Finite Element Analysis of a Shape Memory Polymer for Space Actuator Applications

Sreetam Das, Sourabh Kumar Singh, Avadesh Yadav, Satish Kumar* and Abhishek Kumar

Department of Applied Mechanics, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India

sreetam28197@gmail.com, sks314285@gmail.com, avadesh.yadav2008@yahoo.com, satistme@mnnit.ac.in, abhishek@mnnit.ac.in

Abstract

Shape memory polymer (SMP) belongs to a unique class of smart materials that has the ability to return to its original shape from a deformed temporary shape when subjected to external stimuli such as electricity, light, magnetism, pH value, moisture, and heat. This external stimulus helps the polymer recover its permanent shape by increasing the temperature above the polymer's glass transition temperature (Tg). The popularity of inflatable space structures has increased due to their low weight, high reliability, low volume, low cost, and easy packing. Antennas are one such space structure used to send and receive information over large distances. Antennas keep on moving in a constant path around the earth in different orbits. During movement in the orbits, the antennas are exposed to a constant variation in the temperature. This variation in temperature affects the dimensions of the antenna, thus having an adverse effect on the transmission of desired information. So, the idea of using shape memory polymer is to restrict the deviation of required dimensions. SMP plays a vital role in compensating for the dimension variation to keep the antenna structure in a definite shape due to its shape memory effect (SME). In the present study, the property of an SMP material is assigned to a beam which is modeled and simulated on a commercial finite element software Abaqus FEA. A hyperelastic model (Neo-Hookean) and generalized Maxwell model with viscoelastic property were used for simulation. It was found that when heat is provided to the SMP, viscoelastic prony's parameters, thermal expansion coefficient with varying heating rates, and temperature range have a significant effect on the total time taken to regain the desired shape.

Keywords: Shape memory polymer, glass transition temperature, finite element, viscoelastic, hyperelastic, antenna.

1. INTRODUCTION

Shape memory materials have the property to remember their original state of shape when deformed. Shape memory alloy (SMA) is a prime shape memory material which has varied applications ranging from space to biomedical. These alloys are able to transform between austenite and martensite phases based on temperature variation. This phase transition is used to deform the permanent shape and also to recover the distorted shape. Some of the common examples of SMAs are Ni-Ti and Cu-Zn. One such recent advancement is the emergence of shape memory polymer (SMP). Nowadays, polymers and their composites are widely used due to their outstanding properties like high strength to weight ratio, higher corrosion resistance, as well as excellent tailorability with low processing cost. SMPs return to their previous shape after a substantial plastic deformation under externally applied stimuli like direct heating, electrically induced heating, magnetically induced heating, light, and chemicals [1–4]. The most frequent triggering stimuli is heat, which raises the polymer's temperature over its glass transition temperature (Tg), where the permanent shape is distorted and regained.

Moreover, SMPs have extraordinary properties, such as higher recoverable strain (~400%) than conventional SMAs (~8%), which makes them viable for many researchers and industrialists [5–7]. Since weight is an important factor in any space mission, the use of SMP becomes advantageous as they have a weight significantly lower than that of SMA. Antennas are one of the most often used space structures for transmitting and receiving data over long distances. Antennas constantly rotate around the earth, experiencing a continuous temperature variation. These temperature variations alter the antenna component, changing the size and inhibiting data transmission. To limit the deviation of the components, SMPs can be used to constrain the changes allowing the antenna to maintain its shape without any change in the dimensions [8]. When the temperature hits a particular threshold value, the SMP starts to deform. As the temperature on the surface of the antenna is constantly fluctuating owing to the earth's rotation, SMP goes through many stages of expansion and contraction in a single day. Hence, there would be many recovery cycles during the course of its lifespan and experimentally verifying these cycles could be a challenging task. Polymeric bonds, cross-linking (chemically or physically), and functional groups all have a role in determining SMP characteristics [9]. There are primarily five steps to program a shape memory polymer. The polymer is first heated above Tg. The polymers stretch a little when the heat opens up the bonds. The chains are twisted around each other and locked while the polymer is below Tg. However, when the temperature increases above Tg, the polymeric chains gets soften and starts to behave like rubber. In the second stage, an external load is given to the polymer, altering its dimension to achieve a temporary shape occurring at a high temperature. In the third stage, the temperature is allowed to lower below Tg. In the presence of load applied from the outside, cooling the polymer locks it in the transitional form. Unloading is done in the fourth stage, which determines the stress relaxation factor, thereby helping to find the shape fixity of the polymer. In the final stage, the polymer is reheated to regain its original permanent shape. External stimuli such as heat, electricity, and light are delivered to the SMP, activating the polymer's bond and causing it to restore its form. The temperature at which an SMP transitions is determined by a number of parameters [1,10,11]. The Tg varies in direct proportion with the molecular weight of the polymer. A higher molecular weight means the chains are less mobile, which raises the Tg. Due to double bonds and bulky functional groups, the chain's mobility is restricted, resulting in a more significant Tg. The Tg value also increases due to cross-linking in the polymer.

The thermomechanical properties of an SMP are determined by using the constitutive equations. A typical linear viscoelastic model may be used to characterise the polymer's overall properties. Under varied conditions, the constitutive equation may predict the strain for different programming stages [12]. In the present study, programming of an SMP material is done to analyse the compression behaviour for three temperature ranges from 25-

45, 25-55 and 25-65 °C. The strain fixity and shape recovery ratio have been reported for the listed temperature ranges.

2. MODELLING AND PROGRAMMING

In the present work, two constitutive models are used to model SMPs. Primarily, the thermo-viscoelastic is the first model, while the secondary is phase transition model. The material is considered viscoelastic in the thermo-viscoelastic model, which is just an assembly of springs and dashpot, commonly known as the Maxwell model [13]. The thermo-viscoelastic model is quietly able to predict the polymer's behaviour based on time-temperature dependent responses for a full shape memory cycle. The thermo-viscoelastic model requires a high number of material parameters, and fitting the numerous parameters into one equation to obtain a generalized curve is complex and cumbersome.

2.1. Viscoelastic Model

Viscoelasticity is a term that refers to materials that are both viscous and elastic. One of the most prominent viscoelastic models is the generalized Maxwell model, which recognizes that material relaxation is a continuous process rather than an instantaneous event. A dashpot and a spring are linked in series in the Maxwell model. They are placed in parallel in the extended Maxwell model. When the temperature reaches the material's glass transition, the relaxation modulus (E) has a strong reliance on time. However, this dependency is greatly reduced when the temperature range is far away from Tg [14].

$$\mathrm{E}(t, T_{ref}) = \mathrm{E}(a_T t, T) \tag{1}$$

The Time-Temperature Superposition (TTS) principle is very well applicable to explain the influence of viscoelastic materials over a varied time and temperatures [15]. The shift factor (a_T) is used to connect the modulus at a reference temperature (T_{ref}) and time (t) to the modulus of relaxation at any time ($a_T t$) and temperature (T), as shown in equation (1). The T_{ref} and shift factor are usually determined from the Tg of the polymer as stated by WLF or Arrhenius equation [16]. After changing the curves, the master curve is obtained. Finally, the equation is fit onto the master curve where prony's series parameters are produced as shown in the equation (2).

$$\mathrm{E}(t) = E_\infty + \sum_{i=1}^{n} E_i \, e^{\frac{-t}{\tau_i}} \tag{2}$$

2.2. Hyperelastic Model

Rubber-like materials with a high elastic deformation region relative to other materials are modeled using the hyperelastic material model [17]. The stress-strain relationship in a hyperelastic model is derived from the density function of strain energy. This model is utilized near Tg in which the rubbery state of polymer is seen. The material hyperelastic reaction is modeled using the Neo-Hookean material model with a slow uniaxial strain rate.

2.3. Programming

The simulation is performed using the finite element-based software Abaqus FEA. Five phases of programming are performed on the SMP. The first stage is heating the polymer to a specific temperature and maintaining it. The second phase entails introducing uniaxial compression as an external load. The dimension of the beam is 200 mm x 15 mm x 3 mm where one end is rigidly fixed, and a compressive deformation of 20 mm is given in the form of load on the other end. The material is cooled to room temperature in the third stage. The load is removed and then reheated again in the final stage to witness the SME. For this purpose of model analysis, the Neo-Hookean parameters and viscoelastic parameters are drawn from the paper of Arrieta et al. [18]. Shape memory behaviour was observed for the polymer for different temperature ranges and the recovery and fixity ratios were calculated.

3. RESULTS AND DISCUSSION

The relationship between shape memory effect, and the temperature variation were found to be in good agreement. The simulation of SME in the temperature range of 25-45 °C is shown in Figure 1. After compression, when unloading takes place, the strain developed in the polymer significantly reduces from 20 mm to 11.49 mm, showing the shape fixity to be 58.95%, indicating poor SME. This indicates that the transition temperature is far away as many spring-back effects are seen. But as the temperature increases, it is seen that the shape fixity reaches 90.95% in the temperature range of 25-55 °C (Figure 2), which improves even further in the range of 25-65 °C (Figure 3), showing a fixity value of 93.29%. This indicates that the spring-back effect gets lower as the temperature increases up to a certain value offering a good range of shape fixity.

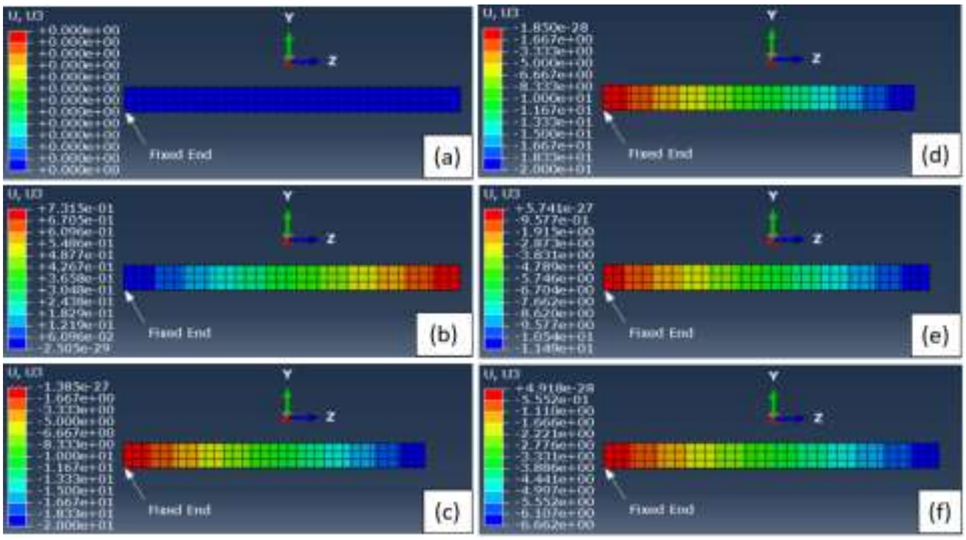

Figure 1. SME simulated in Abaqus FEA subjected to a compressive load during 25-45 °C: (a) Initial temperature of 25 °C, (b) Heat at 45 °C, (c) Load at 45 °C, (d) Cool up to 25 °C, (e) unload, (f) and again, reheat up to 45 °C.

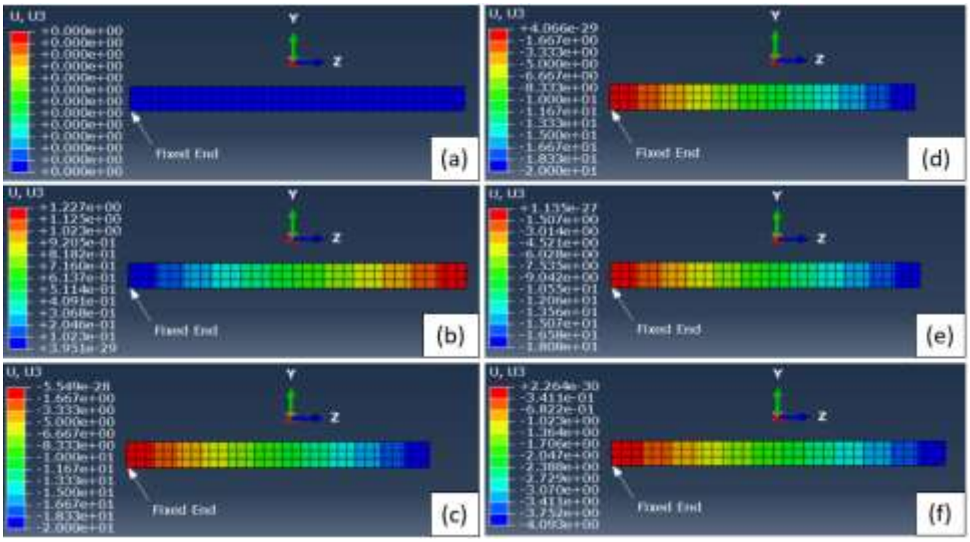

Figure 2. SME simulated in Abaqus FEA subjected to a compressive load during 25-55 °C: (a) Initial temperature of 25 °C, (b) Heat at 55 °C, (c) Load at 55 °C, (d) Cool up to 25 °C, (e) Unload, (f) and again, reheat up to 55 °C.

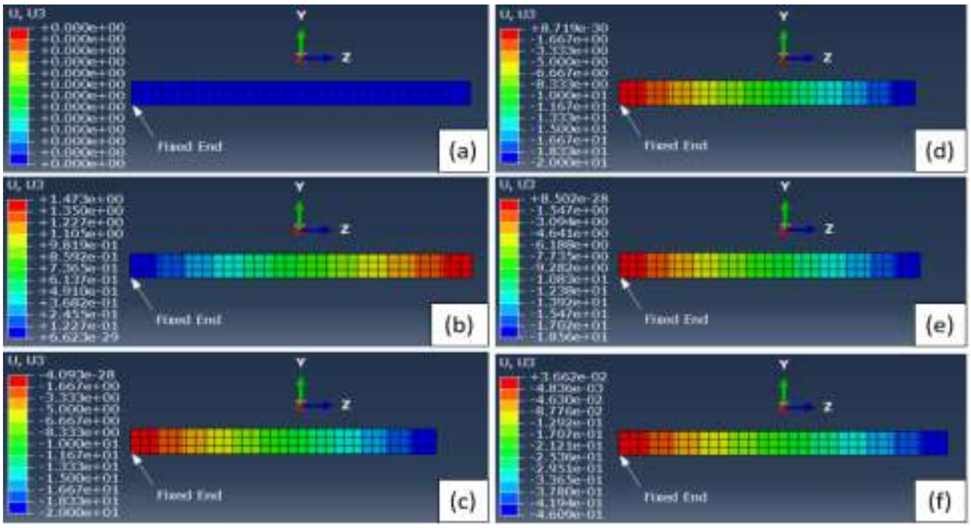

Figure 3. SME simulated in Abaqus FEA subjected to a compressive load during 25-65 °C: (a) Initial temperature of 25 °C, (b) Heat at 65 °C, (c) Load at 65 °C, (d) Cool up to 25 °C, (e) Unload, (f) and again reheat up to 65 °C.

Similarly, the shape recovery ratio also increases as the temperature reaches Tg. The values obtained are 64.33%, 74.93% and 90.99% when temperature rises from 45, 55 and 65 °C, respectively (Figure 1-3). This shows that as we move towards Tg, the spring back effect decreases, thus increasing fixity and recovery, which is depicted in Figure 4. Initially, the stresses are high at lower temperatures, and the polymeric chain is intact. As temperature increases, the chain starts opening and bond breakage takes place, making it more flexible and easy to recover. Hence, it can be inferred that the SMP is not programmable at lower temperatures showing poor fixity and recovery. But as the temperature keeps on rising and reaches in the range of Tg, a good amount of shape fixity and recovery is achieved, which makes it suitable for various space applications.

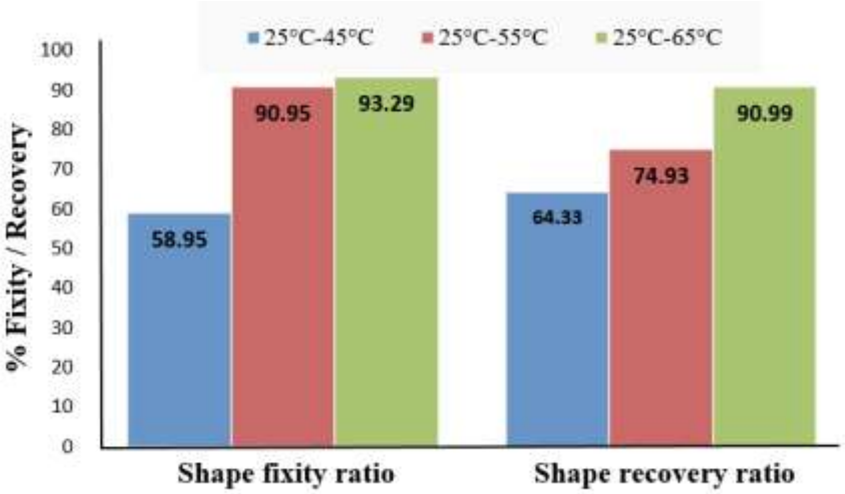

Figure 4. Shape fixity and shape recovery ratio for different temperature ranges.

4. CONCLUSION

In the current work, the shape memory effect of the SMP under uniaxial compressive strain was investigated using temperature variations as the external stimulus. Modeling and simulation is performed using the Abaqus FEA software by adopting the thermo-visco-hyperelastic theory. Many space actuators are subjected to compressive loads, and this model helps to determine the variation of SMEs under this loading condition. It is observed that the temperatures have a tremendous impact on the shape fixity and shape recovery of smart materials. At temperatures lower than that of Tg, the shape fixity is low due to the large spring-back effect as the material is unable to retain its shape. With the increase in temperature, the shape fixity and recovery improve. The fixity ratio increases with temperature because of stable and rigid bonds after the unloading stage, which keeps the deformed shape intact. As the polymer reaches a rubbery state in Tg region, the shape recovery becomes easier. In the temperature range of 65 °C, the fixity along with recovery was found to be above 90%. Thus, for an SMP to show a good SME, it has to be programmed just above the value of Tg. There are still many parameters that may affect the recovery behaviour of SMP and needs to be explored, which include holding duration, rate of temperature rise, environmental conditions, loading rate and polymer composition.

5. LIMITATIONS AND FUTURE SCOPE

During modeling and simulation, the material's properties are required to input which are obtained from the experimental results and it itself is a challenging task. The SMP made for the antenna has to be tested before being actually deployed in space. To test the SMP for the cycle of contraction and expansion, as well as its fatigue life, rigorous tests and space testing conditions must be further developed.

ACKNOWLEDGMENTS

The authors express their sincere obligation to Motilal Nehru National Institute of Technology Allahabad, Prayagraj for allocating finite element based simulation facility in order to model and simulate the shape memory behaviour.

REFERENCES

[1] Q. Zhao, H.J. Qi, T. Xie, Recent progress in shape memory polymer: New behavior, enabling materials, and mechanistic understanding, Prog. Polym. Sci. 49–50 (2015) 79–120.

[2] J. Hu, Y. Zhu, H. Huang, J. Lu, Recent advances in shape–memory polymers: Structure, mechanism, functionality, modeling and applications, Prog. Polym. Sci. 12 (2012) 1720–1763.

[3] A. Yadav, B.N.V.S.K.G. Gupta, A.O. Fulmali, R.K. Prusty, B.C. Ray, Effect of cure kinetics and nanomaterials on glass fiber/vinyl ester composites: An assessment on mechanical, thermal and fracture morphology, Mater. Today Proc. 33 (2020) 4937–4941.

[4] S.K. Singh, D. Singh, A. Kumar, A. Jain, An Analysis of Mechanical and Viscoelastic Behaviour of Nano-SiO_2 Dispersed Epoxy Composites, Silicon 2019 1210. 12 (2019) 2465–2477.

[5] L. Sun, W.M. Huang, Z. Ding, Y. Zhao, C.C. Wang, H. Purnawali, C. Tang, Stimulus-responsive shape memory materials: A review, Mater. Des. 33 (2012) 577–640.

[6] W.M. Huang, Z. Ding, C.C. Wang, J. Wei, Y. Zhao, H. Purnawali, Shape memory materials, Mater. Today. 13 (2010) 54–61.

[7] H. Li, C. Yu, R. Chen, J. Li, J. Li, Novel ionic liquid-type Gemini surfactants: Synthesis, surface property and antimicrobial activity, Colloids Surfaces A Physicochem. Eng. Asp. Complete (2012) 116–124.

[8] M. Chandra, S. Kumar, S. Chattopadhyaya, S. Chatterjee, P. Kumar, A review on developments of deployable membrane-based reflector antennas, Adv. Sp. Res. 68 (2021) 3749–3764.

[9] S.C. Arzberger et al., Elastic memory composites (EMC) for deployable industrial and commercial applications, SPIE. 5762 (2005) 35–47..

[10] R. Xiao, C. Zhang, W.M. Huang, Programming of Shape-Memory Polymers, Shape-Memory Polym. Device Des. (2017) 113–137.

[11] O.K.C. Tsui, H.F. Zhan, Effects of Chain Ends and Chain Entanglement on the Glass Transition Temperature of Polymer Thin Films, Macromolecules. 34 (2001) 9139–

9142.

[12] H. Tobushi, K. Okumura, S. Hayashi, N. Ito, Thermomechanical constitutive model of shape memory polymer, Mechanics of Materials. 33 (2001) 545–554.

[13] B. Radovskiy, B. Teltayev, Relaxation modulus and complex modulus, Struct. Integr. 2 (2018) 41–72.

[14] K.K. Westbrook, P.H. Kao, F. Castro, Y. Ding, H. Jerry Qi, A 3D finite deformation constitutive model for amorphous shape memory polymers: A multi-branch modeling approach for nonequilibrium relaxation processes, Mech. Mater. 12 (2011) 853–869.

[15] W.B. Luo, C.H. Wang, R.G. Zhao, Application of Time-Temperature-Stress Superposition Principle to Nonlinear Creep of Poly(methyl methacrylate), Key Eng. Mater. 340–341 (2007) 1091–1096.

[16] P. Liu, Viscoelastic bilinear cohesive model and parameter identification for failure analysis of adhesive composite joints using explicit finite element analysis, Damage Model. Compos. Struct. (2021) 175–190.

[17] J. Bergström, Mechanics of Solid Polymers: Theory and Computational Modeling, Mech. Solid Polym. Theory Comput. Model. (2015) 1–509.

[18] S. Arrieta, J. Diani, P. Gilormini, Experimental characterization and thermoviscoelastic modeling of strain and stress recoveries of an amorphous polymer network, Mech. Mater. 68 (2014) 95–103.

Biographies

Sreetam Das received his bachelor's degree in Mechanical Engineering from College of Engineering and Technology, Bhubaneswar in 2018. He is currently pursuing his master’s degree in Material Science & Engineering from Motilal Nehru National Institute of Technology Allahabad, Prayagraj.

Sourabh Kumar Singh received his bachelor's degree in Mechanical Engineering from Lovely Professional University, Punjab in 2020. He is currently pursuing his master’s degree in Material Science & Engineering from Motilal Nehru National Institute of Technology Allahabad, Prayagraj.

Avadesh Yadav received his bachelor's degree in Mechanical Engineering from Dr. A.P.J. Abdul Kalam Technical University, Lucknow in 2017 and completed his master’s in Metallurgical and Materials Engineering from National Institute of Technology Rourkela in 2020. He is currently pursuing his Ph.D. in the Applied Mechanics Department from Motilal Nehru National Institute of Technology Allahabad, Prayagraj. His thesis work is focussed on the shape memory polymer for structural applications

Dr. Satish Kumar is currently working as an Assistant Professor at Applied Mechanics Department from Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India. He has completed his B. Tech from NIT Jalandhar, M. Tech, and Ph.D. from IIT Roorkee. His research interests lie in the design, fabrication, and mechanical characterization of adaptive membrane-based lightweight structures for space applications, which he plans to study using a combined experimental and numerical approach.

Dr. Abhishek Kumar is currently working as an Associate Professor in the Applied Mechanics Department from Motilal Nehru National Institute of Technology Allahabad, Prayagraj. He completed his Ph.D. in the Department of Metallurgical and Materials Engineering from Indian Institute of Technology Roorkee in 2014. His research areas include design and development of microwave absorbers, synthesis and characterisation of nanomaterials, mechanical and corrosion behaviour of metals and alloys.