Temperature effect on buckling properties of ultra-thin-walled lenticular collapsible composite tube subjected to axial compression

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Abstract This paper seeks to outline the temperature effect on the buckling properties of ultra-thin-walled lenticular collapsible composite tube (LCCT) subjected to axial compression. The buckling tests of the LCCT specimens subjected to axial compression were carried out on INSTRON-500N servo-hydraulic machine in dry state and at the temperatures of 25 °C, 100 °C and −80 °C. The load–displacement curves and buckling initiation loads were measured and the buckling initiation mechanism was discussed from experimental observations. Experiments show that the buckling initiation load, on average, is only about 2.2% greater at the low temperature of −80 °C than at the room temperature of 25 °C due to the material hardening, demonstrating an insignificant increase in the buckling initiation load, whereas it is about 19.5% lower at the high temperature of 100 °C than at the room temperature owing to the material softening, implying a significant decrease in the buckling initiation load. The failure mode of the LCCT in axial compression tests at three different temperatures can be reckoned to be characteristic of the buckling initiation and propagation around the central region until rupture. The finite element (FE) model is presented to simulate the buckling initiation mechanism based on the eigenvalue-based methodology. Good correlation between experimental and numerical results is achieved.

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1. Introduction

Owing to the high specific strength and specific modulus as well as packaging convenience, foldable and deployable thin-walled composite structures (e.g. composite booms and hinges) are being widely investigated and applied in aerospace. ¹,² A large number of researches are grouped according to some important issues such as folding/deploying properties³–⁶ and axial compression,⁷–¹⁰ and bending¹³–¹⁶ strengths as well as biaxial tension–compression¹⁷
behaviour for foldable and deployable thin-walled composite structures/tubes based on experimental databases, analytical models and numerical techniques, etc. Ishai et al.7 carried out a series of tests of filament wound thin-walled CFRP and GFRP composite tubes under axial compressive loading to evaluate the influence of lay-up configuration on elastic strength properties. It showed that the hoop layers can effectively improve uniaxial compressive strength of composite tubes. Al-Hassani et al.8 conducted the theoretical analysis on the buckling of composite tubes subjected to different loading types (e.g., compression, torsion and internal pressure) under free-free and clamped-clamped boundary conditions. New exact equation for predicting buckling load was validated with the existing experiments. Weaver and Dickenson9 presented an interaction formula to theoretically analyze the effect of various lay-up on the interactive local/Euler buckling load of composite tubes under axial compression. It showed that the knockdown in buckling load was dependent on the predominant fibre angle of reinforcement and varied from 10% to 30%. Harte and Fleck10 experimentally and theoretically investigated the deformation and fracture behaviour of glass fibre-epoxy braided circular tubes subjected to compression, torsion and combined tension-torsion and compression-torsion. It was found that failure mode of tubes was governed by fibre microbuckling in torsion and combined compression-torsion tests. Kim et al.11 numerically simulated the delamination buckling of a short composite tube subjected to axial compression loading based on the theory of energy release rate. Delamination growth stability and critical buckling load of delaminated tube were calculated. Laurin et al.12 developed a multi-scale model to predict buckling strength of composite tubes under compressive loadings. Predictions had good agreement with experimental data. Sickinger et al.13–16 predicted axial compressive and bending bucking properties of deployable LCCT (lenticular collapsible composite tube) by using the FEA method and validated the predictions with the experiments. Kaddour et al.17 experimentally investigated static strength behaviour of ±45° E-glass/MY750 (GRP) tubes with different thickness under biaxial tension-compression loading. The influencing factors (e.g., bulging, scissoring, thermal stresses and stress variation through the thickness) on the deformations and damage processes of tubes were discussed. Softening characteristics resulting from the interaction between early matrix damage initiation and propagation and shear stress in the embedded lamina were observed.

From previous reviews, it is interesting to note that the buckling performance is one of the most important mechanical properties of thin-walled composite structures/tubes. In reality, the temperature has a significant influence on the buckling mode and strength of thin-walled composite tubes. Thus there is a need for understanding the temperature effect on the buckling performance of thin-walled composite tubes for engineering designs, particularly in the aerospace field. However, there is a lack of knowledge about the temperature effect on the buckling properties of ultra-thin-walled lenticular collapsible composite tube subjected to axial compression, which is the focus of this paper.

2. Buckling tests under axial compression

2.1. Material and specimen

Generally, ultra-thin-walled lenticular collapsible composite tube (LCCT) (here “lenticular” and “collapsible” respectively represent the geometry of cross section and the functions of folding and deploying of tube) can be folded into a roll to minimize storage space before launch (shown in Fig. 1) and then recover its original shape in working conditions by using the stored elastic strain energy derived from folding deformation. The cross-section of specimens of ultra-thin-walled LCCT used in tests is shown in Fig. 2, where the cross section of the specimens can be simplified to consist of two same “Ω” shape shell with two horizontal bonding flanges $CD$ and $CD'0$ and three tangential circular-arcs $BC$, $B'C$ and $BAB'$. The width of horizontal bonding flanges is 10 mm and the curvature radius $R$ and central angles of circular-arcs are respectively 34 mm.
and 60° and 120°. The longitudinal length of the specimens is 330 mm. All the specimens consist of the two same curved CFRP (carbon fibre reinforced plastics) shells with “Ω” shape and have the same thickness of 0.37 mm and stacking sequence of [45/-45/0/-45/45]. The specimens were made by joint of the vacuum bag method and bonding technique. All the specimens were from ultra-thin T300/5228A (a kind of prepreg developed by Beijing Institute of Aeronautical Materials). The main reason of choosing the epoxy resin of the prepreg is for a long-term application in the environments of 100 °C and −80 °C (i.e. limit temperature in working conditions).

2.2. Tests and discussion

The buckling tests of the LCCT specimens subjected to axial compression, the clamped support at one end of the LCCT and the pin support at the other end respectively, were carried out on INSTRON-500N servo-hydraulic machine in dry state and at the temperatures of 25 °C, 100 °C and −80 °C as well as at a continuous displacement rate of 2 mm/min. Figs. 3–5 show respectively the boundary condition and the supported fixtures as well as the test assembly in the tests. Fig. 5(a)–(b) illustrate the temperature-controlled combined with heating

![Fig. 4 Test fixtures for compression buckling tests of LCCT.](image)

![Fig. 5 Test assembly and temperature-controlled cabinet.](image)

![Fig. 6 Load–displacement curves of LCCT subjected to axial compression.](image)
system for high and low temperature tests; here the heating system is used for heating up to the desired high temperature of 100 °C, while the liquid nitrogen for cooling down to the desired low temperature of −80 °C. No observable amount of slipping on the boundary conditions was found by visual detection and the load–displacement curves of three LCCT specimens at each temperature were recorded (shown in Fig. 6(a)–(c)) together with the buckling processes were observed during tests (shown in Fig. 7(a)–(c)).

From Fig. 6(a)–(c), it is apparent that the load–displacement curves of the LCCT specimens at three different temperatures follow a similar trend, alternatively, the load–displacement curves first display initial approximate linear and then exist more than one peak marking the buckling initiation and propagation, which causes load drops on the load–displacement curves. It is worth noting that the initial approximate linear portions on the load–displacement curves corresponding to the temperature of 100 °C looks like more curved than those pertinent to the temperatures of 25 °C and −80 °C, marking the material softening.

Since the failure loads are far more easily identified by the catastrophic fracture of the specimens, in order to discuss buckling initiation mechanism, the buckling initiation load is defined as the initial load drop, which is obtained from the load–displacement curves determined by the tests. From Fig. 6(a)–(c), the buckling initiation loads are determined and listed in Table 1. From Table 1, it is obvious that the mean values of buckling initiation load at the temperatures of 25 °C, 100 °C and −80 °C are 4394.7 N, 3537.4 N and 4493.6 N respectively. The buckling initiation load, on average, is only about 2.2% greater at the low temperature of −80 °C than that at the room temperature of 25 °C, which is an insignificant increase in the buckling initiation load, whereas the buckling initiation load is about 19.5% lower at the high temperature of 100 °C than that at 25 °C, which is a significant decrease in the buckling initiation load.

From experimental observation (shown in Fig. 7(a)–(c)), it is clear that with increasing compressive loading along axial direction, the buckling first occurred around the central region near the flange of the LCCT and there was a small load drop on the load–displacement curves (see Fig. 6(a)–(c)). After the initial buckling, the LCCT continued to carry load until the final failure, namely, with the increasing loading, the buckling discontinuously propagated around the central region of the LCCT and the load–displacement curves had load drops.

From test observation, it is clear that more significant buckling folding appeared at high temperature than at the room temperature under the same buckling loads (shown in Fig. 7(a) and (b)), while similar buckling folding occurred at room and low temperatures (see Fig. 7(a) and (c)) and a significant brittle rupture appeared at low temperature (see Fig. 7(c)). These imply material softening and hardening at high and low temperatures. Hence, the failure mode of the LCCT in axial compression tests at three different temperatures can be reckoned to be characteristic of the buckling initiation and propagation around the central region and final failure of brittle rupture occurred at low temperature differing from the situations at room and high temperatures.

3. FE analysis

In order to provide numerical analysis to validate the experimental results, the LCCT shown in Fig. 3 is chosen to be modeled and local coordinate systems is then set up to ensure the
fibre with correct 3D orientation, i.e., the definitions of three axial directions 1–3 of the coordinate system are consistent with the longitudinal, transverse and through-thickness directions of the over laminate (shown in Fig. 8). In order to well suit to model thin-walled curved shell, the higher order 3D, 8-node layered shell element SHELL99 with six degrees of freedom per node in ANSYS code is implemented to model the composite layup in the LCCT to attain a high accuracy of simulation. The orthotropic T300/5228A composite with the stacking sequence of \([45/\pm 45/0/\pm 45/45]\) is used for the curved shells, while the isotropic 5228A resin is used for the bonding layer with the thickness of 0.1 mm between both interfaces in horizontal flanges of curved shells, which is defined as one layer of the shell elements of flanges. It is worth noting that it is unnecessary for shell element SHELL99 employed in the FE modeling to use the contact elements. Therefore, a 3D FE model (see Fig. 8) which includes 6720 quadrilateral elements and 20,496 nodes is generated to model the buckling mechanism of the LCCT in association with relevant material properties listed in Table 2. As shown in Fig. 8, the loading and boundary conditions are defined as the axial compression, the clamped support at one end of the LCCT and the pin support at the other end respectively.

Based on the FE model and the relevant material properties listed in Table 2, the initial buckling modes in the tested LCCT at temperatures of 25 °C, 100 °C and −80 °C are respectively obtained at the axial compressive load of 4841.1 N, 4016.4 N and 5269.2 N by using the eigenvalue-based methodology (shown in Fig. 9 and Table 1). From Fig. 9, it can be seen that the initial buckling at three temperatures occurs around central region near the flanges of LCCT. This correlates well with the experimental observations (shown in Fig. 7(a)–(c)). From Table 1, it is possible to show that the relative deviations of the theoretical predictions from the means of experimental results at three temperatures of 25 °C, 100 °C and −80 °C are respectively 9.2%, 11.9%, and 14.7%, with the acceptable scatter, implying that the FE models can give an insight into understanding the buckling initiation mechanism in the tested LCCT under axial compression at different temperatures.

The experimental results appear relatively less buckling initiation load as against the numerical results. This is probably due to the significant changes in experimental structural stiffness. In fact, even non-observable amounts of slipping and lack of true simple supported conditions can change experimental structural stiffness significantly; however, the numerical model applies perfect boundary conditions. This results in the calculated results being greater than those shown in the experimental ones.

**Fig. 8** FE model of ultra-thin-walled lenticular collapsible composite tube.

| Table 2 Mechanical properties of LCCT. |
|-------------------|-------------------|-------------------|
| Materials        | Properties | 25 °C | 100 °C | −80 °C |
| T300/5228A       | \(E_1\) (GPa) | 80.08 | 67.95 | 84.25 |
|                  | \(E_2\) (GPa) | 6.67  | 3.12  | 7.02  |
|                  | \(E_3\) (GPa) | 6.67  | 3.12  | 7.02  |
|                  | \(v_{12}\)     | 0.34  | 0.36  | 0.30  |
|                  | \(v_{13}\)     | 0.34  | 0.36  | 0.30  |
|                  | \(v_{23}\)     | 0.20  | 0.20  | 0.20  |
|                  | \(G_{12}\) (GPa)| 2.93  | 2.59  | 4.26  |
|                  | \(G_{13}\) (GPa)| 2.93  | 2.59  | 4.26  |
|                  | \(G_{23}\) (GPa)| 2.50  | 2.00  | 3.00  |
| 5228A            | \(E\) (GPa)   | 3.13  | 4.28  | 2.60  |
|                  | \(v\)         | 0.37  | 0.36  | 0.36  |

**Fig. 9** Buckling modes of ultra-thin-walled lenticular collapsible composite tube.
Temperature effect on buckling properties of ultra-thin-walled lenticular collapsible structures

4. Conclusions

The significant results emerging from the studies are as follows.

(1) The failure mode of the ultra-thin-walled LCCT in axial compression tests at three different temperatures can be reckoned to be characteristic of the buckling initiation and propagation around the central region until brittle rupture.

(2) The buckling initiation load, on average, is only about 2.2% greater at −80 °C than at 25 °C, whereas that is about 19.5% lower at 100 °C than at 25 °C.

(3) The buckling modes predicted from FE analysis correlate well with the experimental observations and the relative deviations of the theoretical predictions of buckling initiation load obtained from FE analysis from the means of experimental results at three temperatures of 25 °C, 100 °C and −80 °C are respectively 9.2%, 11.9%, and 14.7%, with the acceptable scatter. The FE models can gain an insight into understanding the buckling initiation mechanism in the LCCT in axial compression tests.

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References


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