Composite Structures 144 (2016) 24–32

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental study on bistable behaviour of anti-symmetric laminated cylindrical shells in thermal environments

Zheng Zhang [a,b,*], Helong Wu [b], Gangfei Ye [a], Jie Yang [c], Sritawat Kitipornchai [b], Guozhong Chai [a]

[a] Key Laboratory of E&M (Zhejiang University of Technology), Ministry of Education & Zhejiang Province, Hangzhou 310014, PR China
[b] School of Civil Engineering, The University of Queensland, St Lucia, QLD 4072, Australia
[c] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora, Melbourne, VIC 3083, Australia

ARTICLE INFO

Article history:
Available online 26 February 2016

Keywords:
Composite structure
Bistable shell
Anti-symmetric
Thermal influence
Mechanical testing

ABSTRACT

Anti-symmetric laminated $[+\alpha/-\alpha]_n$ cylindrical shell (ALCS) is a type of bistable composite structures that can deform between two stable shapes under an external loading. The maximum snap loads and shape deformations in varying thermal environments play a significant role in their bistable characteristic. This paper presents an experimental study on the bistable behaviour of ALCSs at 20 °C, 40 °C, 60 °C, and 80 °C. The load–displacement curves are obtained by using a testing machine with a thermal chamber. The effect of the temperature variation on the shell's curvatures is also investigated by digital image processing technique. The obtained experimental results show the same trend as the analytical and numerical results. The thermal influence on the bistable behaviour in a local temperature field is also studied in detail. The experimental investigations presented in this paper is of great importance in the engineering design and applications of morphing structures manufactured from ALCSs.

1. Introduction

Bistable composite structure has been attracting considerable attention of researchers due to their bistable characteristics. As a novel composite structure, not only does it have the advantages of light weight, superior mechanical properties and higher utilization ratio in space, but also is able to stay in two different stable shapes without the need for an ongoing actuation force [1]. This makes bistable composite structures promising candidates as morphing structures in various fields, such as morphing skins [2], wind turbine blades [3], unmanned air vehicle (UAV) wings [4] and vibration energy harvesting [5], etc. There are two kinds of bistable structures in general: $[0/90]_n$ unsymmetric cross-ply laminate [6] and $[+\alpha/-\alpha]_n$ anti-symmetric laminated cylindrical shell (ALCS) [7]. Both of them can deform from one stable state to another under external mechanical forces, piezoelectric patches, temperature field or shape memory alloys (SMAs) [8–13].

Most of bistable laminated cylindrical shells are made of carbon-fiber/epoxy resin composites, which are significantly affected by ambient environment [14] including temperature variation [1,15–17], moisture [18–20] and thermo-oxidative effect [21,22], etc. The variation of temperature field is one of the most important factors that influence the intrinsic bistability of this kind of deployable structure.

The influence of temperature on the material properties and mechanics characteristics such as tensile strength, compressive strength, elastic moduli and thermal expansion coefficient, were discussed in previous studies [23–26]. The effect of temperature variation on the bistable behaviour of laminated cylindrical shells has also been analyzed analytically, experimentally and numerically. Moore et al. [27] investigated the curing process from 180 °C to room temperature for unsymmetric laminates using finite element method. The temperature-dependent material properties were considered. Eckstein et al. [17] presented an analytical and numerical model to account for the temperature-dependent material properties and through-thickness thermal gradients to analyze the bistable behaviour of the unsymmetric orthognal laminate. Tsai et al. [18] developed a novel experimental method to improve the sensitivity in measuring the hygric properties of cross-ply specimens with two lay-ups ($[0_2/90_2]$ and $[0_5/90_5]$), subsequently measured the coefficients of moisture expansion and investigated the relationship between moisture concentration and curvatures with immersion time. Etches et al. [28] demonstrated that substantial changes in the characteristics of bistable CFRP laminates occur when they are exposed to moisture environment.

* Corresponding author at: Key Laboratory of E&M (Zhejiang University of Technology), Ministry of Education & Zhejiang Province, Hangzhou 310014, PR China. Tel.: +86 571 88320244.
E-mail address: zzhangme@zjut.edu.cn (Z. Zhang).

http://dx.doi.org/10.1016/j.compstruct.2016.02.062
0263-8223/

Previous studies are primarily focused on the curing process from high temperature to room temperature or thermal/hygrothermal effect on the bistable behaviours of the asymmetric orthognal laminate [29–32]. The results show that the material properties and bistable behaviours of the laminated cylindrical shell are highly sensitive to temperature variation.

ALCSs [33] have same curvature direction in both stable states and can successfully avoid the bending-twisting coupling effect. Guest and Pellegrino [34] presented a simple two-parameter (principal curvature and twisting angle) model to describe the bistable behaviour of ALCSs. Zhang et al. [35,36] presented a new experimental method to capture the bistable behaviour of ALCSs. The bistable snap processes of the cylindrical shell were discussed systematically using analytical, numerical [37] and experimental methods. Subsequently Zhang et al. [38] analyzed the thermal effect including uniform temperature field and a through-thickness thermal gradient on the bistable behaviour of ALCSs using the analytical and numerical method. To the best knowledge of the authors, no experimental work has been done on the bistable behaviour of ALCSs with temperature-dependent properties under a thermal environment.

This paper presented an experimental investigation on the effect of thermal environments on the bistable behaviour of ALCSs. Testing machine (Reger3010) with a thermal chamber is used to capture the whole snap process in a uniform and local temperature field. The influence of temperature variation on the load–displacement curves and shell curvatures is studied by combining thermal chamber, digital camera and image processing technique. Comparison between the results obtained from theoretical analysis, numerical simulation and experimental test is given to discuss the effect of the thermal loading on the bistable behaviour of ALCSs.

2. Experimental investigation

2.1. Specimens preparation

Two groups of specimens were manufactured: one group was used for measuring temperature-dependent material properties, including the longitudinal modulus E_1, transverse modulus E_2, Poisson ration ν_{12}, in-plane shear modulus G_{12}, longitudinal thermal expansion coefficient $\alpha_{1,}$ and transverse thermal expansion coefficient $\alpha_{2.}$ The manufactured specimens used to measure temperature-dependent material properties are shown in Fig. 1.

The material properties of the manufactured specimens in the first group were measured three times at 20 °C, 40 °C, 60 °C and 80 °C respectively by Shanghai R&D Center for Polymer Materials. Shanghai R&D Center for Polymer Materials conducted the materials testing using tensile testing machine, Dynamic Mechanical Analyzer (DMA) and thermal chamber according to the testing standards (GB/T 1040.1-2006 Plastic-determination of tensile properties-Part 1: General, GB/T 3355-2005 Test method for longitudinal transverse shear (L-T shear) properties of fiber reinforced plastics and ASTM E831-14 Standard test method for linear thermal expansion of solid materials by thermomechanical analysis). The average values of the test data from three same specimens were selected as the final material properties. According to the previous studies [39,40], Poisson's ratio of carbon fiber polymer matrix laminated structures is weakly dependent on temperature change hence can be considered constant and temperature independent for simplicity. Therefore, Poisson ratio at room temperature was used and assumed to be constant in the present study. The other temperature-dependent material properties of T700/Epoxy resin unidirectional lamina are listed in Table 1.

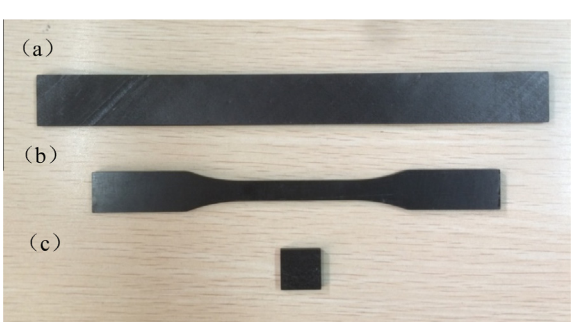

Fig. 1. Photos of the manufactured specimens for measuring temperature-dependent material properties. (a) Specimen for the measure of G_{12}; (b) specimen for the measure of E_1, E_2 and ν_{12}; (c) specimen for the measure of α_{11} and $\alpha_{22.}$

Based on the test data in Table 1 and by employing different numerical fitting functions, material properties at a given temperature can be presented as follow

$$E_1 = (108.05 + 0.0235(T_0 + \Delta T) - 0.00162(T_0 + \Delta T)^2) \times 10^9 \text{ Pa}$$

$$E_2 = (2.9191 + 22.069e^{-0.08356(T_0+\Delta T)}) \times 10^9 \text{ Pa}$$

$$G_{12} = (5.9375 - 0.04053(T_0 + \Delta T) - 5.625 \times 10^{-6}(T_0 + \Delta T)^2) \times 10^9 \text{ Pa}$$

$$\nu_{12} = 0.31$$

$$\alpha_1 = (0.000125(T_0 + \Delta T)^2 + 0.0025(T_0 + \Delta T) - 2.2) \times 10^{-6}$$

$$\alpha_2 = (-0.1975(T_0 + \Delta T) + 68.2833) \times 10^{-6}$$

where T_0 is the reference temperature in degree centigrade (room temperature 20 °C in this paper), and ΔT is the temperature change.

The ALCS specimens were manufactured in a cylindrical steel mold from 0.12 mm thickness unidirectional laminas of T700 carbon-fibers in an epoxy matrix in the required sequence. The geometric parameters of the ALCS with lay-up of [45°/−45°/45°/−45°] are given in Table 2. Fig. 2 shows the two stable shapes of the manufactured ALCS specimen.

2.2. Test Apparatus

A test machine (Reger3010) with a thermal chamber as shown in Fig. 3 was used in this study. The experimental temperature was controlled by the thermal chamber which provides a temperature ranging from 20 °C to 350 °C. The test machine was used to capture the whole snap-through and snap-back process. Four temperatures (20 °C, 40 °C, 60 °C, and 80 °C), which are lower than the glass transition temperature T_g (85 °C), were applied to the specimens.

As shown in Fig. 4, the bottom of the specimen was supported by the clamps and the load induced by the indenter was applied on the center of the top surface of the specimen. With the indenter moving downward, the ALCS specimen was snapped from one stable state to another. The whole loading process was conducted in the thermal chamber to investigate the bistable behaviour of the ALCS under thermal environments.

Table 1
Temperature-dependent material properties of T700/Epoxy resin unidirectional lamina.

T/°C	E_1/GPa	E_2/GPa	$G_{12(13)}$/GPa	ν_{12}	α_1/(×10^{-6}/°C)	α_2/(×10^{-6}/°C)
20	108	7.07	5.17	0.31	−2.1	64.33
40	106	3.68	4.03		−1.9	60.9
60	104	3.13	3.50		−1.6	55.4
80	99.4	2.90	2.27		−1.2	53