MODELING SHAPE MEMORY POLYMER FILLED HONEYCOMB AS A COMPOSITE SKIN FOR A MORPHING WING

An Undergraduate Research Scholars Thesis

by

BROOKELYNN RUSSEY

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Research Advisor: Dr. Dimitris Lagoudas

May 2014

Major: Aerospace Engineering

TABLE OF CONTENTS

Page

ABSTRACT

Modeling Shape Memory Polymer Filled Honeycomb as a Composite Skin for a Morphing Wing. (May 2014)

Brookelynn Russey
Department of Aerospace Engineering
Texas A&M University

Research Advisor: Dr. Dimitris Lagoudas
Department of Aerospace Engineering

Due to its complex phase transformation behavior, a Shape Memory Polymer filled honeycomb composite has been proposed as an efficient material for skin on a morphing wing. This work develops a finite element model of the honeycomb composite that captures the material behavior while morphing through all geometric phases. To model the shape memory polymer filling, the simulation implements an experimentally calibrated user defined material subroutine in Abaqus, a commercially available finite element software. In order to validate the model, the modeled behavior is compared to experimentally determined behavior of shape memory polymers. The geometry and deformations of representative unit cells are then discussed.

ACKNOWLEDGEMENTS

I would first like to thank the Shape Memory Alloy Research Team (SMART) under Dr. Dimitris Lagoudas for use of their resources and guidance. I would also like to thank the UMAT's developer Dr. Brent Volk for teaching me to use it during previous research assistantships under the UMAT's creator, Dr. Brent Volk. Finally, I would like to thank University of Dayton Research Institute and the Air Force Research Laboratory for collaborating to create a working model of the honeycomb structure.

NOMENCLATURE

SMP	Shape Memory Polymer
AFRL	Air Force Research Laboratory
UMAT	User material subroutine
2D	Two Dimensional
3D	Three Dimensional
GUI	Graphical user interface

CHAPTER I

INTRODUCTION

Morphing wings have recently been a focus in the aerospace industry because of their ability to obtain more efficient configurations for different mission profiles. Although the graceful flight of birds has inspired flight for centuries, the complex and fluid motion of bird wings are difficult to model and reproduce mechanically. However, recent discoveries of advanced materials and actuators and the increased capacity of computer models have allowed researchers to reconsider mimicking bird flight mechanics for small aircraft. A bird’s wing efficiently provides lift by changing shape in different stages of flight. Geometry factors such as twist, cross-section camber, and sweep are different for take-off, gliding, and landing. Modern aircraft already use geometry variation to increase efficiency for different mission profiles, but not to the degree of that bird flight utilizes [1]. Mechanical actuators can be heavy. Movement of heavy aircraft requires more fuel, so designers must conduct trade-off studies to determine maximum efficiency. However, if the geometry can be altered without heavy mechanical actuators, designers can use a larger range of geometry variations. Recently developed “smart” materials can change shape without mechanical actuations. Stimuli such as temperature change, magnetic field, and electricity alter the materials at a microstructural level.

The skin on the morphing wing must satisfy two constraints: the in-plane stiffness must be low enough to easily manipulate the shape of the skin and the out-of-plane stiffness must be high enough to avoid deformation due to aerodynamic loads. While smart materials can satisfy the first constraint, they cannot satisfy the second without sacrificing morphing capabilities. One solution proposed involves the use of a honeycomb configuration. The honeycomb provides high stiffness along the plane of the honeycomb wall, while the filling material defines the in-plane stiffness [2].

Shape memory polymers (SMP), the proposed smart material filler, cure into an initial shape called the parent configuration. While the temperature of the SMP is above its glass transition temperature, the SMP is in the rubbery phase. The material properties of the SMP in the rubbery phase include a high elastic modulus and low stiffness, and the SMP can be easily manipulated into a secondary shape. If the SMP is held in the secondary shape while being cooled to below the glass transition temperature, the secondary shape can be maintained without applied force. The SMP then has a new set of material properties that include a low elastic modulus and high stiffness in a second state called the glassy phase. Upon reheating to above the glass transition temperature, the SMP returns to the rubbery phase and the parent configuration. This cycle, shown in Figure 1, can be repeated numerous times with different secondary shapes, allowing wing configurations for several mission profiles [3, 4, 5] .

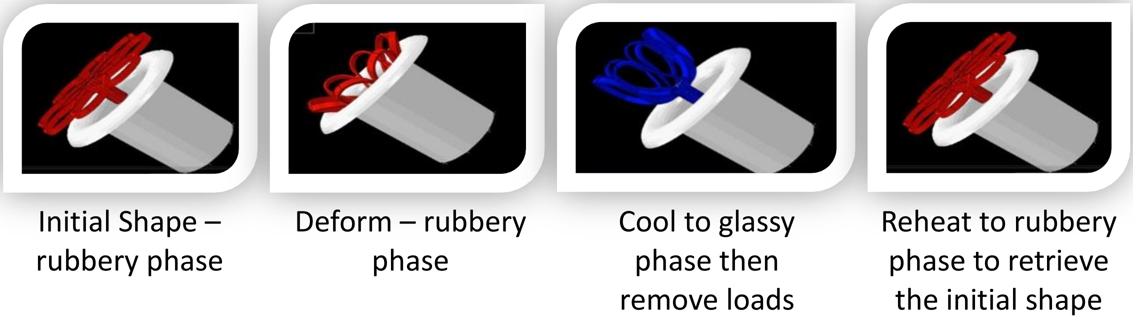


Figure 1: Phases of the shape memory cycle

Modeling the honeycomb composite requires understanding of the material in three phases: the rubbery phase, the glassy phase, and the transition phase between the two. During the transition phase, the material properties vary non-linearly with the temperature change. While models of the composite have been created for the rubbery phase and the glassy phase, few models attempt to incorporate the transition phase [6]. To fully model and optimize a morphing skin, all phases must be incorporated and analyzed.

A finite element model of all three phases is possible with the experimentally calibrated user material subroutine (UMAT) described in Volk et al. When the UMAT is implemented in Abaqus, a commercially available finite element software, a simulation of an SMP structure in the transition phase from glassy to rubbery can be produced.

Initially, the finite element model first included a single unit cell of the honeycomb structure to determine the computation requirements for a simple structure. Once the simple unit cell model is functional, a multi-cell skin will be modeled. Select cells will be heated and cooled through a phase cycle to morph the shape of the skin. Simulation results will be compared to experimental results. After the model is validated by experimental results, the skin will be optimized for a given wing configuration.

CHAPTER II

METHODS

2.1 Materials

2.1.1 Shape Memory Polymer

The shape memory polymer used for this study is a thermally crosslinked polyurethane. The polymer, as adapted from [7], is composed of the monomers 1,6-hexamethylene diisocyanate (HDI), N,N,N0,N0-tetrakis(2-hydroxypropy)ethylenediamine (HPED), and triethanolamine (TEA) [10]. This material is used, because it's highly crosslinked microstructure supports large deformation recoveries of 400% with enough strength to manipulate the aluminum honeycomb walls. The material has also been used in several demonstrations of applications of the SMP UMAT with Abaqus, and the computation methods in the UMAT were optimized using this material. A list of the material properties used for the model is seen in The subscripts r and g denotes a property present only in the glass or rubbery phase. The Shear modulus, Lamé constant, and coefficient of thermal expansion are G, λ, and α respectively. The final eight material properties represent the recovery behavior of the SMP from the deformed glassy phase to the parent rubbery phase. The temperatures at the beginning and end of the transformation phase are θ_{min} and θ_{max}. The variable A is the temperature at the inflection point and is also called the glass transition temperature. The scaling factor B is shown in

$$\phi(\theta) = \frac{\tanh\left(\frac{\theta max-A}{B}\right)-\tanh\left(\frac{\theta-A}{B}\right)}{\tanh\left(\frac{\theta max-A}{B}\right)-\tanh\left(\frac{\theta min-A}{B}\right)} \qquad \text{Eq. 1}$$

where ϕ is the glassy volume fraction as a measure of temperature. The glassy volume fraction is a measure of a fraction of the glassy phase scaled to 1. A visual of this relationship is seen in Figure 2. For this SMP the recovery behavior, a perfect hyperbolic tangent curve does not represent the behavior as well as a combination of two hyperbolic tangent curves. NormFact scales the first curve, and θ_{switch} is the temperature at which the first curve transfers to the second curve. The variables A_2 and B_2 are the inflection point and the scaling factor for the second curve [3,4,5].

Table 1. The subscripts r and g denotes a property present only in the glass or rubbery phase. The Shear modulus, Lamé constant, and coefficient of thermal expansion are G, λ, and α respectively. The final eight material properties represent the recovery behavior of the SMP from the deformed glassy phase to the parent rubbery phase. The temperatures at the beginning and end of the transformation phase are θ_{min} and θ_{max}. The variable A is the temperature at the inflection point and is also called the glass transition temperature. The scaling factor B is shown in

$$\phi(\theta) = \frac{\tanh\left(\frac{\theta max - A}{B}\right) - \tanh\left(\frac{\theta - A}{B}\right)}{\tanh\left(\frac{\theta max - A}{B}\right) - \tanh\left(\frac{\theta min - A}{B}\right)} \qquad \text{Eq. 1}$$

where ϕ is the glassy volume fraction as a measure of temperature. The glassy volume fraction is a measure of a fraction of the glassy phase scaled to 1. A visual of this relationship is seen in Figure 2. For this SMP the recovery behavior, a perfect hyperbolic tangent curve does not represent the behavior as well as a combination of two hyperbolic tangent curves. NormFact scales the first curve, and θ_{switch} is the temperature at which the first curve transfers to the second

curve. The variables A_2 and B_2 are the inflection point and the scaling factor for the second curve [3,4,5].

Table 1: Material Properties of the SMP entered into the UMAT

Property	
G_r (MPa)	8.5
λ_r (MPa)	4200
α_r (°C^{-1})	2.1E-04
G_g (MPa)	650
λ_g (MPa)	2600
α_g (°C^{-1})	7.8E-05
θ_{min} (K)	320
θ_{max} (K)	360
A (K)	350
B	3.1
NormFact	0.93
θ_{switch} (K)	340
A_2 (K)	510
B_2	18

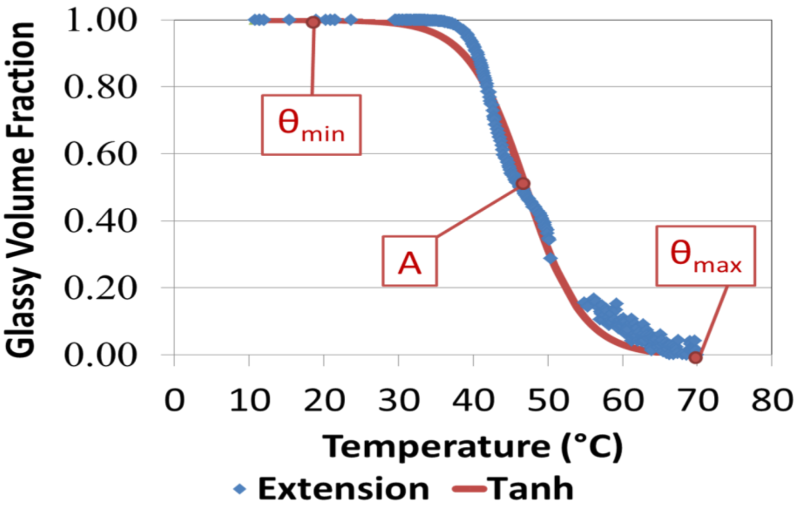


Figure 2: The transition phase as described by the glassy volume fraction. Θ_{min} and Θ_{max} denote the initial and final temperatures, respectively, of the transition between the glassy and rubbery phase. The glassy volume fraction is a measure of the fraction of glassy phase present out of 1.

2.1.2 Aluminum

The honeycomb walls in the model are composed of aluminum alloy 3003 and were constructed to mimic the honeycomb structure as purchasable from McMaster-Carr. In the model, the elastic modulus is 210 GPa and the Poisson's ratio is 0.33 [2].

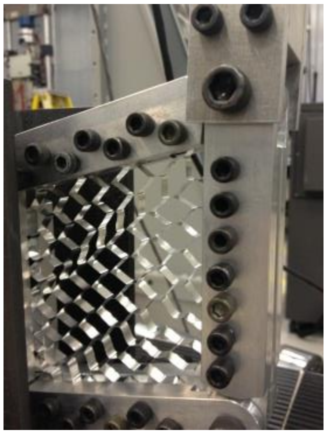
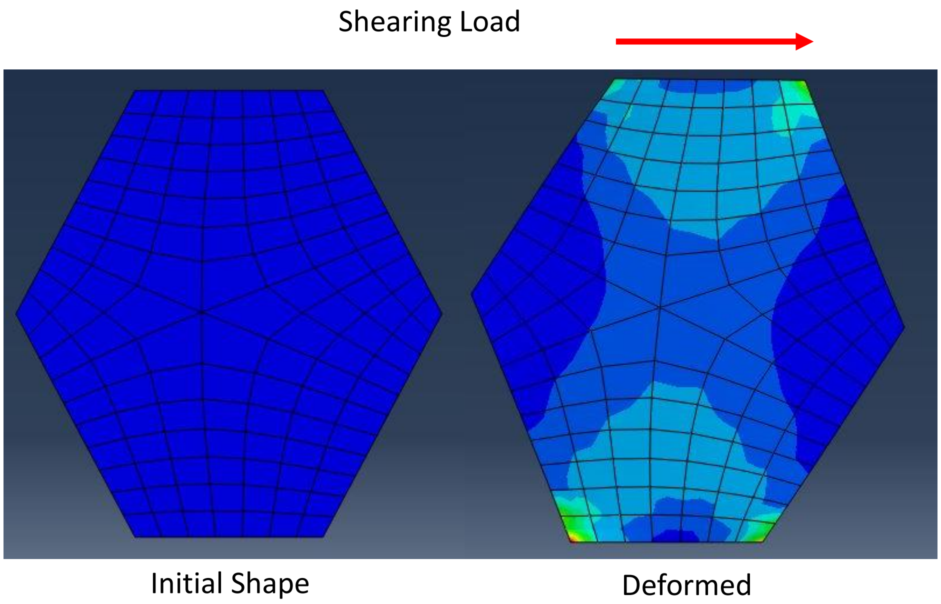


Figure 3: Empty aluminum honeycomb compressed in-plane.

2.2 Modeling Methods

The material properties are inserted into Abaqus to be used as parameters in a user material subroutine (UMAT). The UMAT overrides the simple finite element models for elastic materials and replaces it with a user defined model of the material's behavior. Abaqus is a commercially available finite element software with a graphic user interface (GUI). The interface was used to create unit cell models to determine appropriate geometry and strain limitations for individual cells. The unit cell models are split into three different types: SMP only, SMP/aluminum composite, and SMP/aluminum composite with periodic boundary conditions.

The SMP only unit cell models the only the hexagonal shape of the SMP filling. A boundary condition is applied to the bottom face that restricts displacement in all directions, and a shear load is applied to the top surface in the x-direction as shown in Figure 4. The SMP/aluminum composite had similar boundary conditions and loading. The geometry is shown in Figure 5. The final unit cell model is a 1 element thick 3D model of a representative unit of the honeycomb structure. Periodic boundary conditions are then applied to represent the interactions from the neighboring cells. The mesh of elements was created by cutting the unit cell into simple geometries to use the structured meshing module. Structured meshing reduces computation costs of the model. A screenshot of the Abaqus GUI is shown in Figure 6 with the elements of the unit cell model visible. The unit cell split into simple geometry is shown in Figure 7.



\

Figure 4: SMP unit cell with shearing load

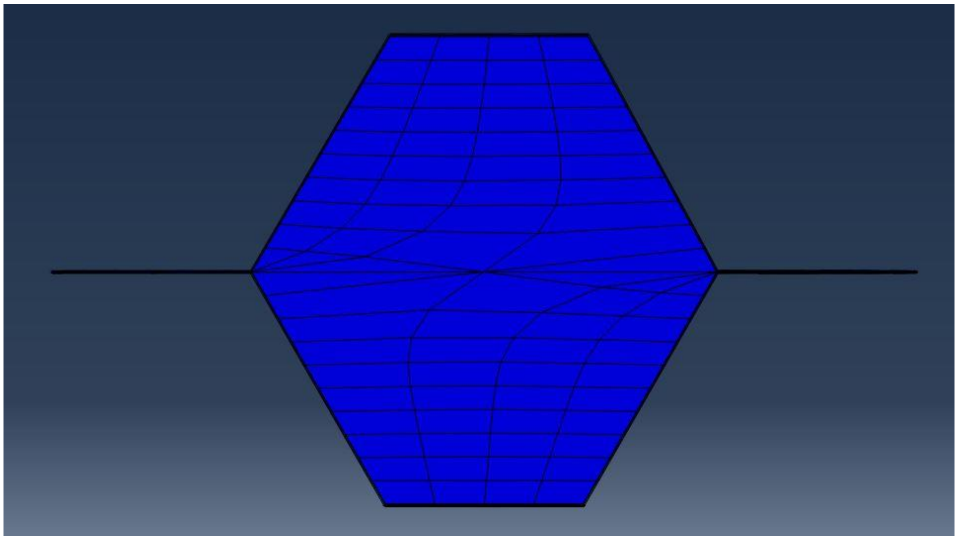
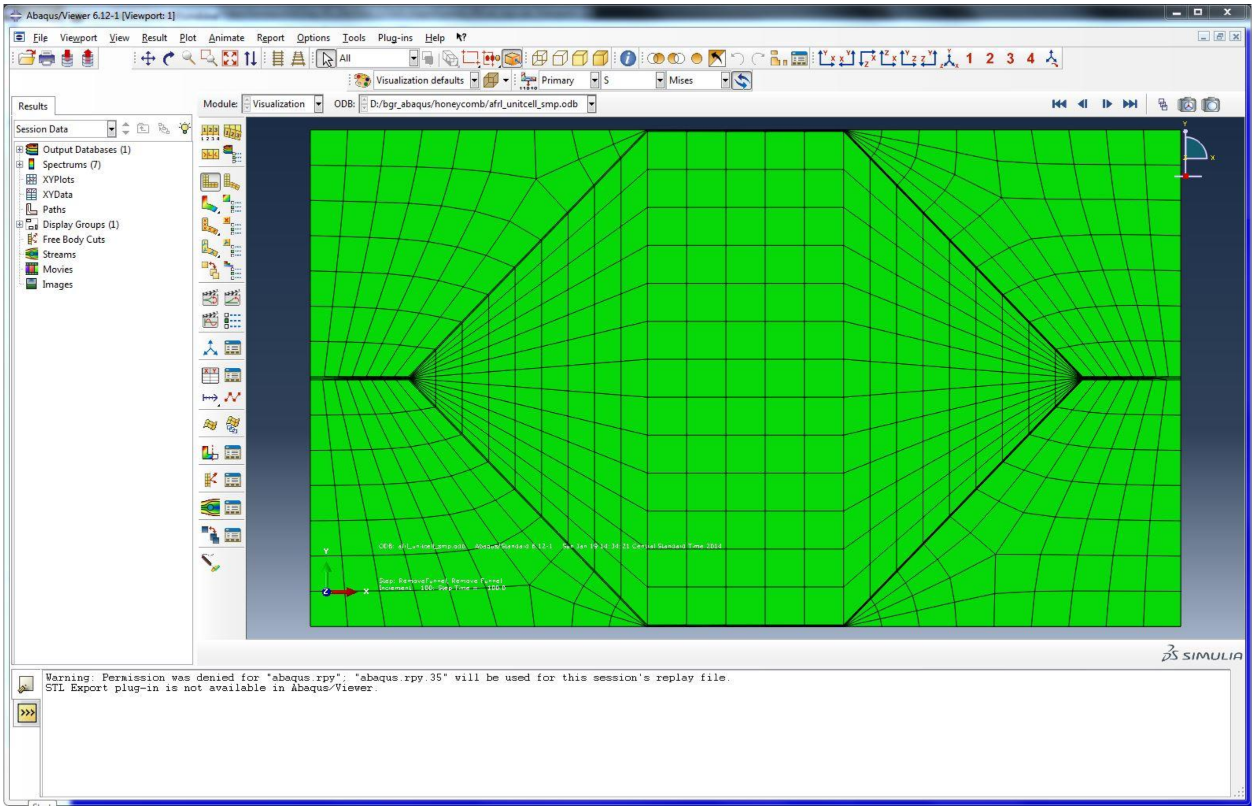


Figure 5: SMP/aluminum composite unit cell



Visualization defaults

Primary S Mises

Module: Visualization

ODB: D:/bgr_abaqus/honeycomb/afrl_unitcell_smp.odb

```
ODB: afrl_unitcell_smp.odb    Abaqus/Standard 6.12-1    Sun Jan 19 14:34:21 Central Standard Time 2014

Step: RemoveFunnel, Remove Funnel
Increment    100: Step Time =    100.0
```

```
Warning: Permission was denied for "abaqus.rpy"; "abaqus.rpy.35" will be used for this session's replay file.
STL Export plug-in is not available in Abaqus/Viewer.
```

Figure 6: Abaqus GUI with unit cell model.

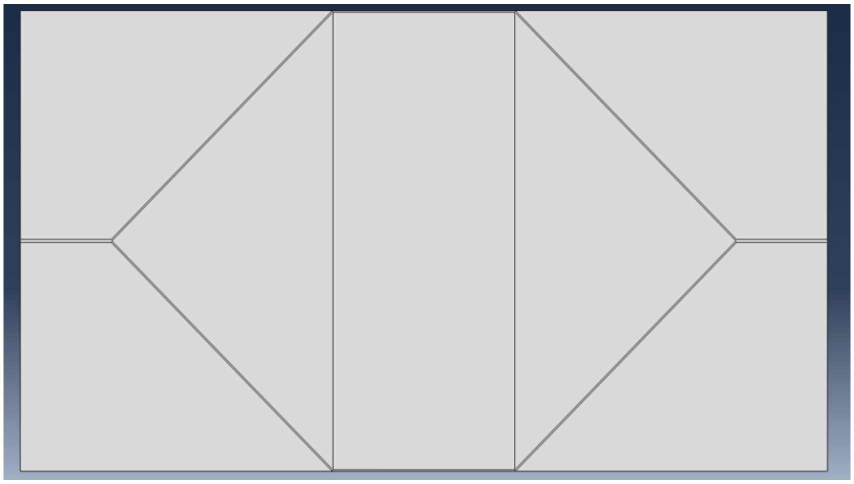


Figure 7: The unit cell split into simple geometries to create a mesh.

CHAPTER III

RESULTS

A successful simulation of the shape memory effect was accomplished with the model of the SMP only unit cell. The stress gradient at the end of each step is shown in Figure 8. The geometric deformation was reduced until the simulation converged, however the simulation took 3 days of computation time to complete. All deformation is recovered upon reheating, but residual stress is still present after fully reheating to the initial shape in the rubbery phase. Deformations in compression were also attempted, but the crosslinked microstructure of the SMP resists this type of deformation during the cooling phase.

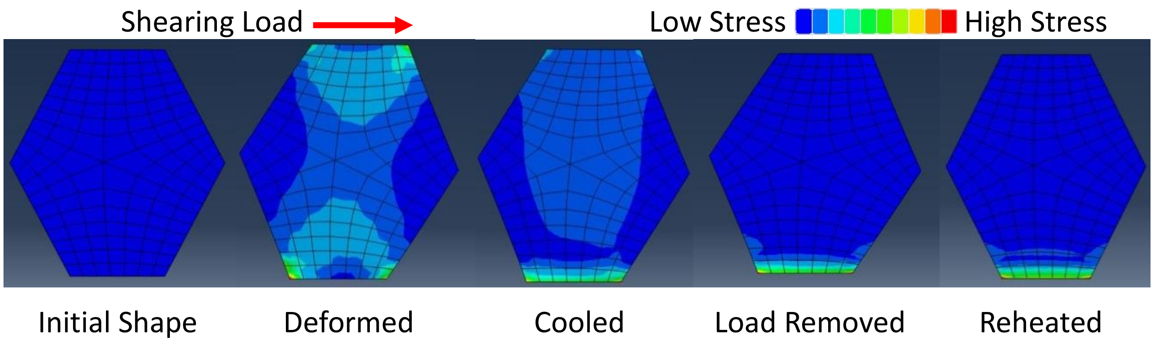


Figure 8: Successfully modeled shape memory cycle of the SMP only unit cell

The model of the SMP/aluminum composite unit cell shown in Figure 5 can only produce simulations for limited deformations as well. The aluminum further restricts recoverable strain by requiring the recovery force of the reheated SMP to overcome any plastic deformation in the aluminum. Since the elastic modulus of the aluminum is 5 orders of magnitude greater than that of the SMP in the rubbery phase and 3 orders of magnitude greater than that of the SMP in the glassy phase, a very thin aluminum honeycomb wall was selected. The final configuration has an aluminum wall that is 3 orders of magnitude thinner than the SMP honeycomb. This allows for slight deformations in the wall without preventing full recovery of the SMP upon reheating. The periodic boundary conditions were originally written for elements incompatible with the SMP UMAT. A new compatible version is currently in progress.

CHAPTER IV

CONCLUSIONS

The SMP unit cell results show a modeling limitation that does not exist physically. It is shown experimentally that an SMP can deform up to 400% and fully recover this deformation upon reheating. However, the SMP only unit cell could only deform up to 10% in the simulation and required 3 days to converge. The simulation is computationally expensive; however modern parallelization methods could improve performance. The language in which the UMAT is written Fortran is an older language that is less compatible with modern parallelization methods, but further improvements can be made. Further modeling of SMP composites is very limited by the high computation time and may not be very useful for complex models at the UMAT’s current state.

The geometry and possible deformations of a unit cell is limited in several ways. Deformations in compression would be limited to a fraction of the deformations in tension and shear. The aluminum walls must be at least 3 orders of magnitude thinner than the SMP filling to avoid unrecoverable plastic deformation in the aluminum. Plane strain problems involving 1 element thick models have shown to produce greater deformations than thicker models. Currently, simulations with thinner unit cells and greater deformations are being attempted.

In order to use the SMP UMAT, the recovery behavior must be observed experimentally and a hyperbolic tangent function must be fit to the experimental data. Currently, this process has only been completed for a few types of SMP. To ensure proper material selection, more types of SMP should be explored and modeled for an optimized design.

REFERENCES

[1] J. Valasek, Morphing Aerospace Vehicles and Structures, 2nd ed., Chichester, England: hovoken: John Wiley & Sons, 2012.

[2] R. V. Beblo, J. P. Puttman, N. E. DeLeon, J. J. Joo and G. W. Reich, "SMP Filled Honeycomb as a Reconfigurable Skin: Model and Experimental Validation," in *The International Conference on Composite Materials,* Montreal, 2013.

[3] B. Volk, D. Lagoudas and Y.-C. Chen, "Analysis of the finite deformation response of shape memory polymers: II. 1D calibration and numerical implementation of a finite deformation, thermoelastic model," *Smart Materials and Structures,* vol. 19, no. 7, 2010.

[4] B. Volk, D. Lagoudas, Y.-C. Chen and K. Whitley, "Analysis of the finite deformation response of shape memory polymers: I. Thermomechanical characterization," *Smart Materials and Structures,* vol. 19, no. 7, 2010.

[5] B. Volk, D. Lagoudas and D. Maitland, "Characterizing and modeling the free recovery and constrained recovery behavior of a polyurethane shape memory polymer," *Smart Materials and Structures,* vol. 20, no. 9, 2011.

[6] J. Puttman, R. Beblo, J. Joo, B. Smyers and G. Reich, "Design of a Morphing Skin by Optimizing a Honeycomb Structure with a Two-phase Material Infill," in *Smart Materials, Adaptive Structures, and Intelligent Systems*, Stone Mountain, 2012.

[7] T. S. Wilson, J. P. Bearinger, J. L. Herberg, J. E. Marion, W. Wright, C. L. Evans and D. J. Maitland, "Shape Memory Polymers Based on Uniform Aliphatic Urethane Networks," J. Appl. Poly. Sci., vol. 106, pp. 540-551, 2007.