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Bistable behaviour and microstructure characterization of carbon fiber/epoxy resin anti-symmetric laminated cylindrical shell after thermal exposure

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A B S T R A C T

Bistable behaviour and microstructure characterization of carbon fiber/epoxy resin anti-symmetric cylindrical shells after thermal exposure are investigated by experimental method in this paper. The effect of thermal exposure temperature and duration on the curvatures, load-displacement curves and snap loads of bistable shells are discussed systematically. The results show that both the thermal exposure temperature and duration have a significant influence on the bistable behaviour of those antisymmetric laminated cylindrical shells. Some interesting phenomena after high-temperature exposure are found in snap-through and snap-back processes. The microstructure of the shell before and after thermal exposure is characterized using scanning electron microscope (SEM), which provide an insight into bistable deformation mechanism of those shells after being exposed to elevated temperature.

1. Introduction

Carbon fiber/epoxy bistable composite shells have potential applications in aeronautical and mechanical engineering due to their multifunctional advantages and superior mechanical properties [1]. Several studies have been done on bistable behaviour of laminated cylindrical shells in recent years [2–10]. The bistable characteristics in high-temperature environment depends largely on the mechanical properties of fiber reinforced polymer composites around or above the glass transition temperature (T_g) of the resin matrix [11,12]. In many engineering application, the bistable shells are adjacent to a thermal source, by which the shells are first are exposed to a high temperature then are cooled down to room temperature after the thermal source is removed [13–18]. The effect of high-temperature exposure on bistable laminated cylindrical shells should be investigated and well understood before they are used as load-bearing or actuating structures in thermal environments.

Mouritz et al. [19] reported a research progress of the structural modelling of laminates and sandwich composites in fire. The influences of temperature, decomposition, phase change, damage, mechanical properties, and failure on composite structures were discussed in the paper. Foster et al. [20] investigated the residual properties of externally-bonded FRP systems after high-temperature exposure through five different series of tests. Severe reductions in residual tensile strength and stiffness were observed at temperature exceeding the thermal decomposition temperature of the epoxy polymer matrix. Akay et al. [21] examined the effect of long-term exposure to high-temperature environment on the interlaminar-shear strength and impact performance of carbon fiber reinforced bismaleimide composite. The results showed that the degradation of matrix and fiber-matrix interface with ageing, accordingly the interlaminar-shear strength deteriorated progressively and the failure mode of the impact specimens changed from a brittle failure in the unaged state to a progressive delamination in the aged state. Liu et al. [22–26] studied the mechanical behaviours of carbon fiber composite sandwich structures with vertical lattice truss and pyramidal lattice truss cores at high and low temperatures by experimental and

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theoretical methods. The out-of-plane compressive and shear behaviours of composite sandwich structures after high-temperature exposure with different temperatures and durations were investigated. Thermal and mechanical properties of different carbon fiber composites have been studied by various researchers [27–29]. To the best knowledge of the authors, no previous work has emphasized on the bistable behaviour and microstructure characterization of anti-symmetric laminated cylindrical shell after thermal exposure.

The present paper studies the effect of thermal exposure on bistable behaviour and microstructures of anti-symmetric laminated cylindrical shells. First, the bistable shells were exposed to different temperatures for different durations. After high-temperature exposure, the snap processes of specimens are tested at room temperature using assembled testing machine [7]. The effects of thermal exposure temperature and duration on the bistable behaviour are investigated. In addition, the surfaces and fiber-matrix interfaces of specimens are observed by a scanning electron microscope (SEM) to provide an insight into the effect of high-temperature exposure from micro scale.

2. Experimental methods

In order to study the effect of thermal exposure on the bistable characteristics, a testing machine (Reger 3010) with the thermal chamber is used in the experiment. The adjustable temperature range is 20 °C–350 °C, the glass transition temperature T_g of anti-symmetric laminated cylindrical shell is 85 °C. The environmental temperature is controlled by the thermal chamber and the whole snap-through and snap-back processes are captured by the testing machine [9]. The thermal chamber is heated and stabilized at a certain temperature. Some specimens are exposed to temperatures of 20 °C (room temperature), 40 °C, 80 °C, 120 °C and 200 °C respectively for a duration of 1 h to study the effect of thermal exposure temperature. Other specimens were exposed to a temperature of 200 °C for different durations of 1 h, 3 h and 6 h to study the effect of thermal exposure duration.

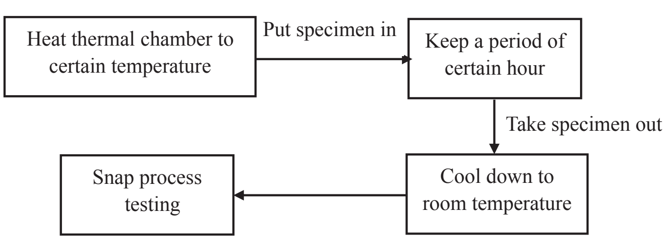

Fig. 1. Entire experimental flowchart of bistable behaviour of T700/epoxy resin anti-symmetric laminated cylindrical shell after thermal exposure.

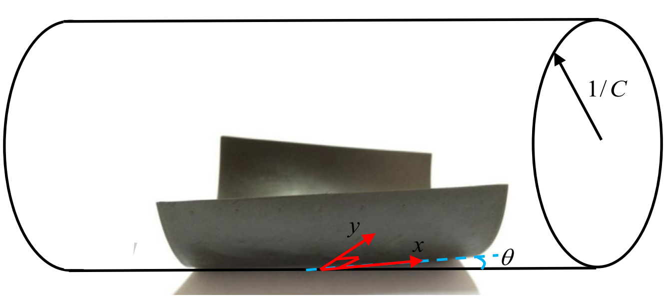

Fig. 2. Twisting phenomenon of bistable cylindrical shell after thermal exposure.

The anti-symmetric laminated cylindrical shells made from 4-plies 0.48 mm (0.12 mm thickness each ply) unidirectional T700/epoxy prepreg with the stacking sequence $[45°/-45°]_2$ are cured and cooled in a cylindrical steel mold before thermal exposure experiments. The entire experimental process for bistable behaviour of T700/epoxy resin anti-symmetric laminated cylindrical shell under thermal exposure is shown in Fig. 1. The specimens are exposed to temperatures of 20 °C (room temperature), 40 °C, 80 °C, 120 °C and 200 °C for duration of 1 h. All of the specimens are cooled down to room temperature, and the snap process of bistable shells are tested at room temperature. Each specimen is tested three times at every thermal exposure condition, and the average values of the experimental results are obtained as final results.

Using the testing method mentioned above, the load-displacement curves and snap loads are recorded by the computer using data acquisition software. The principal curvature C and twisting angle θ of the bistable shells are measured by digital image processing technique [30]. Twisting deformation of bistable cylindrical shell after thermal exposure is observed, especially in the second stable state, as shown in Fig. 2.

The curvature in the x direction k_x, the curvature in the y direction k_y, the twisting curvature in x-y plane k_{xy} can be obtained using a Mohr's circle [31,32] as below:

$$k_x = (C/2)(1 - \cos 2\theta) \tag{1}$$

$$k_y = (C/2)(1 + \cos 2\theta) \tag{2}$$

$$k_{xy} = C \sin 2\theta \tag{3}$$

3. Results and discussion

The effect of different thermal exposure temperatures and durations on the bistable behaviour including the load-displacement curves and curvatures of bistable shells are discussed. The microstructure characterization of bistable shell after high-temperature exposure at 200 °C for different durations is also given in this section.

3.1. Effect of thermal exposure temperature

3.1.1. Effect on the curvature of bi-stable shell

The principal curvature radii R ($R = 1/C$) and twisting angles θ of

Table 1
Principal curvature radii and twisting angles of bistable specimens under different exposure temperatures.

Thermal exposure temperature, T/°C	Principal curvature radius of first stable state, R_1/mm	Principal curvature radius of second stable state, R_2/mm	Twisting angle of first stable state, θ_1/°	Twisting angle of second stable state, θ_2/°
20	25.00	31.11	0.00	0.00
60	26.23	32.21	2.86	3.56
80	26.84	33.29	3.08	4.70
120	26.78	32.85	4.06	5.46
200	26.15	30.71	5.15	7.29