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Study of thermal buckling behavior of plain woven C/SiC composite plate using digital image correlation technique and finite element simulation

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ABSTRACT

In this study, the thermal buckling behavior of plain woven C/SiC composite plate is investigated by a non-contact measurement based on the three-dimensional digital image correlation (DIC) technique and finite element analysis. The plain woven C/SiC composite plate is fixed by a water-cooling steel frame and one-side heated by quartz lamp array heating apparatus. The buckling temperature and the first buckling mode shape of the C/SiC composite plate are determined from the temperature-displacement curves and full-field deformation that are obtained from the DIC-based experiment. A nonlinear finite element buckling analysis with initial imperfection is performed using the ANSYS software. In order to improve the accuracy of the numerical simulation, a clamping frame model is further proposed for simulating the real clamping boundary in experiment. The results of the finite element simulation and DIC-based measurement coincide well regarding the temperature-displacement curve tendency and critical buckling temperature. Finally, a parametric study is performed using the presented numerical model to investigate the thermal buckling behavior of plain woven C/SiC composite plates with various dimension sizes.

1. Introduction

The application of carbon fiber-reinforced silicon carbide ceramic matrix composite (C/SiC) in aerospace thermal protective system is increasing rapidly due to their high stiffness and strength, high impact and damage tolerance, low specific weigh and excellent resistance to ablation [1–4]. Plain woven C/SiC composite has been considered as one of the most suitable materials for thermal protective structures in the hypersonic flight vehicles, and widely used as high thermal protection structure, e.g. the body flap of X-37 and the thrust chamber in the liquid rocket engine [5–7]. Hypersonic aircrafts bear rigorous aerodynamic heating loads in service environment. The thermal load induces the thermal expansion deformation of thin-walled composite structures and thus generates the compression stress within the composites structures. A high internal compression stress would induce the buckling failure of the composites structures, which would seriously disrupt the stability of the structure. Therefore, the thermal buckling behavior of thin-walled composite structure is one of the most significant properties for designing the hypersonic flight vehicle.

Extensive theoretical researches have been devoted to thermal buckling behavior of laminated composite plates over past decades. The Rayleigh-Ritz method was widely applied to analyze the thermal buckling behavior of laminated composite plates in the last century [8–10]. Chen et.al [11] studied the thermal buckling of laminated composite plates with clamped and simply supported boundary conditions under a uniform temperature rise through Galerkin's method in conjunction with the displacement equation of equilibrium. Where after, the optimum design of laminated composite plates under thermal buckling loads became the focus of researchers [12–15]. So far, thermal buckling load, i.e. critical buckling temperature is still the most important parameter for the structural design considering thermal buckling behavior. Therefore, how to obtain accurate critical buckling temperature has always been concerned by researchers.

In practical applications, the complex structural geometries, temperature distributions and boundary conditions bring great difficulty in theoretical studying of the thermal buckling behavior of composite structures. Many researchers began to employ the finite element method to investigate the thermal buckling of composite plates. Babu

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and Kant [16] developed two discrete finite element models for the thermal buckling analysis of composite laminates and sandwiches with refined higher order theories. Euler eigenvalue method [17–20] was widely used to determine critical buckling temperature. Maloy [21] et al. studied the thermal post-buckling behavior of graphite/epoxy multi-layered rectangular plates of various boundary conditions using the finite element method. They carried out nonlinear analysis of laminated plates with temperature dependent material properties by the modified Newton-Raphson technique. Xu et al. [22] discussed and reviewed the finite element methods and technologies of buckling analysis of laminated plates, and thus further demonstrated the versatility and practicability of finite element method for complex buckling problems.

Most researchers paid attention to the theoretical and numerical analysis of thermal buckling, while few researchers concerned the experiment of thermal buckling. NASA published an experimental report about the thermal buckling of hat-stiffened panel measured by a large number of strain gages and thermocouples [23]. Utilizing the thermal mismatch between specimen and frame, Murphy and Ferreira [24] measured the thermal buckling of aluminum plate by linear voltage displacement transducer. Rakow and Waas [25,26] determined the critical buckling temperature of metal foam sandwich panels and obtained the full field mode shape using Morie interferometry technique. The non-contact optical measurement technique provides a novel tool in studying the thermal buckling of structures. Jin et al. [27] used the Digital Image Correlation (DIC) technique to investigate the thermal buckling of circular glass/epoxy laminated composite plate in a titanium ring. Through DIC technique, the full field deformation and critical buckling temperature were obtained. Gong et al. [28] used DIC technique to investigate the thermal buckling behavior in thin-walled structures for hypersonic aircrafts.

Most of the investigations have been focused on metal materials or laminated composites during the past decades. Recently, researchers show interests for the thermal buckling behavior of the functional composites, e.g. the shape memory alloy composites and functionally graded materials (FGM) [29–32]. However, the investigation of thermal buckling behavior of C/SiC composite plate has not been found in the literature.

Motivated by the work done by Rakow and Waas who pioneered the concept of examining the thermal buckling response of actively cooled structures [25,26], an experimental setup is designed to investigate the thermal buckling experiment of plain woven C/SiC composite plate. The plate is fixed with a water-cooling steel frame and one-side heated using the quartz lamp array heating apparatus. The plate is heated to 300 °C and 500 °C respectively with different heating rates. The critical buckling temperature and buckling mode are obtained using the displacement field from the DIC measurement. A finite element analysis is executed in ANSYS software to perform nonlinear thermal buckling analysis with the influence of imperfections. In order to accurately simulate the real clamping boundary in experiment, a clamping frame model is further introduced into the finite element analysis. Finally, the presented numerical model is employed to investigate the thermal buckling behavior of plain woven C/SiC composite plates with various dimension sizes.

2. Material and methods

2.1. The plain woven C/SiC composite plate

In this study, the plain woven C/SiC composite plates with the size of $380 \times 260 \times 1.5\,\text{mm}^3$ are provided from Laboratory of Science and Technology on Thermostructural Composite Materials (TSCM), Northwestern Polytechnical University, China. Fig. 1 presents a schematic of plain weave structure. Warp (longitudinal direction) and fill yarns (transverse direction) are interlaced in a regular sequence of one under and one over [33]. The composite plate is manufactured through densification of the carbon fiber plain woven preform via a chemical vapor infiltration (CVI) process. The material consists of SiC ceramic matrix, pyrolytic carbon (PyC) interphase and carbon fiber. The mechanical and thermal properties of the plain woven C/SiC composite in temperature range of 27–900 °C are listed in Tables 1 and 2, which are provided by TSCM. It is shown that the mechanical and thermal properties of the C/SiC composite are both sensitive to temperatures. Therefore, the properties at other temperatures which are not listed in Tables 1 and 2 are determined by a linear interpolation.

2.2. Experimental setup

The coefficient of thermal expansion (CTE) of the C/SiC composite is quite low compared with the clamping frame made of steel. Consequently, the large thermal deformation of steel frame during the temperature rising process would lead to an incomplete clamping of the C/SiC composite plate. Therefore, in this study a water-cooling steel frame is designed for fully clamping the C/SiC composite plate. Fig. 2 shows a schematic of the water-cooling clamp frame. Cooling channel (the blue dash line) is distributed along the boundary of frame. During the experiment, recycle cooling water flows through the cooling channel to keep the frame nearly room temperature. The in-plane deformation of composite plate is limited by the bolts around the plane in the grooves. The size of testing region is $350 \times 230 \times 1.5\,\text{mm}^3$.

The experimental setup used to measure the thermal buckling of the C/SiC composite plate is shown in Fig. 3. In this experiment, a computer controlled heating apparatus (quartz lamp array shown in Fig. 4) heats the assembly of water-cooling clamp frame and sample in one side. The peak power of a single lamp can reach 3000 W. The heating apparatus is controlled by universal processing system and thermocouples are used to adjust the temperature of the heated side. The DIC system consists of the PMLAB software, two CCD cameras, the blue light sources and a controller box. The image resolutions and optical focuses of the cameras are 2048×2048 pixels and 50 mm, respectively. To accurately determine the deformation of the sample, the cameras should be calibrated using a panel with uniformly spaced markers. After calibration, the measurement area is set to be $350 \times 230\,\text{mm}^2$ with a calibration deviation of 0.024 pixels.

Note that the principle of the DIC technique which can be found in many existed references [34–36] is not discussed in this paper. Here, the DIC based measure procedure of the thermal deformation and buckling is described. Firstly, the no-heating surface of C/SiC composite plate is sprayed with high-temperature black speckles on a white background, as displayed in Fig. 2. Usually the speckle pattern cannot stably exist in a high-temperature environment over 1000 °C [37]. Since in this study the maximum heating temperature is 500 °C, the stability of the speckle pattern is neglected. However, it should be noted that how to produce the stable speckle pattern is the core problem of DIC method at high temperatures [37]. To address this problem, Meyer and Waas have developed a new speckle technique for high temperature measurement in which the surface of the structure does not have a speckle pattern [38]. They used a novel algorithm and a new technique with blue light and filters to optically obtain a measurement that is far superior to any other technique available at elevated temperature. The camera system is placed in front of the no-heating side of the C/SiC composite plate, where the speckle pattern is visible. The light sources are used to illuminate the sample surface during thermal measurement. The starting temperature is set to be room temperature, and the corresponding image is recorded as the reference image. The C/SiC composite plate is then heated and deformed images are captured after the desired temperatures are reached.

In the experiment, the room temperature is kept as 20 °C. The center of plate is heated to 300 °C with 0.2 °C/s (noted as 300 °C experiment) and 500 °C with 0.5 °C/s (noted as 500 °C experiment), respectively. The temperature curves of two different heating rates are captured from the thermocouple of center point in the heated surface. The