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# Viscoelastic bistable behaviour of antisymmetric laminated composite shells with time-temperature dependent properties

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## ABSTRACT

Due to the bistable characteristics, antisymmetric laminated ($[+\alpha/-\alpha]_n$) composite bistable shells have been used as novel morphing structures in many engineering fields. Previous theoretical analyses were mainly based on the hypothesis that the composite shell is elastic, which leads to unexpected calculation and prediction errors. In this paper, the fiber reinforcements are assumed to be elastic while the matrix is treated as a viscoelastic material. The resulting viscoelastic material properties of the composite shell are obtained through the experimental test and numerical modeling. Based on the classical lamination theory, together with the principle of minimum potential energy and Maxwell viscoelasticity model, a theoretical model is developed to predict the bistable behaviour of those composite shells with viscoelastic material properties. Subsequently, the influences of applied temperature and relaxation time on the second stable configuration of bistable composite shells are analytically investigated. The results are then compared with those obtained from the experiments and numerical modeling. Comprehensive results show that the principal curvature of the shell's second stable state increases as the applied temperature and relaxation time increase. In contrast, the twisting curvature of the second stable shape generally decreases with the relaxation time increasing but increases with the applied temperature rising.

## 1. Introduction

There has been an urgent demand to the multifunctional and lightweight structures in aviation and aerospace fields. Traditional morphing structures are composed of complex mechanical and hydraulic systems that restricts their applications in modern aviation and aerospace fields [1]. In contrast, smart morphing structures made of those bistable composite structures [2,3] have the advantages of lightweight and multifunctional characteristics. Those bistable composite structures can even be used to develop the small-sized, lightweight and adaptive multi-stable morphing structures [4,5]. These advanced composite structures have been applied in morphing airfoils [6], pipelines [7] and air inlets [8].

Bistable composite structures possess two stable shapes each of which have a reasonable load-carrying capacity and are able to transform to the other stable state under the suitable exterior loading [9–12].

Bistable composite structures are usually made of carbon-fiber or glass-fiber/resin matrix composites, the material properties of which are affected by the ambient environment during their storage and service life. For example, the bistable composite structures applied in the aeronautic and astronautic engineering often undergo extreme environments, such as high/low temperature, dramatic temperature change, loading time, etc. that consequently degrade the mechanical properties and structural performances of bistable composite structures.

In earlier studies, the bistable composite structures were assumed to be elastic and the viscoelastic behaviour was neglected for simplicity. The carbon fiber reinforced polymer composite, which is widely used in the laminated composite structures, is a typical viscoelastic composite material. Its mechanical properties are sensitive to the variations of the ambient temperature and relaxation time. After undergoing a long duration of cycling thermal load and stress relaxation, the mechanical properties and deploy characteristics are diverged from simulation results and the scheduled deploy action is delayed [13].

The micromechanical viscoelastic behaviour of fiber reinforced epoxy composites have been widely studied [14–16]. Based on a simplified composite model, viscoelastic characteristics of the composites

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were analyzed by Abadi [17]. Dasappa et al. [18] analytically and experimentally investigated the thermal effect on the creep behaviour of resin based composites. The deployment of long time deployable low density Polyethylene shell and woven composite shells were studied by Kwok et al. [19,20]. Their results revealed that both the relaxation time and high temperature have significant effects on the deploy process of composite shells.

The experimental test on the viscoelastic response of the woven bistable deployable composite structure was conducted by Brinkmeyer et al. [21]. The results indicated that the time of recovery process was prolonged for reduced stress as the temperature and relaxation time increase, and an irreversible deformation was observed after a long relaxation time. Viscoelastic properties of composites with two and three constituents were analyzed by whom using the finite element method [22,23] and the results were verified by the Mori-Tanaka model [24,25]. The effect of fiber alignment on the viscoelasticity of composites was discussed by Broakenbrough et al. [26] using the finite element method. A numerical approximation method was proposed by Levin and Sevostianov [27] to model micromechanical viscoelastic composites and the viscoelastic properties were expressed in Prony series. The viscoelasticity of fibrous composites was analyzed by Naik using the commercial finite element program ABAQUS [28]. The unit cell model of fiber reinforced composites was proposed by Yu and Tang et al. [29,30] based on the variation approximation and homogenization principle to estimate the elasticity and viscoelasticity of such composites.

In the research field of Antisymmetric Laminated Composite Shells (ALCSs), a simplified elastic model was firstly proposed by Iqbal et al. [31,32] and the theoretical predictions of the bistable shapes of ALCSs were validated by the finite element modeling. Subsequently, a beam model and a shell model were successively proposed by Galletly and Guest [9,10]. A two-parameter model considering cylindrical curvature and shell direction was developed by Guest and Pellegrino [33]. The curvatures of ALCSs and energy expressions can be obtained by the Mohr's circle. The deploy process of ALCSs was studied by Brinkmeyer et al. [34] based on the two-parameter model and conservation of energy. Zhang et al. [35–37] carried out a systematic investigation on the bistable behaviour of ALCSs in thermal environments through the theoretical analysis, experiments and finite element modeling. Their results demonstrated that both the uniform temperature rise and through-thickness thermal gradient have significant effects on the bistable curvatures of ALCSs. A deviation between experimental and theoretical results was observed, one possible reason for which may be the existence of viscoelastic behaviour in ALCSs that were caused by the hygrothermal environment and long loading time.

Hence, this paper is devoted to investigate the effect of the viscoelasticity on the bistable behaviour of ALCSs by taking into account the time-temperature dependent material properties. To this end, a viscoelastic model is proposed in this paper, by which the influences of ambient temperature and relaxation time on the bistable behaviour of such composite structures are investigated. Experimental tests and numerical simulation are carried out to validate the proposed model. Viscoelastic property test and analysis of carbon-fiber reinforced epoxy resin composites are given in Section 2. Theoretical analysis, experimental investigation and numerical simulation of viscoelastic behaviour of the bistable shells are presented from Section 3 to Section 5, respectively. The influences of relaxation time and applied temperature are discussed in Section 6 by comparing theoretical, experimental and simulation results. Conclusions are drawn in Section 7.

## 2. Test and analysis of viscoelastic properties

A combined experimental and numerical method is used here to obtain the viscoelastic properties of carbon-fiber reinforced epoxy resin composites. A series of Dynamic Mechanical Analyzer (DMA, Type: TAQ800) tests is conducted to gain the epoxy resin matrix's viscoelastic properties, after which the carbon-fiber reinforced epoxy resin composites' viscoelastic properties are obtained through the finite element simulation by the unit cell model.

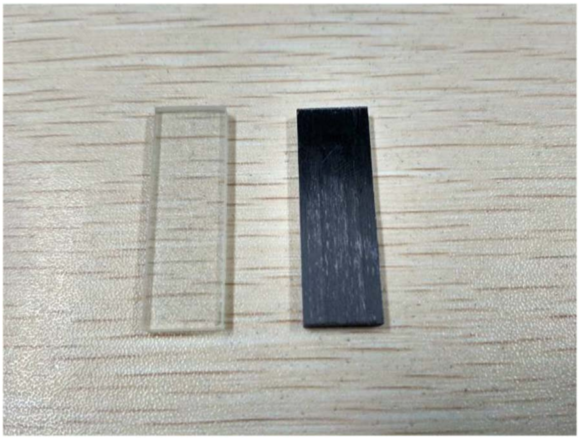

**Fig. 1.** Specimen for the DMA test.

### 2.1. DMA test

#### 2.1.1. Test of glass transition temperature $T_g$

The glass transition temperature $T_g$ is a significant parameter for the composite materials since the viscoelastic behaviour of the composite structure gets the most evident when the ambient temperature is close to $T_g$.

DMA, with a single cantilever clamp is used in this paper. Two specimens for the DMA test are shown in Fig. 1 where the left one is the specimen made of epoxy resin and the right one is made of T700/epoxy composites. The geometrical sizes of the specimens are 30 mm × 12 mm × 3 mm. Working mode is set as the multi-frequencies. The measuring temperature ranges from the room temperature to 150 °C, and the heating rate is 5 °C/min. The excitation amplitude is 5 mm and the excitation frequency is 1 Hz.

The moduli versus temperature curves are depicted in Fig. 2. The glass transition temperature $T_g$ can be determined by the beginning point of the rapid decrease stage of the storage modulus curve and the peak point of the loss modulus curve. For example, in Fig. 2(a), the rapid decrease stage of the storage modulus begins at 70 °C and the peak point of the loss modulus is at 80 °C. Thus, the glass transition temperature $T_g$ of epoxy resin is located between 70 and 80 °C. The glass transition temperature $T_g$ of carbon fiber composite can be determined in the same way as 110–120 °C from Fig. 2(b).

#### 2.1.2. Stress relaxation test

DMA stress relaxation model is used in the stress relaxation test, the test time is 1 h, and the constant strain is 0.1%. Tests are conducted at four different temperatures: 20 °C, 40 °C, 60 °C and 80 °C, respectively. Before the stress relaxation test, each specimen was kept in the thermal environment of a specified temperature for 5 mins so that the specimen can be heated uniformly. The relaxation moduli of epoxy resin at different temperatures are displayed in Fig. 3.

According to the Williams–Landel–Ferry (WLF) equation [38], we have

$$lg\ a_T = lg\ \frac{E(T)}{E(T_s)} = -\frac{c_1(T-T_s)}{c_2+(T-T_s)} \Rightarrow \frac{1}{lg\ E(T_s) - lg\ E(T)} = \frac{c_2}{c_1}\frac{1}{T-T_s} + \frac{1}{c_1} \tag{1}$$

Time-temperature shift $a_T$ for some viscoelastic materials is used to time-temperature superposition (TTS) principle. $T_s$ is the initial