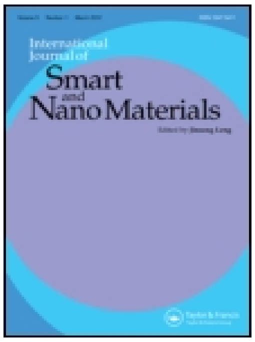


Taylor & Francis
Taylor & Francis Group

International Journal of Smart and Nano Materials

ISSN: 1947-5411 (Print) 1947-542X (Online) Journal homepage: http://www.tandfonline.com/loi/tsnm20

Preliminary design and analysis of a cubic deployable support structure based on shape memory polymer composite

Fengfeng Li, Liwu Liu, Xin Lan, Xiaojun Zhou, Wenfeng Bian, Yanju Liu & Jinsong Leng

To cite this article: Fengfeng Li, Liwu Liu, Xin Lan, Xiaojun Zhou, Wenfeng Bian, Yanju Liu & Jinsong Leng (2016) Preliminary design and analysis of a cubic deployable support structure based on shape memory polymer composite, International Journal of Smart and Nano Materials, 7:2, 106-118, DOI: 10.1080/19475411.2016.1212948

To link to this article: http://dx.doi.org/10.1080/19475411.2016.1212948

INTERNATIONAL JOURNAL OF SMART AND NANO MATERIALS, 2016
VOL. 7, NO. 2, 106–118
http://dx.doi.org/10.1080/19475411.2016.1212948

Preliminary design and analysis of a cubic deployable support structure based on shape memory polymer composite

Fengfeng Li[a], Liwu Liu[a], Xin Lan[b], Xiaojun Zhou[b], Wenfeng Bian[c], Yanju Liu[a] and Jinsong Leng[b]

[a]Department of Astronautical Science and Mechanics, Harbin Institute of Technology (HIT), Harbin, People's Republic of China; [b]Centre for Composite Materials, Science Park of Harbin Institute of Technology (HIT), Harbin, People's Republic of China; [c]Department of Civil Engineering, Harbin Institute of Technology, Weihai, China

ABSTRACT

The deployable structures based on shape memory polymer composites (SMPCs) have been developed for its unique properties, such as high reliability, low-cost, lightweight, and self-deployment without complex mechanical devices compared with traditional deployable structures. In order to increase the inflatable structure system's robustness and light the weight of it, a cubic deployable support structure based on SMPC is designed and analyzed preliminarily. The cubic deployable support structure based on SMPC consists of four dependent spatial cages, each spatial cage is composed of 12 three-longeron SMPC truss booms and end connections. The shape recovery of arc-shaped deployable laminates drive the three-longeron SMPC truss booms to unfold, thus realize the expansion of the deployable support structure. The concept and operation of the cubic deployable support structure are described in detail. A series of experiments are performed on the three-longeron deployable laminates unit and the simplified cubic deployable support structure to investigate the shape recovery behavior in the deployment process. Results indicate that the cubic deployable support structure has a high deployment-tgo-stowage volume ratio and can achieve self-deployment, package, and deploy without complex mechanical devices.

ARTICLE HISTORY
Received 20 May 2016
Accepted 11 July 2016

KEYWORDS
Shape memory polymer composites; deployable structure; shape recovery experiment

1. Introduction

Since the discovery of the shape memory polymers (SMPs) in the 1980s, international research interest into the shape memory effect in polymers has been rapidly growing [1–8]. SMP is a typical kind of smart material, which presents high strain capacity (an order of 100% reversible strains), low density and low cost, etc. [1–12]. However, SMPs also have some drawbacks, such as low strength, low stiffness, and low recovery stress [1–14]. Consequently the fiber-reinforced shape memory polymer composites (SMPCs) have been developed in practical applications to satisfy demand, the results of studies

CONTACT Jinsong Leng lengjs@hit.edu.cn Centre for Composite Materials, Science Park of Harbin Institute of Technology (HIT), P.O. Box 3011, No. 2 YiKuang Street, Harbin 150080, People's Republic of China

on SMPCs indicate that SMPCs have higher strength, higher stiffness, and certain special characteristics determined by what fillers are added, which can offer further advantages over SMPs [9–19]. Due to the excellent qualities of SMPs, they are considered as promising alternatives for the future's tunable components in various applications, such as microelectromechanical systems, surface patterning, biomedical devices, aerospace deployable structures, and morphing structures [15,20–27].

In the early of the twenty-first century, the space inflatable structure is one of the emerging enabling technologies for space applications because inflatable structures are lightweight and have a small packing volume [28–31]. It can potentially revolutionize the designs and applications of large space structural systems. Currently existing deployment approaches of large space structures typically rely upon electromechanical mechanisms, which ensure them to unfold and maintain the fully deployed, operational configuration [32]. For traditional inflatable structures, these support structures and their associated deployment mechanisms, launch restraints and controls, comprise more than 90% of the total mass budget for a deployed assembly [33,34]. In order to light the weight and reduce the mechanical complexity of the inflatable structure system, we have designed and analyzed a cubic deployable support structure based on SMPC preliminarily. The cubic deployable support structure performs high packaging efficiency for launch, self-deployment without complex mechanical devices and can improve the robustness of the inflatable structure system.

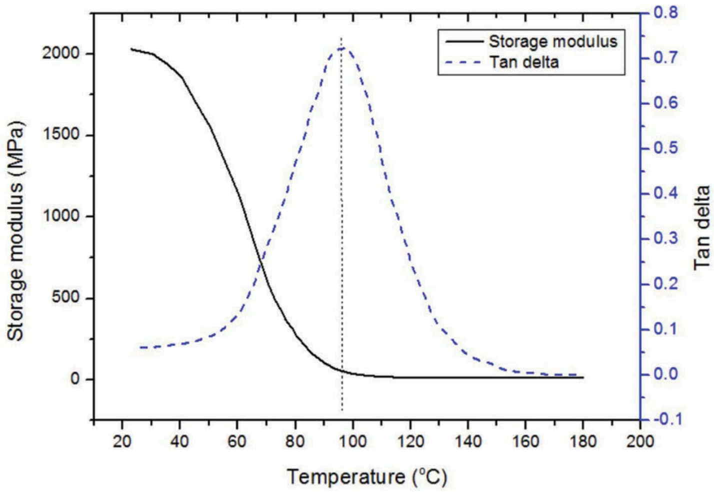
2. Dynamic mechanical analysis test

In this study, a type of carbon fiber-reinforced epoxy-based SMPC is chosen as the primary material. The matrix used in this work is epoxy-SMP proceed by Leng's research group [11]. The SMPC is fabricated by the hand molding technique for fiber-reinforced composite materials and the reinforcement is four plies carbon plain fabric. Dynamic mechanical analysis tests are carried out to investigate the basic thermo-mechanical performances of the SMP and SMPC. The test mode is tension. The scanning range of temperature is 20 ~ 180 °C at a heating rate of $2^{o}C/\min$ and a frequency of 1 Hz. The dimensions of specimens are 18 mm × 2 mm × 3 mm. The results of the DMA tests are presented in Figure 1.

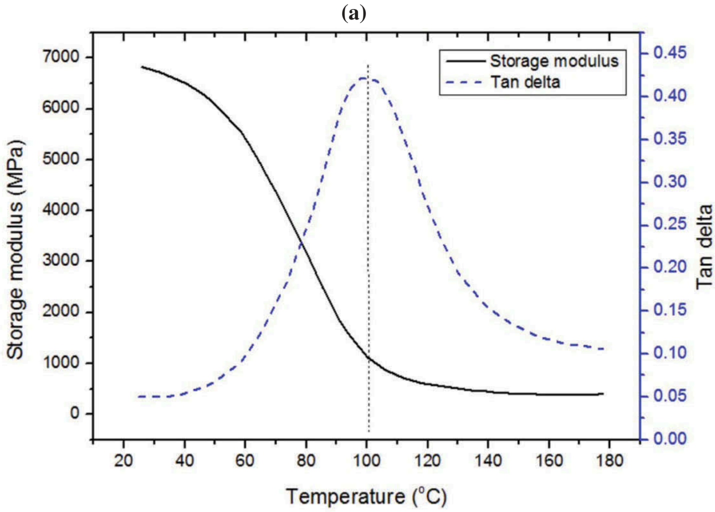
The peak value of tangent delta is defined as the glass transition temperature (T_g). The glass transition temperature of epoxy-SMP is about 96.2°C as indicated in Figure 1 (a). The storage modulus of epoxy-SMP is 2.03 GPa at 20°C. With the increasing of temperature, storage modulus decreases from 2 GPa to 15 MPa (100°C) due to the phase transition. Figure 1(b) shows that the T_g of SMPC fabricated in this study is 100.2°C. The storage modulus of SMPC is about 7 GPa at 20°C; and it decreases from 6 GPa to 1 GPa precipitously within the region of 60 ~ 100°C, when the temperature above 100°C, the SMPC's matrix turns to viscoelastic state, the storage modulus is about 0.5 GPa.

3. Design of the cubic deployable support structure

The cubic deployable support structure based on SMPC consists of four dependent spatial cages; each spatial cage is composed of 12 three-longeron SMPC truss booms



(a)



(b)

Figure 1. (a) Curves of storage modulus and tangent delta versus temperature for epoxy-SMP. (b) Curves of storage modulus and tangent delta versus temperature for carbon fabric-reinforced epoxy-based SMPC.

and end connections, as shown in Figure 2. The three-longeron SMPC truss boom is the main component of the structure; it consists of one extendable central bracket, arc-shaped deployable laminates, and connectors. The extendable central bracket is made up of sleeves. Three arc-shaped deployable laminates with an angle of 120° to each other can be treated as one cell (as shown in Figure 2(b)) and every cell is connected by connectors. A resistor heater is stuck to the surface of every arc-shaped deployable laminate. The arc-shaped deployable laminates are the longerons of the SMPC truss boom, which are packaged into an 'V-shape' first; when the resistor heaters are electrified, the laminates gradually deploy with increasing time. The laminates provide the deployable driving force and undergo the tip payloads at the end of deployment. Once the deployment is done, the three-longeron SMPC truss

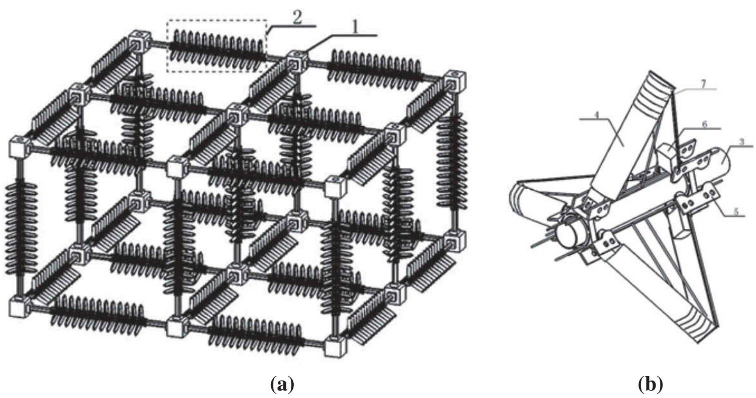


Figure 2. (a) Cubic deployable support structure, (b) three-longeron deployable laminates unit, 1 – end connection, 2 – three-longeron SMPC truss boom, 3 – extendable central bracket, 4 – arc-shaped deployable laminate, 5, 6 – connectors, 7 – resistor heater.

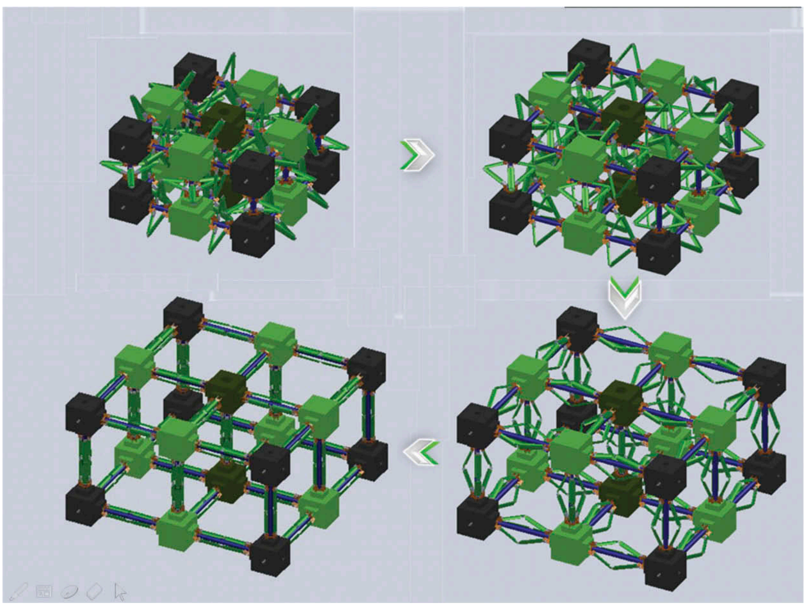
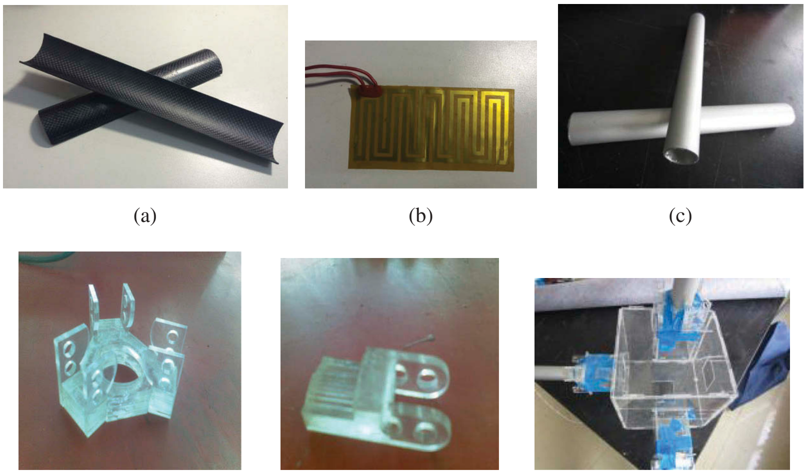


Figure 3. The process of all SMPC truss booms deploy simultaneously.

booms will form a tubular-shaped boom. Here are the two ways of deploying, one is the SMPC truss booms in all three orthotropic directions deploy simultaneously, which can save time (as shown in Figure 3); the other is the SMPC truss booms in the same direction deploy simultaneously, when the deployment in one direction finishes, the next deployment of different direction starts. The time of second way would be longer, but it can reduce the incoordination possibility in deployment process.

For the requirements of different deployment-to-stowage volume ratio of the cubic deployable support structure, it can be realized by changing the size of three-longeron



(a) (b) (c) (d) (e) (f)

Figure 4. The components: (a) arc-shaped deployable laminate, (b) resistor heater, (c) extendable central bracket, (d, e) connectors, (f) end connection.

SMPC truss boom. Also, the changes of sleeves, arc-shaped deployable laminates' geometry parameters, and the angle between the two adjacent arc-shaped deployable laminates can meet the specific requirements of the three-longeron SMPC truss boom.

4. Manufacture of the deployable structure

For verifying the feasibility of the cubic deployable support structure, we manufactured a simplified one. The simplified structure has one cage, which comprises 12 three-longeron deployable laminates units. The deployed three-longeron deployable laminates unit (as shown in Figure 2(b)) consists of three arc-shaped deployable laminates, two connectors, and two sleeves. Figure 4 shows the components of the structure, the arc-shaped deployable laminate is made of carbon fiber-reinforced SMPC, the extendable central bracket is made of aluminum alloy sleeve, the connector, and end connection are made of acrylic board. Figure 5 presents the simplified structure.

5. Experiment

In the cubic deployable support structure based on SMPC, the basic effective unit is three-longeron deployable laminates unit whose properties reflect the characteristics of the whole structure. Two experiments of the three-longeron deployable laminates are carried out to test its recovery properties. One experiment of the simplified cubic deployable support structure is done to test its recovery feasibility. The parameters of the arc-shaped deployable laminate used in the experiment are: length 300 mm, outer radius 25 mm, inner radius 23 mm, thickness 2 mm, arc angle 120°, carbon fiber-reinforced epoxy-based SMPC, the four ply carbon fiber orientation is 0°/90°/0°/90°.

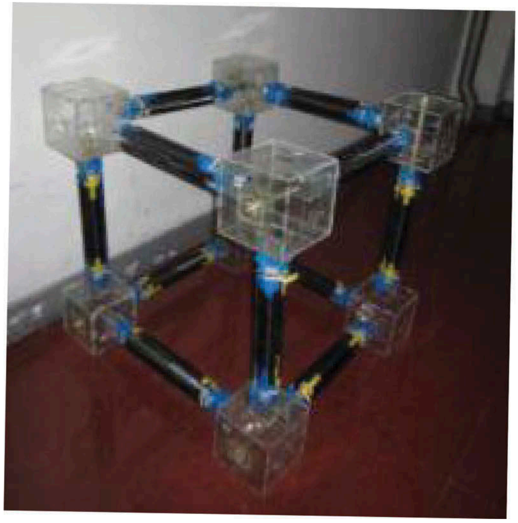
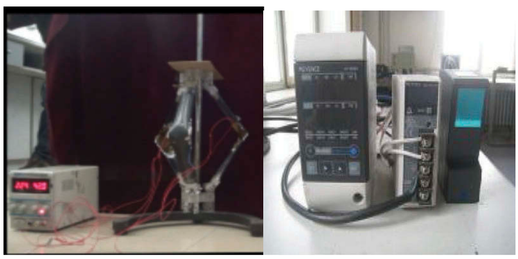


Figure 5. The simplified cubic deployable support structure.



(a) (b)

Figure 6. (a) The three-longeron deployable laminates unit and (b) laser rangefinder.

5.1 *Experiment of three-longeron deployable laminates unit bending recovery*

In this experiment, laser rangefinder equipment is used to measure the displacement of the three-longeron deployable laminates unit in deployment process (as shown in Figure 6).

The experimental method is as follows: First, stick one resistor heater to the inside surface of the arc-shaped deployable laminate, use a high temperature furnace (the temperature is above the T_g) to heat the arc-shaped deployable laminate until it soften, bend the arc-shaped deployable laminate to 180° along the shortest center line. Second, assemble the three-longeron deployable laminates with three bent arc-shaped deployable laminates and two connectors, then fix one end of it, the other end fixed a level paper baffle (light) for laser ranging (as shown in Figure 6(a)). Third, put the laser rangefinder above the three-longeron deployable laminates unit, measure the initial distance between level paper baffle and laser rangefinder, clear the instrument reading to zero. Finally, electrify the resistor heaters simultaneously; the actual output voltage is 40 V. The resistor heaters heat the arc-shaped deployable laminates and the three-

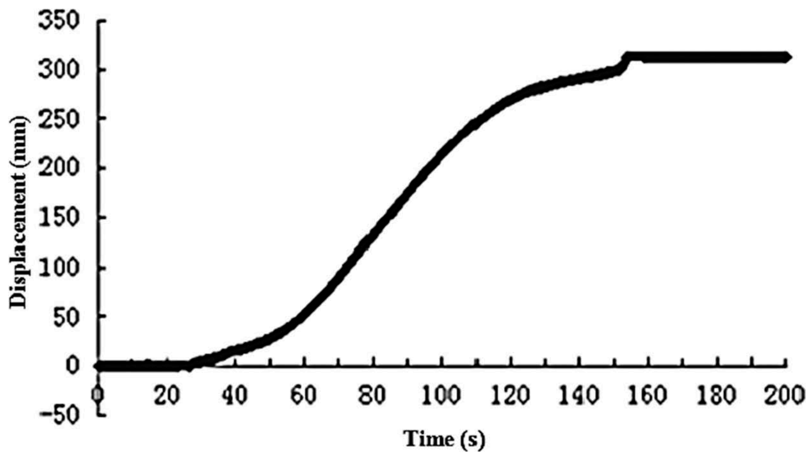


Figure 7. Deployment time–displacement curve.

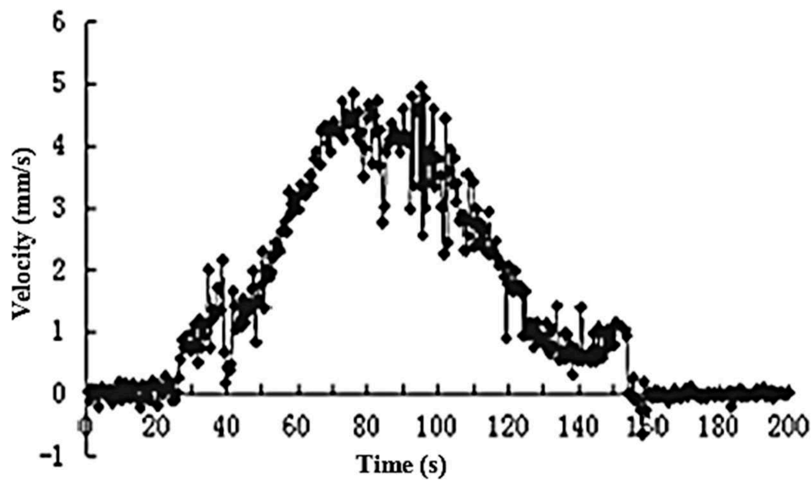


Figure 8. Deployment time–velocity curve.

longeron deployable laminates unit begins to shape recovery automatically. The laser rangefinder records the displacement data and sends it to the computer to obtain experimental data.

The deployment time–displacement curve (Figure 7) and the deployment time–velocity curve (Figure 8) are obtained. Figures 7 and 8 indicate that the displacement and velocity are almost zero before 30 s, because there is a preheating process at the beginning; then after the temperature above T_g, the arc-shaped deployable laminates begin recovering, the displacement curve increases linearly, and the velocity reaches the maximum 4.66 mm/s at about 80 s; with the deployment towards to the end, the displacement curve upward trend becomes slower, the velocity curve has a small peak before the end which means there is a sudden speed, the reason is the bended arc-shaped deployable laminate has buckling deformation and the geometry shape recover

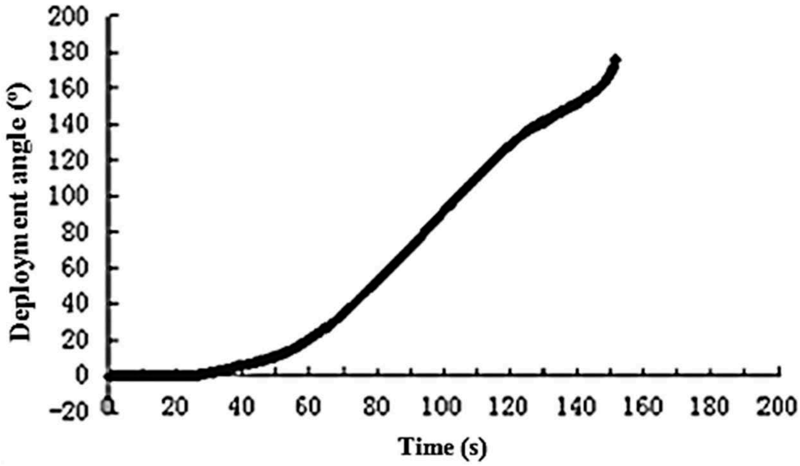


Figure 9. Deployment time–deployment angle curve.

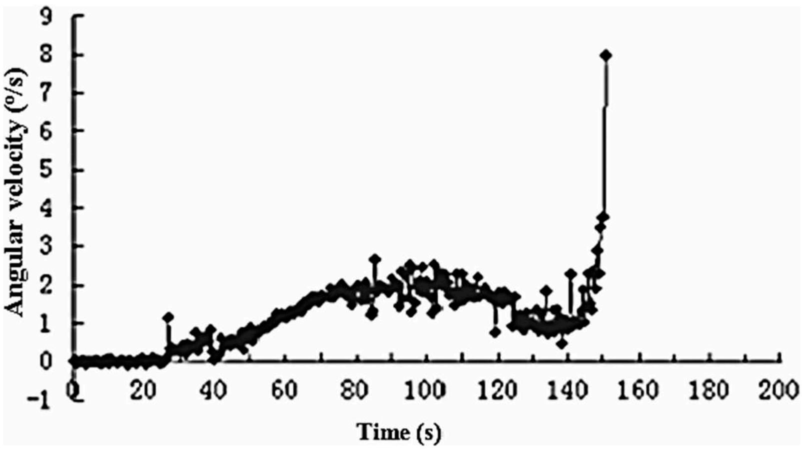


Figure 10. Deployment time–angular velocity curve.

after deployment. Although there is a small impact, the whole process of deployment is stable.

According to the existing three-longeron deployable laminates unit's deployment time–displacement data, we obtain the relationship of the arc-shaped deployable laminate's deployment time and deployment angle (Figure 9), deployment time and angular velocity (Figure 10).

From Figures 7 and 9, it can be seen that the tendency of deployment time–deployment angle curve is similar to the deployment time–displacement curve. At the beginning, the curves of deployment time–deployment angle and deployment time-angular velocity increase slowly; after 60 s, the deployment angle increases linearly, the angular velocity reaches the maximum about 2.08°/s; in the end, there is sudden angular velocity, the reason is the same as in the deployment time–velocity curve.

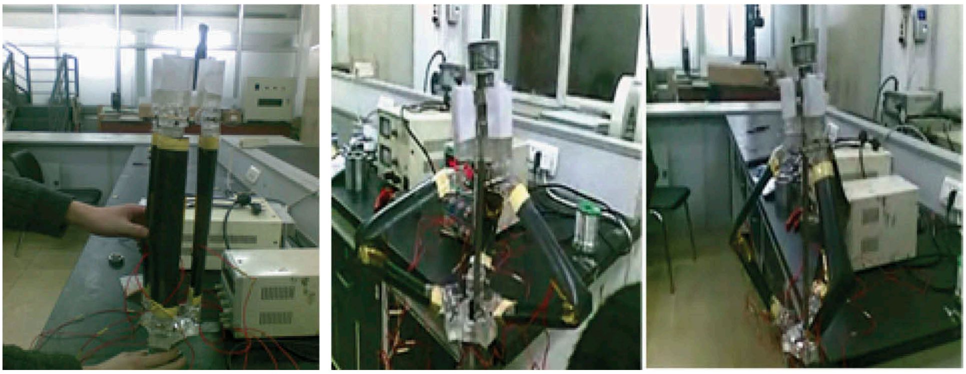


Figure 11. Experiment of three-longeron deployable laminates unit bending recovery force.

5.2 *Experiment of three-longeron deployable laminates unit bending recovery force*

Since it is difficult to measure a single arc-shaped deployable laminate's recovery force and the basic effective unit is three-longeron deployable laminates unit whose main consideration is the axial thrust, we propose the method: measure the maximum vertical load of the three-longeron deployable laminates unit, with the load the three-longeron deployable laminates unit can deploy fully, to get the bending recovery force (as shown in Figure 11). The detailed experiment method is as follows: assemble a three-longeron deployable laminates unit, place it vertically and fix one end of it, load weights on the other end, get the maximum vertical load with which the three-longeron deployable laminates unit can deploy successfully. The experiment result is that the three-longeron deployable laminates unit's maximum vertical load is about 8.5 N. Considering the rough experiment design, the result of the experiment is just a reference value.

5.3 *Experiment of the simplified cubic deployable support structure's recovery feasibility*

In order to verify the feasibility of the cubic deployable support structure and the synchronization of parallel three-longeron deployable laminates units, a test of the simplified cubic deployable support structure's recovery feasibility is carried out. Considering the support structure is symmetric and the deployment process of every direction is same, we select the maximum load direction (vertical), three-longeron deployable laminates units of three different directions deployed one after another. The average weight of every three-longeron deployable laminates unit is about 8.37 N.

Stick the resistor heaters to the inside surfaces of the arc-shaped deployable laminates, bend them to 180° along the shortest center line; assemble the simplified cubic deployable support structure with three-longeron deployable laminates units and end connections; electrify the resistor heaters of the same direction three-longeron deployable laminates units simultaneously; shoot the video of the whole deployment process. Figure 12 shows the deployment process of every direction.

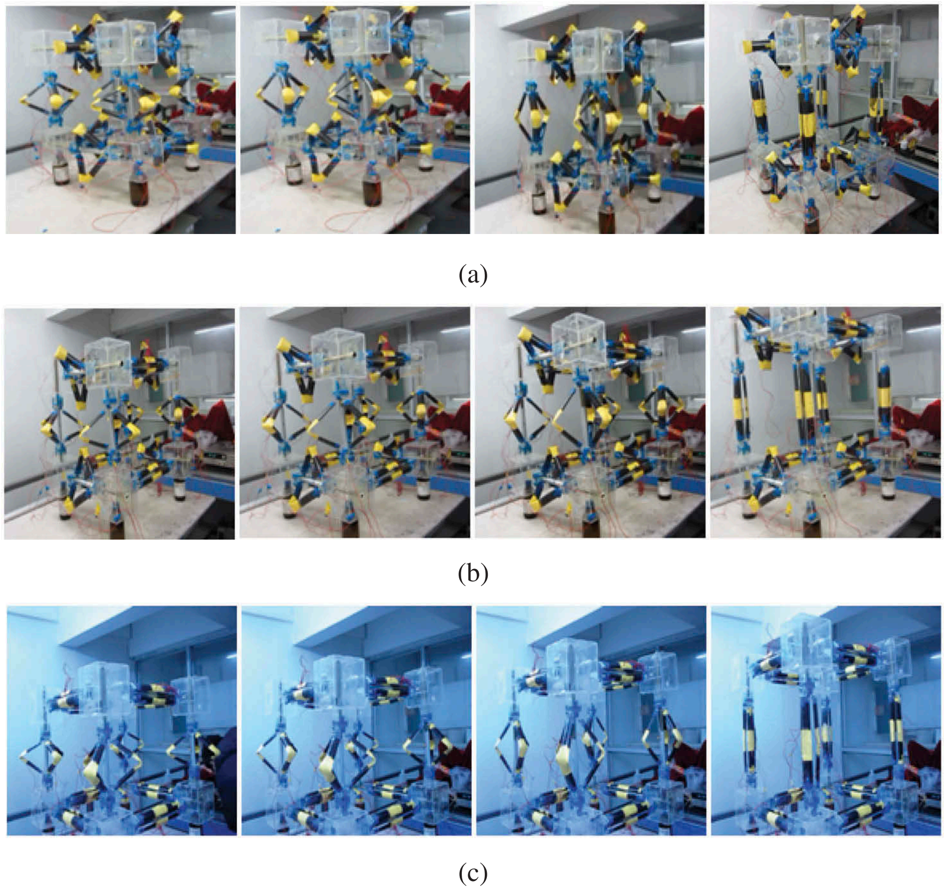


Figure 12. The recovery process of every direction: (a) in the first direction, (b) in the second direction, and (c) in the third direction.

Table 1. The result of the simplified cubic deployable support structure's recovery process.

	Voltage (V)	Time (s)
In the first direction	40	502
In the second direction	40	473
In the third direction	40	420

The result of the experiment (as shown in Table 1) is that the spatial parallel three-longeron deployable laminates units deploy simultaneously. The process is similar to the single three-longeron deployable laminates unit's. The average time of deploying is 465 s, because the average load-bearing of every three-longeron deployable laminates unit is 8.37 N.

6. Conclusion

In this article, a cubic deployable support structure, which can realize self-deployment without complex mechanical devices, is introduced. The primary component of the structure is arc-shaped deployable laminate based on SMPC, the deformed arc-shaped laminate recovers to its original shape when heated, thus it can drive the folded structure to expand. The three-longeron deployable laminates unit's bending recovery regularity is slow-fast-slow, because there is a preheating process of resistor heater and the bending recovery force is small when the shape recovery is almost done. The maximum of three-longeron deployable laminates unit recovery force is about 8.5 N. The simplified cubic deployable support structure can self-deploy successfully and the average deployment time in every direction is 465 s. This study is one of the explorations of SMPs and SMPCs in large-scale deployable structures and can provide some preliminary reference for SMPCs-based deployable structures in future aerospace applications.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (Grant No.11225211, No.11272106, No. 11102052).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [11225211]; [11272106]; [11102052].

Notes on contributors

Fengfeng Li has been working for her Doctoral Degree Program in the Department of Mechanics, Harbin Institute of Technology, majoring in Mechanics. Her research fields are shape memory polymer, deployable structures and mechanics of composites.

Liwu Liu works in Department of Astronautical Science and Mechanics, Harbin Institute of Technology. He is a associate professor and he is expert in mechanics of smart soft active materials, such as dielectric elastomers, shape memory polymer, ferroelectric polymers, electrocaloric and pyroelectric energy conversion.

Xin Lan is currently working at the Department of Aeronautics and Mechanics at Harbin Institute of Technology. He obtained his PhD in the field of Mechanics in 2010. His research fields are shape memory polymer, solid mechanics, smart materials and structures system, structural dynamics.

Xiaojun Zhou obtained his Bachelor's degree from Harbin Institute of Technology, China in 2014, he is working for his Master Degree Program in the Department of Mechanics currently. His research fields are shape memory polymer and smart structure design.

Wenfeng Bian obtained her PhD in the field of Engineering Mechanics and Composite Materials in 2006 from Harbin Institute of Technology, China. Currently, She is a professor at Center for Composite Materials and Structures of Harbin Institute of Technology at Weihai, China. Her research interests are focused on composites integration of structural design and manufacturing process.

Yanju Liu is a faculty member of the Department of Aerospace Engineering and Mechanics at Harbin Institute of Technology. She obtained her PhD degree in the field of Materials from Centre for Composite Materials & Structures of Harbin Institute of Technology, China in 1999. Until now, she has authored or co-authored 4 books chapters, 13 issued patents, and over 150 scientific papers in different journals and conference proceedings, including Progress in Material Science, Applied Physics Letters, and Smart Materials & Structures.

Jinsong Leng obtained his BSc and PhD from Harbin Institute of Technology, China in 1990 and 1996, respectively. From 1993 to 1998 he was an assistant professor, lecturer and associate professor at Harbin Institute of Technology, China. He joined Nanyang Technological University in Singapore as a research fellow from 1998 to 2000. From 2000 to 2002, he was a research fellow at Defence Academy of the United Kingdom, Cranfield University. Then, he worked at Phtotonics Research Group of Aston University in the UK as a research fellow from 2002 to 2004. Now, he is a full professor and the Director of the Center for Smart Materials and Structures (CSMS) at School of Astronautics of Harbin Institute of Technology, China.

References

[1] J.L. Hu, Y. Zhu, H.H. Huang, and J. Lu, *Recent advances in shape memory polymers: Structures, mechanism, functionality, modeling and applications*, Prog. Polym. Sci. 37 (2012), pp. 1720–1763. doi:10.1016/j.progpolymsci.2012.06.001

[2] M. Behl and A. Lendlein, *shape memory polymers*, Mater. Today 10 (2007), pp. 20–28. doi:10.1016/S1369-7021(07)70047-0

[3] J.S. Leng, X. Lan, Y.J. Liu, and S.Y. Du, *Shape memory polymers and their composites: Stimulus methods and applications*, Prog. Mater. Sci. 56 (2011), pp. 1077–1135. doi:10.1016/j.pmatsci.2011.03.001

[4] W.M. Huang, Z. Ding, C.C. Wang, J. Wei, Y. Zhao, and H. Purnawali, *Shape memory materials*, Mater. Today 13 (2010), pp. 54–61. doi:10.1016/S1369-7021(10)70128-0

[5] C. Liu, H. Qin, and P.T. Mather, *Review of progress in shape memory polymers*, J. Mater. Chem. 17 (2007), pp. 1543–1558. doi:10.1039/b615954k

[6] I.S. Gunes and S.C. Jana, *Shape memory polymers and their nanocomposites: A review of science and technology of new multifunctional materials*, J. Nanosci. Nanotechnol. 8 (4) (2008), pp. 1616–1637. doi:10.1166/jnn.2008.038

[7] T. Xie, *Tunable polymer multi-shape memory effect*, Nature 464 (2010), pp. 267–270. doi:10.1038/nature08863

[8] M. Behl, M.Y. Razzaq, and A. Lendlein, *Multifunctional shape memory polymers*, Adv. Mater. 22 (2010), pp. 3388–3410. doi:10.1002/adma.200904447

[9] Q.B. Meng and J.L. Hu, *A review of shape memory polymer composites and blends*, Compos. Part. A: Appl. Sci. Manuf. 40 (2009), pp. 1661–1672. doi:10.1016/j.compositesa.2009.08.011

[10] Y.J. Liu, H.Y. Du, L.W. Liu, and J.S. Leng, *Shape memory polymer composites and their applications in aerospace: A review*, Smart Mater. Struct. 23 (2014), pp. 023001. doi:10.1088/0964-1726/23/2/023001

[11] J.S. Leng, X.L. Wu, and Y.J. Liu, *Effect of a linear monomer on the thermomechanical properties of epoxy shape-memory polymer*, Smart Mater. Struct. 18 (2009), pp. 095031. doi:10.1088/0964-1726/18/9/095031

[12] Y.J. Liu, H.B. Lv, X. Lan, J.S. Leng, and S.Y. Du, *Review of electro-activate shape memory polymer composite*, Compos. Sci. Technol. 69 (2009), pp. 2064–2068. doi:10.1016/j.compscitech.2008.08.016

[13] A. Basit, G.L. Hostis, and B. Durand, *High actuation properties of shape memory polymer composite actuator*, Smart Mater. Struct. 22 (2) (2013), pp. 025023. doi:10.1088/0964-1726/22/2/025023

[14] K. Yu, Y.J. Liu, and J.S. Leng, *Shape memory polymer/CNT composites and their microwave induced shape memory behaviors*, RSC Adv. 4 (6) (2014), pp. 2882–2889.

[15] Z. Wang, C. Hansen, Q. Ge, S.H. Maruf, D.U. Ahn, H.J. Qi, and Y.F. Ding, *Programmable, pattern-memorizing polymer surface*, Adv. Mater. 23 (2011), pp. 3669–3673. doi:10.1002/adma.v23.32
[16] C.S. Zhang and Q.Q. Ni, *Bending behavior of shape memory polymer based laminates*, Compos. Struct. 78 (2013), pp. 153–161. doi:10.1016/j.compstruct.2005.08.029
[17] H. Tobushi, S. Hayashi, and S. Kojima, *Mechanical properties of shape memory polymer of polyurethane series: Basic characteristics of stress–strain–temperature relationship*, JSME Int. J. Ser. 1. Solid Mech. Strength Mater. 35 (1992), pp. 296–302.
[18] H.B. Lv, K. Yu, S.H. Sun, Y.J. Liu, and J.S. Leng, *Mechanical and shape memory behavior of shape memory polymer composites with hybrid fillers*, Polym. Int. 59 (2010), pp. 766–771.
[19] T. Ohki, Q.Q. Ni, N. Ohsako, and M. Iwamoto, *Mechanical and shape memory behavior of composites with shape memory polymer*, Compos. Part. A: Appl. Sci. Manuf. 35 (9) (2004), pp. 1065–1073. doi:10.1016/j.compositesa.2004.03.001
[20] K. Yu, T. Xie, J.S. Leng, Y.F. Ding, and H.J. Qi, *Mechanisms of multi-shape memory effects and associated energy release in shape memory polymers*, Soft Matter 8 (20) (2012), pp. 5687–5695. doi:10.1039/c2sm25292a
[21] K. Yu, Q. Ge, and H.J. Qi, *Reduced time as a unified parameter determining fixity and free recovery of shape memory polymers*, Nat. Commun. 5 (2014), pp. 3066. doi:10.1038/ncomms4066
[22] Y. Liu, K. Gall, M.L. Dunn, and P. McCluskey, *Thermomechanics of shape memory polymer nanocomposites*, Mech. Mater. 36 (10) (2004), pp. 929–940. doi:10.1016/j.mechmat.2003.08.012
[23] A. Lendlein and S. Kelch, *Shape memory polymers as stimuli-sensitive implant material*, Clin. Hemorheol. Microcirc. 32 (2) (2005), pp. 105–116.
[24] L. Zhang, H.Y. Du, L.W. Liu, Y.J. Liu, and J.S. Leng, *Analysis and design smart mandrels using shape memory polymers*, Compos. Part. B: Eng. 59 (2014), pp. 230–237. doi:10.1016/j.compositesb.2013.10.085
[25] K. Yu, Z.C. Zhang, Y.J. Liu, and J.S. Leng, *Carbon nanotube chains in a shape memory polymer/carbon black composite: To significantly reduce the electrical resistivity*, Appl. Phys. Lett. 98 (2011), pp. 074102. doi:10.1063/1.3556621
[26] Q. Tan, L.W. Liu, Y.J. Liu, and J.S. Leng, *Post buckling analysis of a shape memory polymer composite laminate with a built-in stiff film*, Compos. Part. B: Eng. (2013), pp. 218–225.
[27] L. Sun, Y. Zhao, W.M. Huang, H. Puranwali, and Y.Q. Fu, *Wrinkling atop shape memory materials*, Surf. Rev. Lett. 19 (2) (2012), pp. 9–23. doi:10.1142/S0218625X12500102
[28] J. Hill and J. Jacob, *Deployment of inflatable space habitat models*, 48th AIAA Aerosp. Sci. Meeting Incl. New Horiz. Forum Aerosp. Exposition (2010), pp. 793.
[29] K.J. Kennedy, *TransHab and the space architects*, Fabr. Archit. 24-30 (1999), pp. 48–50.
[30] K.J. Kennedy, J. Raboin, G. Spexarth, and G. Valle, Inflatable habitats, In *Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications*, C.H.M. Jenkins, ed. Progress in Astronautics and Aeronautics Vol. 191, AIAA, Reston, VA, 2001, pp. 527–552.
[31] J. Carey, E. Goldstein, D. Cadogan, L. Pacini, and M. Lou, *Inflatable sunshield in space (ISIS) versus next generation space telescope (NGST) sunshield–a mass properties comparison*, AIAA Struct, Struct. Dyn. Mater. Conf. 6 (2000), pp. 505–519.
[32] W.M. Sokolowski and S.C. Tan, *Advanced self-deployable structures for space applications*, J. Spacecr. Rockets 44 (4) (2007), pp. 750–754. doi:10.2514/1.22854
[33] J. Huang, *The development of inflatable array antennas*, IEEE Antennas Propag. Mag. 43 (4) (2001), pp. 44–50. doi:10.1109/74.951558
[34] H. Fang, M. Lou, and J. Hah, *Deployment study of a self-rigidizable inflatable boom*, J. Spacecr Rockets 43 (1) (2006), pp. 25–30. doi:10.2514/1.3283