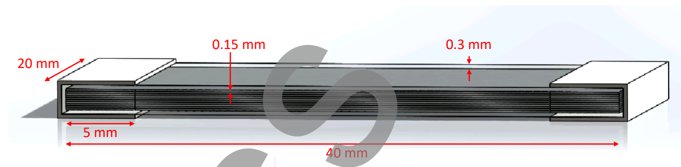

FIGURE 3. DIMENSIONS OF LAMINAR BEAM FOR FINITE ELEMENT ANALYSIS.

walls of the silicone casing. The horizontal forces on the ends of the beam due to the vacuum pressure are neglected since they do not cause significant deformation. The loads and contact sets for each study are summarized in Tab. 2.

RESULTS

Physical Tests

The 3-point bend test conducted on the physical test piece demonstrates the 3 different capabilities of the laminar beam. As seen in Fig. 2 (a), the beam bends freely into a C-shape when the ends are free as slippage occurs throughout the entire length of the beam. Fig. 2 (b) shows different behavior when the ends of the beam are clamped to prevent slip between layers at the ends of the beam. In this case, the beam deflects in the center, but cannot form the natural C-shape. The clamps at the ends of the beam restrict deformation and prevent rotation of the ends of the beam. This restraint forces the ends of the beam to remain parallel. Figure 2 (c) illustrates the high stiffness achieved when a vacuum is applied to the beam. The vacuum pressure increases the frictional force between layers, resisting slip at any point on the beam. This added resistance essentially prohibits both translation and rotational deformation of the beam.

FEA Simulation

The FEA study results predict the deformation of the beam under a cantilevered loading as would be seen by a wrist. Noting the relative positions and orientations of the steel end casings reveals the rotational and translational freedom of the beam or wrist in each state. Figure 4 (a) shows the rotational freedom allowed when the ends of the beam are free. Note the rotation of the right end relative to the fixed left end. Conversely, the ends of the clamped-end beam shown in Fig. 4 (b) remain parallel although translation is allowed. The vacuum applied to the beam in Fig. 4 (c) resists any substantial rotation and translation of the joint. As seen in the color scale legends of the plots in Fig. 4, the maximum vertical deformation of the free-ends, clamped-ends, and vacuumed beam under this particular loading are 23.3 mm, 10.8 mm, and 1.3 mm respectively.

TABLE 2. FINITE ELEMENT ANALYSIS STUDY PARAMETERS.

Study	Free-Ends	Clamped-Ends	Vacuumed
Fixture	Left end casing fixed	Left end casing fixed	Left end casing fixed
Load	1.5 N downward on right end casing	1.5 N downward on right end casing	1.5 N downward on right end casing
Pressure			500 kPa inward pressure
Global friction coefficient	0.4	0.4	0.4
Global contact set	No penetration	No penetration	No penetration
Local contact sets	Ends of silicone bonded to steel casing	Ends of silicone bonded to steel casing End regions of laminae bonded to each other and to steel casing	Ends of silicone bonded to steel casing
Mesh	Curvature based	Curvature based	Curvature based
Solver	Direct sparse	Direct sparse	Direct sparse

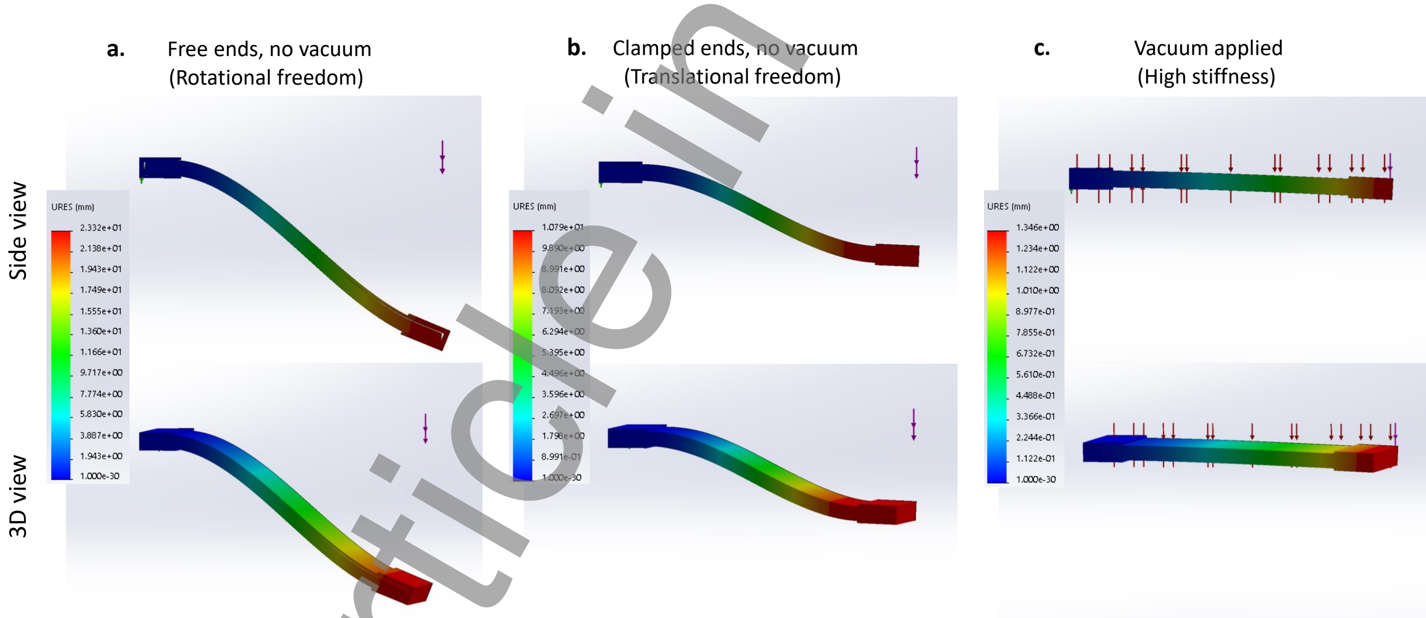

FIGURE 4. FINITE ELEMENT ANALYSIS OF CANTILEVERED LAMINAR BEAM IN 3 DIFFERENT STATES.

DISCUSSION

Prior to use in practical applications, a smart clamping mechanism should be developed to turn on/off a clamping force at the ends of the beam using a simple stimulus. This could perhaps be achieved by squeezing two opposing end plates using a shape memory alloy wire, or by pressurizing a ring around the ends of the beam that squeezes the laminae together at the ends. However, further study is needed to optimize such a design.

Once a smart clamping mechanism is designed, laminar beams of this type could be particularly useful for soft robot joints as they enable independent control of the rotational and translational DOF's while offering variable stiffness capabilities. Arrangements of multiple beam structures at different orientations could allow control of more DOF's within the system, even rivaling the capabilities of the human wrist.

Arranging these laminar beams in strategic geometric patterns could enable directional stiffness control without the limitations of heat dissipation that limits cycling time in many variable stiffness structures.

CONCLUSION AND FUTURE WORK

A laminar beam structure has been proposed that exploits clamping the ends of the beam as a means of independently controlling the beam's rotational and translational DOF's. Preliminary testing of a physical test piece demonstrate the improved controllability with end clamping. Finite element analysis of the beam under cantilevered loading demonstrates the usefulness for joints that benefit from independent control of rotation and translations, such as a robotic wrist. The beam is capable of switching rapidly between 3 states: high stiffness (under vacuum), translational freedom (with clamped ends, no vacuum), and rotational freedom (with ends free to slide, no vacuum).

In moving forward with this project, a smart clamping mechanism needs to be designed to easily and rapidly modulate the clamping force on the ends of the beam. The FEA model should also be compared with experimental measurements to validate the model. Then the model may be simplified to a rudimentary yet representative form that will lend itself to control schema.

It will be interesting to explore the application of clampable laminar jamming beams to more complex geometric arrangements that enable directional stiffness control of bulk robotic materials. Clamping these beams at different locations throughout the length could enable finer control of the DOF's throughout the beam structure.

Ultimately, the laminar jamming beam with clamping capabilities warrants further study as it shows great promise for enabling variable stiffness soft robotic materials without the hindrance of thermal cycling time.

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