MACHINE AUGMENTED COMPOSITES UTILIZING AN HOURGLASS SHAPED CORE ELEMENT IN A SOFT NEARLY INCOMPRESSIBLE MATRIX

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Abstract

Machine Augmented Composites (MAC) have small, simple machines embedded in a matrix. MACs might provide materials with advantageous properties or new functions. Example properties are materials with increased damping or negative Poisson's ratio. New functions might include the ability to change shape or to adjust stiffness. In the MAC material studied here the matrix is a soft polyurethane elastomer and the embedded machine is a nylon, hourglass-shaped element. The desired improvements should give the composite material the ability to change shape and perform useful work. The hourglass core elements elongate as they are pressurized, which actuates the structure. The elastomer matrix, which is nearly incompressible, aids the expansion. The commercial code ABAQUS was used to study the MAC's deformation and to predict its response. Potential applications for this research in the automotive industry are in energy absorption and dissipation. Sandwich panels that change shape could increase driver and passenger safety by adapting the automotive body shell to road conditions or by damping noise and vibration. These panels might deploy like an air bag to absorb energy around passengers during an accident. Machine augmented composites are a promising field with potential to produce materials that serve as both structure and mechanism.

Introduction

Machine augmented composites are a material research area with wide possibilities for applications. The design investigated here uses internal pressure to actuate. The internal pressure causes the hourglass-shaped element to extend in two ways. First, the pressure pushes on the top and bottom of the hourglass core causing the core to extend. In this case the pressure works directly on extension. Second, the internal pressure bends the hourglass element's curved side walls. When the sides straighten, they push the top and bottom of the hourglass core element and aid the element's extension. The soft incompressible elastomer matrix material between each hourglass core element also assists in the extension; the elastomer pushes out on the top and bottom of surface between each core element when the side walls of the hourglass core element push in on the elastomer.

Background

Machine augmented composites try to efficiently incorporate simple machines to create a desirable material property or allow the material to perform useful work. They could serve in applications where traditional mechanical actuators are used and unique nontraditional material properties are required. As in any machine design, the application dictates the simple machines' orientation and arrangement. MACs could potentially reduce an actuated structure's weight and volume. MACs may also be able to reduce actuation time over traditional actuators.

The hourglass core element (HCE) investigated was proposed by Hawkins[1] as a simple machine that could augment a material to cause it to respond with a negative Poisson's ratio. The application studied here is inspired by his idea. McCutcheon[2] and Kim[3] studied an hourglass shape as a way to create high stiffness, low mass materials with increased damping. These applications use the hourglass core as a passive element where force is applied to the material. In the present case the hourglass core element is an active element with internal pressure that causes the HCE to actuate.

Hourglass Core Element Design

The optimum shape of the hourglass was obtained by trying several configurations because there is no analytical formula for the element. The initial optimization criterion is the largest elongation under a constant pressurization. In this study five hourglass shapes were analyzed. All the hourglass side walls have arcs with 5 mm radius. The hourglass shape was varied by offsetting the circles whose circumferences make up the 3 side wall arcs. All 5 designs appear in Figure 1 below and all dimensions are in mm. The offset for the five hourglass configurations are 0, 2, 4, 6, and 8 mm and they appear in this order in Figure 1. The offset is the distance between the center of the top and bottom arcs and the middle arc. Offsetting the arc centers shortens the hourglass.

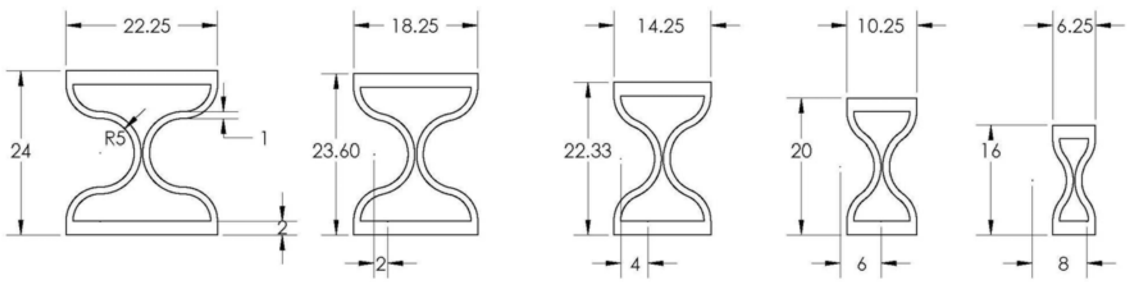

Figure 1. These hourglass core models provide five strain levels; the dimension at each sketch's base shows the offset between the arcs.

The hourglass core element shape with the highest percent elongation under 5 MPa pressure is the 0 mm offset model, which is the left model in Figure 1. Table I shows the change in length and percent elongation for each model.

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[1] *Hawkins G. F. Augmenting the Mechanical Properties of Materials by Embedding Simple Machines. Journal of Advanced Materials 2002;* ***34****:16-20.*

[2] *McCutcheon D. M. "Machine Augmented Composite Materials for Damping Purposes." MS Thesis Texas A&M University, 2004.*

[3] *Kim, Jong Hyun. "Passive Machine Augmented Composite Materials for Multifunctional Properties." PhD Dissertation Texas A&M University, 2005.*

Table I. HCE extension decreases as the space between HCEs increases.

Arc Offset (mm)	h (mm)	Space Between HCEs (mm)	Delta h (mm)	Percent Elongation
0	24.00	8.76	3.249	13.5
2	23.60	10.07	2.615	11.1
4	22.33	11.32	1.947	8.7
6	20.00	12.55	1.124	5.6
8	16.00	13.80	0.4484	2.8

Hourglass element performance was found with finite element modeling using the commercial code ABAQUS. Every hourglass core element was modeled as a 2-D, plane-strain model with symmetry boundary conditions on the left and right sides. Modeling the hourglass element in plane strain is equivalent to a 3-D model that is long in the direction normal to the plane of the hourglass shape. The left and right side symmetry boundary conditions approximate putting the HCE in an infinite, one-dimensional array. An aluminum plate over the HCE keeps the hourglass' top surface from bowing. This aluminum plate would be an actuated surface in an application. The hourglass element is modeled as a linearly elastic material with an elastic modulus, E, at 2000 MPa and a 0.35 Poisson's ratio, or v. The matrix material is also modeled as a linearly elastic solid with E at 30 MPa and v at 0.48. The 0.48 Poisson's ratio makes the material nearly incompressible. A real elastomer matrix does not behave like a simple linear elastic material, but, since elastomers are hard to model accurately the matrix is approximated here by a soft, incompressible, linear-elastic material. In this first analysis the exact strain field and stresses in the elastomer matrix are not of interest. As long as the matrix material is sufficiently soft compared to the hourglass core element material the deformation of the MAC will be dominated by the deformation of the hourglass element. The near incompressibility of the matrix material is the important material property in this case. The reason that this property is important because when the hourglass element deforms the matrix material between the hourglass elements will aid in the extension of MAC.

The HCE wall thickness also could be optimized—for example, wall thickness might vary throughout the element, but here the wall thickness is fixed at 1 mm. There are other areas in which the core element can be optimized. These areas include the material properties of the hourglass core element and the softer elastomer matrix. The shape of the hourglass element side wall could also be optimized. A circular arch with constant curvature might not be the optimum shape

The space between each hourglass comes from the elastomer volume that would be displaced if the hourglass walls straighten completely. The HCEs are spaced so that the volume gained by the elongation of the hourglass length equals the elastomer volume displaced. This might not be the optimum elastomer width, but it is a good starting place for the analysis. The elastomer is nearly incompressible, so the elastomer volume should remain close to constant through the deformation. If the HCE tries to deform in a way that would change the elastomer volume, the nearly incompressible matrix will prevent any further deformation.

Results

The first HCE configuration showed the highest percent elongation with a 5 MPa internal pressure, but this configuration might be improved. The HCE exhibits the largest elongation when there is no space between hourglasses. The elongation when there is no space between HCEs is 5.34 mm or 22.6%. This is not the case for all the configurations. The reason for this is that at 5 MPa the HCEs are not pressurized to full extension. The HCE's shape before and after deformation appears in Figure 2 and Figure 3 respectively.

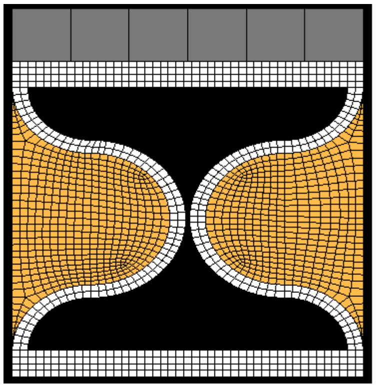

Figure 2. This undeformed HCE shows the aluminum top plate in gray, the HCE wall in white, the HCE interior in black, and the elastomer matrix in yellow.

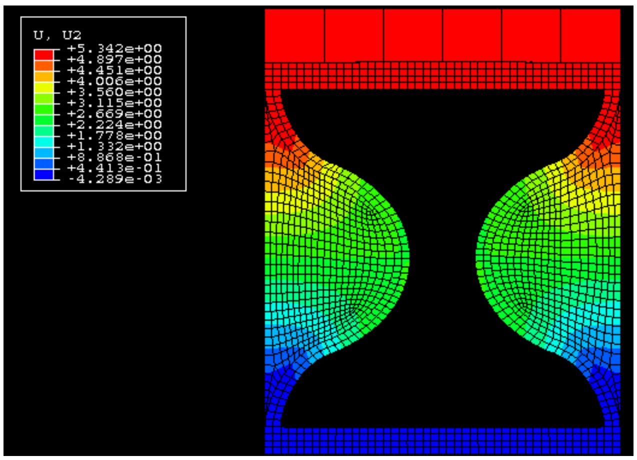

Figure 3. The HCE with deformation is aided by the elastomer matrix. Without the matrix the HCE inflates like a balloon and does not concentrate its action in one direction.

The Force vs. Displacement curve in Figure 4 is almost linear. This might be because 5 MPa pressure does not create enough displacement to drive structural nonlinearity. If the HCE was pressurized to failure large nonlinear response is likely. The area under the force vs. displacement curve predicts a total work of 283 J per meter of length of HCE in the direction normal to the plane of the hourglass shape. This yields a work density of 0.53 MJ/m^3 normalized to the initial, undeformed volume. The work density should increase if higher pressures drive the actuation. The reaction force on the aluminum plate is 107.6 N/mm compared to the 101.3 N/mm applied to the top of the hourglass from the internal pressure. This corresponds to the hourglass shape increasing the force by about 6.2%. This force multiplication is an advantage of the hourglass shape.

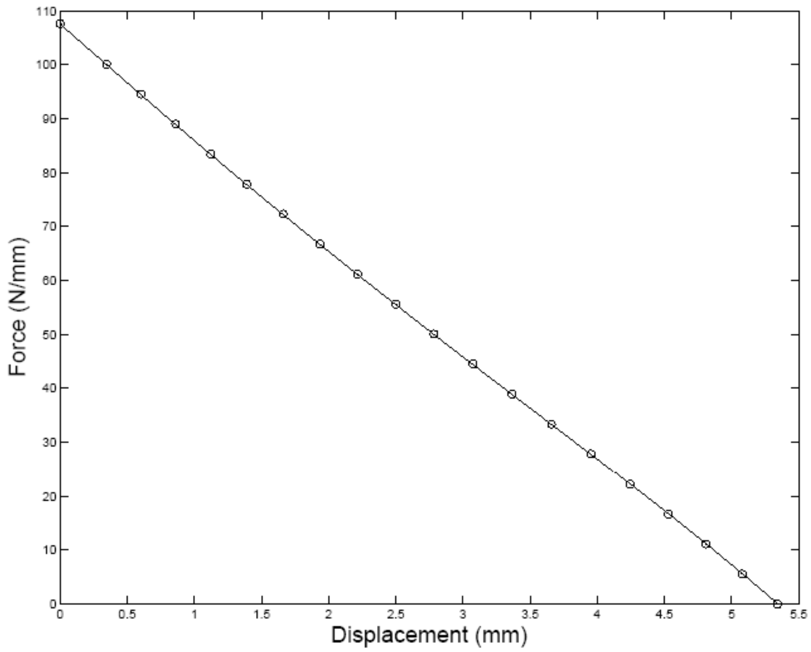

Figure 4. Force vs. Displacement in HCE

Conclusion

The HCE has potential to become an active element embedded in composite materials allowing the material to be both a structural material and an actuator that can perform work. The hourglass shaped studied here is only one possible shape for embedded elements. The shape of an embedded element can be optimized for different criteria depending on the application for which the MAC is designed. Once a well optimized core is completely designed, the next step will be to design an array of these core elements to create a useful MAC.

Acknowledgement

This material is based upon work supported by DARPA and the US Army Research, Development and Engineering Command under contract W911W6-04-C-0069.