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Theoretical analysis and experiments of a space deployable truss structure

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ABSTRACT

Recently, the deployable structures fabricated using shape memory polymer composites (SMPC) have been developed for its unique properties such as highly reliable, low-cost, light weight and cost-effective mechanisms compared with traditional deployable structures. Shape memory polymer is a kind of smart materials which can memorize the permanent shape and can recover to original shape when be exposed to external stimulus. In order to eliminating effects of low stiffness and strength of pure shape memory polymer, shape memory polymer composites reinforced by particles, carbon nanotubes and fibers were studied. A deployable truss structure made of SMPC was analyzed and fabricated in this paper. The truss was made of multilayer carbon fiber reinforced epoxy-based shape memory polymer composites. Through DMA tests, the glass transformation temperature and mechanical properties of laminates which consist in deployable truss were obtained. The curves of recovery moment as a function of curvatures were also obtained in this paper. The deployable experiments were carried out in order to verify the rationality of deployable truss model. And the experimental results showed that the trusses fabricated in this paper can unfold smoothly and can also be applied as a space deployable structure in the field of spacecraft.

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1. Introduction

The deployable structures which are often found in some biological organism were widely used in the field of aircraft in order to solving the problems of packaging and deployment of large space structures during launching process [2,13,17]. So now the antennas, solar panels, radars and masts of satellites are all generally deployable in order to keep devices compact during launching process [24,18]. Recently, a deployable structural configuration has accomplished by using mechanical hinges, motor driven tools and other stored energy devices for traditional aerospace deployable devices [5,19]. But there are still some drawbacks which should also be solved immediately for traditional deployment devices, such as massive mechanisms, complex assembling process and large volumes during the progress of deployment [21,9].

During past decades, shape memory polymer (SMP) which is a new kind of smart materials has been discovered and a new deployable structure which was fabricated using shape memory polymer composite (SMPC) was discussed and manufactured [14,23]. The shape memory polymer which are a class of unique macromolecules have the ability of memorizing their permanent shape after undergoing a shape deformation [8] and can change their shape to original shape when be exposed to appropriate external stimulus such as heat [3,28], light [1,22,12], electricity [16] and magnetic [20]. It has drawn much attention and have been discussed extensively since been discovered during past decades [10,6]. The shape memory polymer which is a typical element in the field of shape memory materials process a series of advantages such as light weight, large recoverable strain, low energy consumption and excellent manufacturability [27,9]. As shown in Fig. 1, the thermo-mechanical cycle of SMP is consist of following steps: (1) heat and deform SMP above the glass transition temperature T_g; (2) cool SMP until under T_g and remove the external force; (3) heat the pre-deformed SMP above T_g and then it will recover to its original shape.

However, the pure SMP is inapplicable in the field of space deployable structure for its low strength and elastic modulus. Therefore, SMP composite (SMPC) filled with particles [7], carbon nanotubes [15], short fibers or continuous fibers [11] which have a higher strength were discussed to satisfy requirements in practical applications. Due to the role of hybrid fillers, the mechanical

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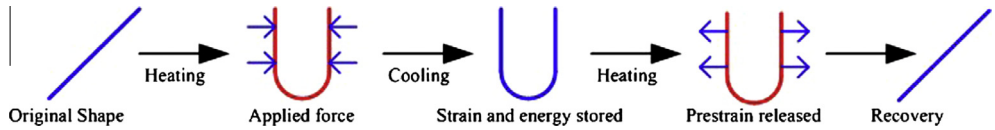

Fig. 1. Schematic of the shape memory effect during typical thermomechanical cycle.

properties of the materials were improved and the application range of shape memory polymer was extended greatly [4].

For the unique properties of shape memory polymer and its composite, they are supposed to have a most potential application in the field of space deployable structures such as hinges, truss, antennas, optical reflectors and morphing skins [25]. So, compared with traditional deployable structures, the new-type deployable devices fabricated using SMPs and their composites are more suitable for spacecraft. Recently, with the increasing of requirements and performance of deployable structures, this new-type deployable devices are playing a more and more important role in the field of deployable structures [13,17,18].

In this paper, a new-type deployable structure–deployable truss fabricated using carbon fiber reinforced epoxy-based shape memory polymer composite was investigated. Generally, the adding of hybrid fillers will weaken the deformability and shape memory effect of shape memory polymer composite. But in this paper, the deformation modes for shape memory polymer composites was bending rather than tensile or compression. The recovery ratio of laminates made of shape memory polymer composite was nearly 90% at or above the temperature of glass transition [26]. The glass transition temperature and mechanical properties of carbon fiber reinforced epoxy-based shape memory polymer composite were also measured through the dynamic mechanical analysis test. The geometry of the deployable truss was also obtained through theoretical analysis and simulations. Finally the unfold experiment of the shape memory polymer composite layer and the deployable truss were accomplished for the sake of confirming the theories established above. The recovery moment of shape memory polymer composite layer and the ratio of the deployable truss during unfold experiment were also obtained.

2. Synthesis and testing of epoxy-based shape memory polymer composite

In this paper, the matrix is epoxy-based shape memory polymer composite and the rein-force materials are carbon fibers tow. The model of carbon fiber tow used for deployable truss is T300-3K fabricated by company of Toray. The other material parameters of carbon fibers tow were listed in Table 1. The shape memory polymer composite laminates were fabricated in the method of compression moulding forming with four layers of carbon fiber tow. Firstly, four layers of carbon fiber tow were put in mould; then epoxy was pour into mould slowly in order to prevent the appearance of bubbles and wrinkles. Finally, the mould was solidified in a drying cabinet. Through the dynamic mechanical analysis test, the material parameters of shape memory polymer composite such as the stored modulus of elasticity, the glass transition temperature can be obtained (Fig. 2). The samples used for dynamic mechanical analysis test were cut into pieces of 50 mm × 9 mm × 3 mm and the test mode was three point bending. The effective span and experiment frequency were 40 mm and 1 Hz, respectively. The temperature range of dynamic mechanical analysis was from 20 °C to 200 °C with a heating rate of 2 °C/min. Here the glass transition temperature was the maximum of mechanical loss factor tan δ.

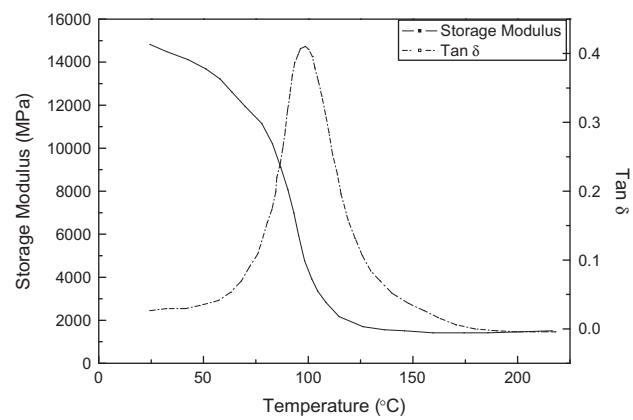

Fig. 2. The dynamic mechanical properties of carbon fiber reinforce SMPC.

The glass transformation temperature of the fiber reinforce epoxy-based shape memory polymer composite is about 100 °C as indicated in Fig. 2. The storage modulus of shape memory polymer composite is 14.5 Gpa at 25 °C With the increasing of temperature, the storage modulus of shape memory polymer composite will decrease especially around 100 °C due to the phase transition. And the storage modulus at 100 °C is 3.2 GPa. In the range of 100–200 °C the modulus of the material is only about 1 GPa.

3. Theoretical analysis and simulations

In order to achieve a higher bending moment, the structure of laminate used in the space deployable structure is thin-shell construction whose arc-angle is $2\pi/3$ and the thickness of the layers is 2 mm. And the laminates were all compression moulding forming structures with a length of 170 mm and a radius of 12.5 mm.

The schematic diagram of the deployable truss is shown in Fig. 3. The intermediate shaft of the deployable is an extensible sleeve. The laminates are all bended and fixed on the shaft. When be heated, the laminates made of shape memory polymer will unfold. And the shaft will also be elongated in the effect of unfolded layers. L_T is the length of single layer while L_C is the height of the single layer when it is compressed. And d_0 and d represent the radius of the intermediate shaft and cross-section when the deployable truss is compressed respectively. t is the thickness of the layer and is 2 mm herein. And the gap between the two joints is p; the angle of laminate can be represented by 2θ. The

Table 1
The material parameters of carbon fibers.

Product	Parameters					
	The class of fiber	The number of fiber tows	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)	Density (g/cm^3)
Carbon fiber	T300	3000	3530	230	1.5	1.8

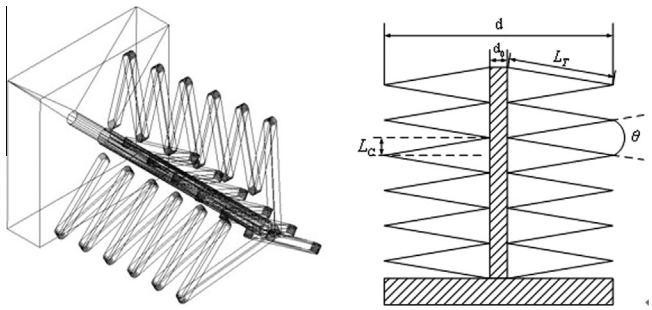

Fig. 3. The schematic diagram of the deployable truss.

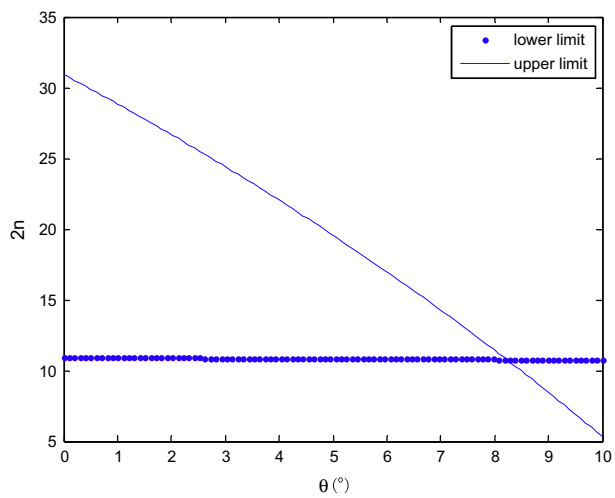

Fig. 4. The range of value allowed for the θ and $2n$ of deployable truss.

deployable truss is constituted by totally $2n$ sections. So the length of compressed truss is $2nL_C$.

The length of elongate truss can be expressed as

$$L_1 = 2nL_T \tag{1}$$

Taken the radius of bending curvature r into account, the length of the compressed truss is

$$L_2 = 2nL_C = 2n\left(L_T - \frac{\pi r}{2}\right)\sin\theta + 2n(t+r) + (n-1)p \tag{2}$$

And the radius of the cross section is

$$d = d_0 + 2(t+r) + (2L_T - \pi r)\cos\theta \tag{3}$$

For a higher compression ratio and practical application, the limitation for L_1, L_2 and d can be expressed as follows:

Table 2
Parameters of the deployable truss.

r (mm)	n	L_T (mm)	θ (°)	d_0 (mm)	p (mm)
5	6	85	⩽7.7	20	1

$$L_1 \geq 1000 \text{ mm} \tag{4a}$$

$$L_2 \leq 200 \text{ mm} \tag{4b}$$

$$d \leq 200 \text{ mm} \tag{4c}$$

For the condition of practical use and assembly results, we have

$$d_0 = 20 \text{ mm},\ p = 1 \text{ mm},\ r = 5 \text{ mm} \tag{5}$$

So the non-equality about n can be expressed as:

$$\frac{2000\cos\theta}{166 + 15.7\cos\theta} \leq 2n \leq \frac{402 - 2000\sin\theta}{13 - 15.7\sin\theta} \tag{6}$$

As shown in Fig. 4, the relationship between θ and $2n$ were simulated and the parameters of deployable truss can be finally confirmed (Table 2).

4. Deployable truss

The deployable truss is assembled by 18 deformed laminates whose length is 170 mm and their arc-angle, radius and thickness are $2\pi/3$, 12.5 mm and 2 mm respectively (Figs. 5 and 6). In this experimentation, the laminates should be firstly heated to glass transformation temperature through electricity using electro thermal film and then be manual bended until to π over against the original place. Cutting off the power, the laminates was cooled down and the stiffness will increase to the same as at general temperature.

Before assembling the shape memory polymer composite deployable truss, the relationship between the recovery moment and the angle of the layer was experimented. Based on the theory of moment balance, the recovery moment of deployable truss was tested using a force meter. In this experiment, one side of laminate was holded while the other side was connected with force meter. All the experimental process was recorded by a camera, therefore the recovery moment and deployable angle of laminates can be easily obtained. As shown in Fig. 7, the recovery moment decreases nonlinearly with the processing of deployment. The recovery moment at the beginning of the unfold process is 0.32 N m while it is only 0.22 N m in the final stage. Obviously, the recovery moment decreases slowly at the beginning and as time goes on, the decreasing rate grows rapidly as a result of phase transition. The rate of decreasing will achieve the maximum value at the glass temperature while the moment of the layer is 0.29 N m.

Fig. 5. The laminates which are used to assemble the deployable truss.

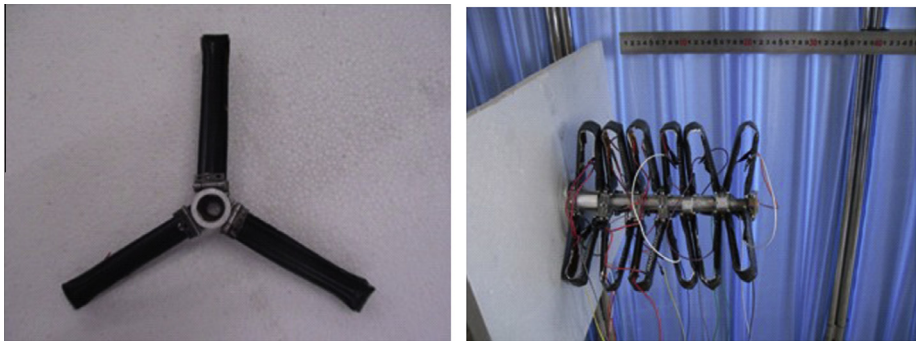

Fig. 6. The deployable truss made of carbon fiber reinforced epoxy-based SMPC.

As shown in Figs. 8 and 9, the unfold process of deployable truss was experimented. The ohm of electro thermal film was 86 Ω; the voltage and current were 0.2 A and 38 V, respectively. In the preliminary stage (0–30 s), the truss unfolded slowly for the reason of incompletely phase transition at a low temperature. With the increasing of temperature, the process of expansion accelerated

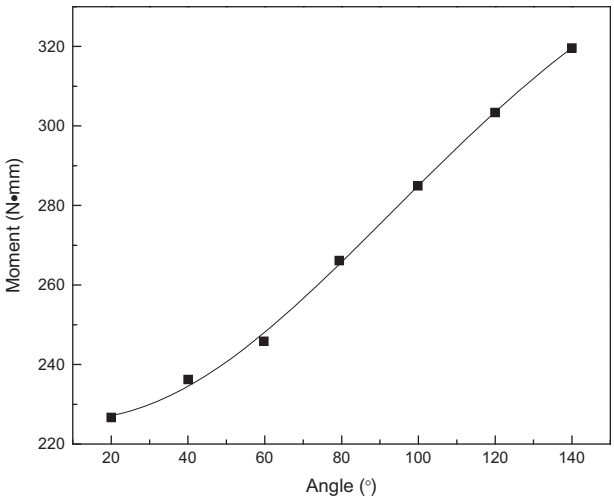

Fig. 7. The recovery moment of the SMPC layer during unfold process.

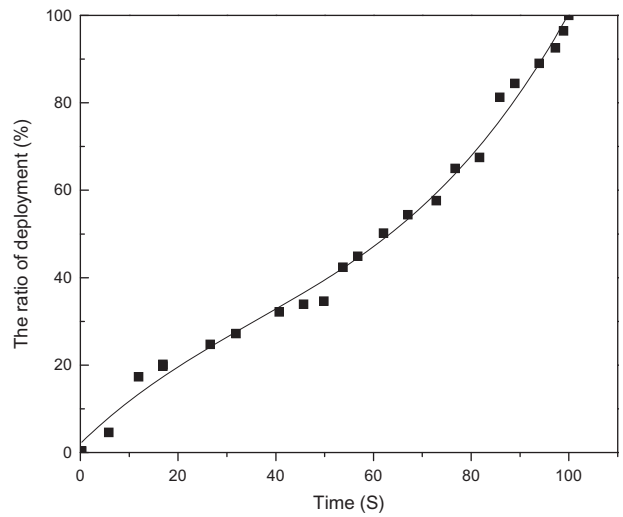

Fig. 9. The ratio of unfold process when the deployable truss was heated.

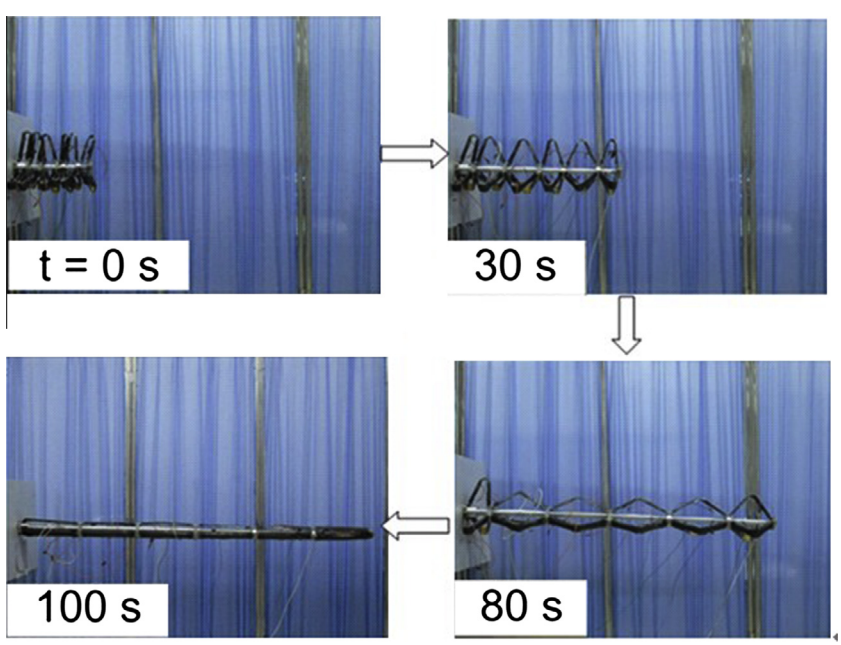

Fig. 8. The unfold process of deployable truss.

associated with the increasing of glass transition and strain energy dissipation in shape memory polymer. As time goes on (80–100 s), the phase transformation nearly accomplished and the unfold rate decreased slowly. Finally, the deployable truss completely expanded and the unfold process ended.

5. Conclusion

A deployable truss structure which can be used as the space deployable structure was fabricated in this paper. In order to determine the mechanical properties of carbon fiber reinforced expo-based shape memory polymer used in the truss, the dynamic mechanical analysis tests were carried out in order to obtain the material parameters such as the glass transition temperature and the elasticity modulus at different temperatures. The storage modulus of shape memory polymer composite is 14.5 GPa at room temperature while it is only 3.2 GPa at glass transition temperature T_g. The arc-angle and measurement of laminate were confirmed and finally a laminate model with a thickness of 2 mm and $2\pi/3$ arc-angle was established. In addition, the length and radius of laminate were 170 mm and 12.5 mm, respectively. The unfold experiment of shape memory polymer composite layer and the deployable truss were accomplished. And the recovery moment at the glass transition temperature was about 0.29 N m. It was turned out that the deployable truss fabricated in this paper can be used as a space deployable structure and can provide the recovery moment for the solar panel and deployable antenna during their process of expansion effectively.

Acknowledgement

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