Design and Analysis of Shape Memory Polymer Mast Base on Numerical Simulation Method

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Abstract. As a space deployable structure, the space masts are widely used in the aerospace field. In the article, a new shape memory polymer (SMP) mast structure was designed and the compression folding behaviours of the SMP mast was investigated. The mast can automatic deployment due to the shape recovery characteristics of SMPs. The thermodynamic model of SMPs were realized by the finite element method. The numerical simulation of the fold and deployment process of the SMP mast were carried out, and the geometric parameters (wall thickness) and the influence of temperature on the folding performance of the mast were also investigated. The results contribute to the design and application of novel SMP mast.

Keywords. Space mast; Shape memory polymers; Finite element analysis; Fold

1. Introduction

SMPs are intelligent polymer materials with shape memory effect. They can change the initial shape under a certain conditions and fix the deformation temporarily, and recover to the original shape reversibly under specific external excitation[1]. SMPs are particularly promising in aerospace[2], biomedical[3], additive manufacturing[4,5] and other fields[6,7] due to their characteristic of high deformability, high shape recoverability and easy processing. There are many kinds of SMPs. According to the response to external excitation, SMPs can be classified into thermal drive[8,9], electric drive[10], light drive[11], chemical drive[12] and so on. Thermally driven SMP is one of the most prospective SMP materials because of its simple excitation form and fast response which is investigated in the present work.

Space mast is a one-dimensional deployable structure, which is a basic type of space deployable structure for constructing large complex space structures[13]. Space mast plays an important role in various space exploration activities. It is widely used in large deployment antennas[14], solar sails and telescope support back frames[15,16], space manipulators, etc. It realizes the function of deploying in space after launching from a small size on the ground[17]. Common space deployable structure has higher requirements on structure design, material design, folding mode, and there are technical difficulties in flexible deployment and post-deployment hardening. SMPs exhibit rubbery state with low modulus and stiffness at high temperatures, while it can transform to glassy state with large modulus and stiffness at low temperatures[18]. Therefore, it is very suitable to applying SMPs to the deployable structures.

The experimental method is difficult in the simulated space microgravity development environment, and the cost of space experiment is high. It is difficult to text a serious of different parameters and view the detailed through the experimental method. Therefore, the numerical simulation method with the advantages of high efficiency, high flexibility and high accuracy has become an effective research
method. In this paper, a folded tubular mast structure is designed based on SMPs. Compared with the traditional deployable structure, this tubular mast with a simple structure can be folded by the phase transition characteristics of SMPs and deployed actively by the shape memory characteristics of SMPs more easily. In order to understand the proposed research, a secondary development function of finite element method for space SMP intelligent structures under complex stress conditions was developed by using the three-dimensional constitutive equation of thermally driven SMPs. Then, the shape memory process of SMP mast structure was simulated and analyzed by finite element method. In addition, the effects of structural parameters (wall thickness) and temperature on the process of compression folding were investigated.

2. Constitutive equation

Study on the thermodynamic properties of SMPs is the key factor for its function realization and engineering application. The thermodynamic constitutive model of SMPs was constructed which is one of the main methods to predict the mechanical behavior of SMPs under different conditions, including stress-strain behavior at constant temperature and the varied temperature, shape memory behavior and other behavior in free and restrained states. In this paper, considering the thermodynamic properties of SMPs, a three-dimensional thermodynamic constitutive equation was introduced based on viscoelastic theory and a three-dimensional finite element program for SMP structures under complex stress conditions. The deformation process of SMP mast with shape memory effect is simulated by finite element method. The viscoelastic constitutive model describes shape memory effect mainly by means of stress advantage, equal strain, equal stress rate, equal strain rate and cyclic strain. It can describe the mechanical behavior of materials intuitively and clearly.

Tobushi et al. [19,20] developed a linear viscoelastic constitutive equation by introducing a slip element into a linear viscoelastic model:

\[ \dot{e} = \frac{\sigma}{E} + \frac{\varepsilon}{\mu} - \frac{\varepsilon - \varepsilon_s}{\lambda} + \alpha T, \quad \varepsilon_s = S \varepsilon_c \]

where \( \sigma, \varepsilon \) and \( T \) donate stress, strain and temperature, respectively. \( E, \mu, \lambda \) and \( \alpha \) are the elasticity modulus, viscosity coefficient, retardation time, Poisson’s ratio, respectively. \( \varepsilon_s \) is creep strain residual strain, \( \varepsilon_c \) is creep strain; \( S \) is the proportional coefficient of unrecoverable strain. Tao et al. [21] assumed that the polymer is an isotropic material and extended equation (1) from one-dimension to three-dimensions. The stress-strain-temperature relationship is as follows:

\[ \dot{\varepsilon}_y = \frac{\sigma_y}{\mu} + \frac{(1 + \nu)}{E} \sigma_y - \frac{\varepsilon_{ys}}{\lambda} + \left( \frac{1}{3 \lambda} - \frac{K}{\mu} \right) \delta_{yy} \delta_{kk} - \frac{\nu}{(1 - 2
\nu)} \delta_{yy} \dot{\varepsilon}_{kk} + \varepsilon' + \alpha \dot{T} \delta_{yy} \]

where \( \nu, C \) and \( \varepsilon' \) donate Poisson’s ratio, temperature-dependent scale factor and creep strain threshold, respectively.

In this paper, the subroutine called by the numerical simulation is the secondary development interface provided the commercial finite element software ABAQUS, and the user material subroutine (UMAT) of SMPs was written in Fortran language.

Equation (2) could be written as tensor compression form to yield equation (3). The three-dimensional constitutive equation is written as follows:

\[ \sigma_y + \frac{\mu (1 + \nu)}{E} \sigma_y = \frac{\mu e_{yj}}{\lambda} + \beta e_{yj} - \frac{1 - 5 \nu}{3(1 - 2 \nu)} \delta_{yj} \dot{\varepsilon}_{kk} - \frac{1}{3 \lambda} - \frac{\tilde{E}}{3 \mu (1 - 2 \nu)} \delta_{yj} \dot{\varepsilon}_{kk} - \mu \left( \frac{\tilde{E}}{3 \lambda} - \frac{\dot{\varepsilon}}{\lambda} \right) \delta_{yj} \]

where \( \tilde{E}, \tilde{\mu}, \tilde{\lambda} \) and \( \tilde{\varepsilon} \) represent elasticity modulus, viscosity coefficient, retardation time, Poisson’s ratio, and irreversible strain under different conditions, respectively.

The intermediate difference method is used to write the constitutive equation into an incremental constitutive, so the intermediate difference form of stress and strain can be written as
Substituting it into formula (3), the updated algorithm of normal stress and shear stress are expressed as follows:

\[
\begin{align*}
\frac{\Delta \sigma_{xx}}{\Delta \varepsilon_{xx}} &= \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} = \frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} = \frac{\Delta \sigma_{ss}}{\Delta \varepsilon_{ss}} = \frac{\Delta \sigma_{yy} + \Delta \sigma_{zz}}{2} + \frac{\Delta \varepsilon_{yy} + \Delta \varepsilon_{zz}}{2} \\
\frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} &= \frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} = \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} = \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} = \frac{1}{2} \left( \frac{\Delta \sigma_{yy} + \Delta \sigma_{zz}}{2} + \frac{\Delta \varepsilon_{yy} + \Delta \varepsilon_{zz}}{2} \right) \\
\frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} &= \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} = \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} = \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} = \frac{1}{2} \left( \frac{\Delta \sigma_{yy} + \Delta \sigma_{zz}}{2} + \frac{\Delta \varepsilon_{yy} + \Delta \varepsilon_{zz}}{2} \right)
\end{align*}
\]

(5)

The Jacobian matrix is expressed as:

\[
\begin{bmatrix}
\frac{\Delta \sigma_{xx}}{\Delta \varepsilon_{xx}} & \frac{\Delta \sigma_{ss}}{\Delta \varepsilon_{ss}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} & \frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} \\
\frac{\Delta \sigma_{ss}}{\Delta \varepsilon_{ss}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} & \frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} \\
\frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} & \frac{\Delta \sigma_{ss}}{\Delta \varepsilon_{ss}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} \\
\frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} & \frac{\Delta \sigma_{yy}}{\Delta \varepsilon_{yy}} & \frac{\Delta \sigma_{zz}}{\Delta \varepsilon_{zz}} \\
\end{bmatrix}
\]

(6)

3. Material parameter equation

The shape memory effect of SMPs is the result of phase transformation between glass state at low temperature and rubber state at high temperature. During glass transition, temperature has an effect on the mechanical properties of SMPs which means that the material parameters such as elastic modulus, viscous coefficient and retardation time vary with temperature. In order to describe the thermodynamic process of SMPs, the relationship between material parameters and temperature must be established. According to the previous research conducted by Balogun and Mo [22], a function describing reversible strain and material parameters is introduced into the model to explain the changes of polymer material parameters and reversible strain during the process of shape memory.

\[
z = 1 - \exp\left(1 + e^{\frac{\Delta \varepsilon}{0.5T_{g}-T}}\right)^{-1}, \quad a = \ln\left(\frac{\mu_{k}}{\mu_{f}}\right)
\]

(7)
where \( \mu_h \) and \( \mu_l \) denote viscosities coefficient at high temperature and low temperature, respectively. \( T_g \) is the glass transition temperature, \( T_{gh} \) is the temperature difference between low temperature and high temperature at the range of glass transition temperature.

The equation of material parameters as a function of the varying temperature is as follows:

\[
E(T) = (1-z)E_h + zE_l, \quad \mu(T) = (1-z)\mu_h + z\mu_l \\
\lambda(T) = (1-z)\lambda_h + z\lambda_l, \quad \nu(T) = (1-z)\nu_h + z\nu_l
\]

(8)

where \( E_h, \mu_h, \lambda_h \) and \( \nu_h \) are elasticity modulus, viscosity coefficient, retardation time, Poisson’s ratio, and threshold value of the creep strain at high temperature, respectively. \( E_l, \mu_l, \lambda_l \) and \( \nu_l \) are elasticity modulus, viscosity coefficient, retardation time, Poisson’s ratio, and threshold value of the creep strain at low temperature, respectively. Table 1 gives the polyurethane SMPs parameters. SMPs have a glass transition temperature of 328 K and a glass transition range of 308 K - 353 K.

| Material Parameters | \( E_h / E_l \) (MPa) | \( \mu_h / \mu_l \) (GPa s) | \( \lambda_h / \lambda_l \) (s) | \( \nu_h / \nu_l \) | \( \alpha \) (K\(^{-1}\)) | \( T_g \) (K) | \( T_{gh} / T_g \) |
|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Values              | 27.6/907            | 2.03/116            | 111/2840            | 0.45/0.33           | 11.6e-5             | 328                 | 353/308             |

4. Results and discussions

4.1. Deformation-process simulation of the SMP mast

The main design parameters of folded tubular mast are shown in Figure 1. \( h \) and \( t \) donate the unit’s height and the wall thickness, respectively. \( R_1, R_2 \) and \( r \) represent the small diameter, the large diameter and the transition arc's radius, respectively. The model was built using finite element software, and the quasi-static Newton-Raphson solution method was used to calculate the nonlinear incremental analysis. C3D8 hexahedron element with a cell size of 2 mm was used to mesh the model as shown in Figure 2. In order to ensure the uniformity of compression folding, a rigid circular plate is set up on the top and bottom of the mast. Frictionless contact was set between the rigid body and the mast. The mast is self-contacted and the displacement load is applied on the rigid body to realize the compression of the SMP mast.

![Figure 1. The diagram of SMP mast](image1)

![Figure 2. Schematic of SMP mast mashing](image2)

Finite element simulation shows the shape memory effect of the SMP folded tubular mast structure. The parameters setting of the initial configuration are set as follows: the wall thickness \( t = 2.5 \) mm, the unit height \( h = 20 \) mm, the small diameter \( R_1 = 50 \) mm, the large diameter \( R_2 = 70 \) mm and transition fillet radius \( r = 2.5 \) mm. In order to save the computational resources while ensuring the accuracy of the simulation, 5 units with a total length of 160 mm were selected considering the axial symmetry of the model.
Four steps for the compression folding and self-deployment process: 1) Set a temperature field of 343K; Reference points were set at the geometric midpoint of the upper and lower rigid plate respectively. Then, fix the lower reference point, constrain the upper reference points U1, U3, UR1, UR2, UR3 and applied a displacement of -130 mm. Due to the existence of contact between rigid body and mast, rigid constraints should be imposed on the top and bottom of the mast to ensure the deformation of the structure and convergence of calculation. Therefore, the upper and lower UR1, UR2, UR3 of the constraint pipe. 2) Changing the temperature field into 313 K without changing the above boundary conditions unchanged. 3) Applied a downward displacement on the rigid plate under the constant temperature of 313 K. After that, the compressive strain of the mast was frozen. The SMP mast retains the temporary shape of the previous step. 4) Recovering the temperature field of 343 K, the frozen strain is released, and the SMP mast restored from the temporary shape to the initial shape.

Figure 3. Deformation and stress distribution during folding process of SMP mast

Figure 3 shows the deformation and stress distribution during compression folding process of the SMP mast. The most important thing in the application of the mast is the stability and reliability of the folding process. Therefore, only the folding process was considered in the present work.

Figure 4. Force-displacement curve during compression folding process

Figure 4 shows the force-displacement curve in the process of compression folding. It can be seen that the folding process can be divided into three stages. The first stage is at the displacement range of 0-40 mm. Under the pressure caused by the displacement of rigid body, the mast is compressed axially, while the length of radial small diameter decreases and the length of large diameter increases. In this stage, the load increases nonlinearly and the increase speed slows down gradually. In the second stage where the displacement range from 40 mm to 120 mm, because of the deformation of mast, the mast
generate more contacts with rigid body. During folding process, the load increases linearly with the increase of displacement. It is worth mentioning that at the end of this stage, the load fluctuates slightly with a slightly unstable deformation. In the third stage, the self-contact of the mast appeared. With the increase of displacement, the load increases sharply. Finally, the compression deformation was completed and the folded mast structure was obtained.

The Strain energy-displacement curve in compression folding process is shown in Figure 5. It can be seen that there is no obvious difference between the first and second stages of compression folding deformation is not obvious. The strain energy increases nonlinearly with the increase of the displacement of the plate, and the rate of rise increases gradually. At the end of the compression folding process, the rate of rise suddenly increases, and strain energy changes to a larger value in a short time, which corresponds to the third stage of the compression process. Generally, the compression folding process of the structure is stable and reliable.

![Figure 5. Strain energy-displacement curve in compression folding process](image)

**Figure 5.** Strain energy-displacement curve in compression folding process

The SMP mast can be used as a deployable structure, requiring automatic recovery to the initial length after compression and folding under external excitation. Displacement-Temperature curves of the top of the structure during the whole process are plotted is shown in Figure 6. After unloading at low temperature in step 3, a small part of the deformation recovered, while most of the deformation was frozen, that is SMP mast can maintain folding state stably. In step 4, temperature risen from 313 K to 343 K, SMPs transformed from glass state to rubber state gradually, the frozen deformation was released, and the structure of SMP mast deploy to the initial state. At the end of this step, there is a small amount of irrecoverable residual strain, which also conforms to the material properties of SMPs[1].

![Figure 6. Displacement-temperature curve of the whole process of mast shape memory](image)

**Figure 6.** Displacement-temperature curve of the whole process of mast shape memory

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**4.2. Effect of the wall thickness**

Although the fold and deployment of SMP mast structure designed and studied in the present work is mainly depends on the difference of mechanical properties between glass and rubber state of SMPs and the shape memory effect of SMPs, its geometric shape and size also have an important influence on the working process. In order to investigate the effects of various factors on structural performance, the compression folding processes of SMP mast with different wall thickness and are simulated. Because of the compression folding process requires that the deformation be as smooth as possible without any bending eccentricity. The different wall thickness were considered first. The structure belongs to the thin-walled structure. In order to ensure the feasibility of the folding process and reduce the possibility of buckling, it is necessary to determine a reasonable wall thickness.
Figure 7. Compression folding process of SMP mast with different wall thicknesses

To explore the effect of the wall thickness on the properties of SMPs mast, the wall thickness is set from 1.5 mm to 3.5 mm, with an interval of 0.5 mm. The values of other structural parameters $R_1$, $R_2$, and $r$ are 50 mm, 70 mm and 2.5 mm, respectively. Figure 7 shows the force-displacement curves and strain energy-displacement curves of SMP mast with different wall thickness during folding. When the wall thickness is 1.5 mm, micro-buckling phenomenon appeared in the second stage of deformation during compression folding will appear due to the small wall thickness, but it has no influence on the completion of folding process. With considering the requirement of structural stability, it is considered that the wall thickness of 1.5 mm is not desirable. With the increase of wall thickness, the load required for each stage of compression folding is increasing and the whole process can be completed smoothly and steadily. Similarly, the strain energy increases with the increase of wall thickness. The strain energy almost doubles with an increment of the wall thickness of 0.5 mm. In addition, compared with the strain energy of the whole process under each wall thickness, the smaller the wall thickness, the easier the sudden change of strain energy occurs, that is, the easier the buckling phenomenon occurs. However, the value of strain energy mutation of the SMPs with different wall thickness is very small, therefore, it can be considered that the whole process of deformation is stable.

4.3. Effect of the temperature

SMPs are temperature-sensitive material which shows different mechanical properties at different temperatures. It is necessary to choose a reasonable temperature according to the requirement of structural mechanical properties. Therefore, the compression folding and deployment process of SMP mast at different temperatures are studied in this paper. Because the SMPs used in the simulations are polyurethane material with glass transition temperature of 328 K, and the loading deformation process needs to be carried out in the rubber state of SMPs. Therefore, the simulation temperature is 333 K - 353 K with an interval of 5 K, and the low temperature is set to 313 K.
Figure 8 shows the force-displacement curves and strain energy-displacement curves of SMP mast during the compression folding process at different temperatures. Due to the thermodynamic properties of SMPs, the higher the temperature, the lower the modulus and bending stiffness of SMPs. Therefore, in the process of compression folding, with the increase of temperature field, the load required in the process of compression folding decreases continuously. And there is no obvious distinction of the load between the first and second stages as well as the changing of strain energy. Moreover, the strain energy decreases gradually with the increase of temperature.

5. Conclusions
In this paper, a new SMP folding tube mast structure was designed and the compression folding behaviors of the SMP mast were investigated based on the construction of SMP three-dimensional constitutive model and the development of finite element UMAT. The structure can be folded to a smaller size at high temperature, the folding deformation can be temporarily maintained after unloading at low temperature, and the mast can actively deploy and recover to the original size after heating. The whole deformation process is stable and reliable.

Then, the shape memory effect of the SPM mast with different geometric parameters under different temperatures were explored. It is found that both the wall thickness and temperature have important effects on the compression folding of the mast. In the case of small wall thickness, the buckling occurs during the compression process of the mast. The deformation of the structure becomes more stable with the increase of the wall thickness. Simultaneously, the force and strain energy required in this process also increase. Above the glass transition temperature, as the temperature increases, compression folding of the mast also requires greater force and strain energy. This paper has certain guiding significance for the design, investigation and application of SMP intelligent materials in space deployable structures.

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