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A study of the thermal buckling behavior of a circular aluminum plate using the digital image correlation technique and finite element analysis

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ABSTRACT

In this study, the thermal buckling behavior of a circular aluminum plate that results from thermal loading was investigated using a digital image correlation (DIC) technique. The aluminum plate was placed in a titanium ring and the structure was heated from room temperature 25 °C to 160 °C. Due to the differences in the coefficients of thermal expansion (CTEs) between aluminum and titanium, the aluminum plate buckles at a certain temperature. The buckling temperature was determined from the full-field deformation shape and temperature-displacement curve that were obtained using the DIC-based ARAMIS® software. In order to obtain an appropriate full-field deformation, a polarized light filter was used to reduce the out-of-plane displacement error, which is an unavoidable error in the experiment. Using this method, the standard deviation of the *z* directional displacement was reduced from $\pm 3.14\ \mu m$ to $\pm 2.70\ \mu m$. In addition, the results demonstrated that the measured buckling temperature was close to the theoretical buckling temperature of the circular plate in a simply supported boundary condition. In order to verify the proposed measurement method, a finite element analysis of the structure was performed using the ABAQUS software. The results of the DIC-based measurement and finite element analysis were in good agreement regarding the deformation curve tendency. The buckling temperature from the finite element method (FEM) was slightly larger than that from the experimental results due to the initial imperfections of the aluminum specimen. These results provide a good method for studying thermal buckling for the design and analysis of engineering structures in diverse fields such as aerospace engineering, oil refineries, and nuclear engineering.

1. Introduction

The buckling of thin plates due to thermal loads has attracted significant attention in the design and analysis of engineering structures in diverse fields such as aerospace engineering, oil refineries, and nuclear engineering. As a result, many theoretical analyses and experimental investigations have been undertaken on thermal buckling in order to adapt to the fast development and changes in technologies. The area of thermal buckling has numerous diverse issues, and a summary of recent works in this field has been presented in the review articles by Tauncher [1] and Thornton [2].

In theoretical studies, the Rayleigh–Ritz minimum energy and Timoshenko methods have mostly been used to identify the buckling mode and critical buckling temperature [3]. These theoretical results should be confirmed with the experimental results; however, using experiments to determine the buckling load is not simple even though there are numerous methods of estimating the buckling load as described by Souza et al. [4]. In the first method, the buckling load is estimated through physical visualization from the load and displacement curves [5]. The second method uses the deformation-load data and linear deformation assumption to predict the buckling load [6]. However, it is difficult to identify the precise buckling load due to the nonlinear behavior of the material. In order to overcome these problems, Murphy and Ferreira [7] proposed a method that uses the load–displacement behavior and nonlinear effects to determine the buckling temperature. In their study, the deformation was measured using a linear voltage displacement transducer (LVDT). However, the use of the LVDT always needs to invent a difficult mounting method to the specimen. In addition, the measurement ranges and resolutions need to be considered too. Strain gauges have also been commonly used for thermal deformation measurements in buckling problems [8]. Similar to the LVDT, strain gauges must be mounted in a suitable position on the structure in order to

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measure the deformation of a single point. Because the mounting position can be difficult to identify and appropriate mounting is difficult to achieve, a non-contact full-field measurement method is an appealing concept for measuring thermal buckling. Resulting from the full-field deformation of the structure and the obtained load–displacement curve, it is simple to identify the buckling temperatures and buckling modes.

Several non-contact optical measurement methods have been proposed including both interferometric techniques such as laser speckle correlation [9], Moiré interferometry [10,11], and electronic speckle pattern interferometry [12], and non-interferometric techniques such as the digital image correlation (DIC) technique [13,14]. The DIC technique is considered the most promising optical full-field measurement method in terms of the level of operational difficulty, price, and quality of measurement results.

Recently, the DIC technique has been used in engineering to measure static deformations, dynamic deformations, and fracture propagation [15–23]. For the thermal deformation measurement, Lyons et al. [24], who first reported thermal deformation measurements using the DIC technique, measured the deformation of an Inconel 718 alloy at temperatures up to 650 °C. However, they stated that the image acquisition system could not obtain clear specimen images due to the specimen radiation at temperatures above 650 °C. Grant et al. [25] proposed an effective counter measurement using filters and blue illumination to acquire the images at temperatures of 1400 °C. Furthermore, Pan et al. [26] used a narrow optical bandpass filter to solve the radiation problem and measured thermal expansions up to 1200 °C. Yang et al. [27] developed a simple high temperature resistant speckle pattern for micro DIC in order to study the real time deformation of thermal barrier coatings near interface regions and surfaces during a thermal shock of 1100 °C. From these studies, it is clear that the DIC technique has significant potential for measuring thermal deformations.

Although the DIC technique can measure the full-field deformation of the structure, the measurement procedure must be undertaken precisely because it can yield significant measurement errors resulting from parameters such as the camera calibration, lighting, speckle patterns, and calculation algorithms [28]. The typical theoretical error in the DIC technique is ± 0.02 pixels for the in-plane displacement and ± 0.04 pixels for the out-of-plane displacement [28]. The errors increase depending on the selected measurement procedure. Thus, it is crucial to distinguish the exact reasons for these errors and reduce them where possible.

In this study, the thermal deformation of an aluminum plate was measured using the DIC technique. The plate was heated in a heating chamber and its surface images were captured using a stereotype camera. It is expected that the circular polarized light (CPL) filter will reduce the displacement error because it increases color saturation and eliminates reflections from nonmetallic surfaces such as glass and water. Hence, the camera can capture higher contrast images through its optical window, thus reducing the deformation error. The buckling mode and buckling temperature are obtained using the displacement field from the DIC technique. In addition, a finite element analysis of the aluminum plate is performed using the ABAQUS software. Finally, the deformation and buckling mode from the DIC technique and finite element analysis are compared.

2. Experiments

2.1. Specimen

In this study, 2024-T3 aluminum, which is widely used in aircraft for numerous applications such as the fuselage, door skin, dorsal fin, and trailing edge panels due to its high mechanical performance and low density, was used to fabricate the buckling specimen. The diameter and thickness of the aluminum plate were 49.999 mm and 1.033 mm, respectively. As shown in Fig. 1, the aluminum plate was placed in the titanium ring without being fixed to the ring. The diameters of the inner and outer titanium ring were 50.036 mm and 69.990 mm, respectively. The gap between the aluminum circular plate and titanium ring was 18.5 μm at 25 °C.

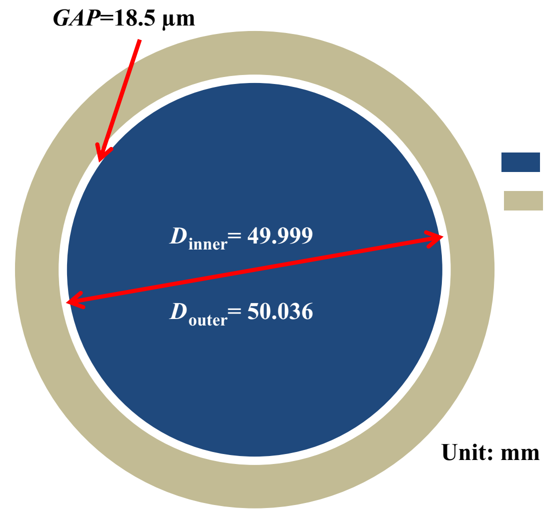

Fig. 1. The aluminum circular plate with a titanium ring.

When the structure was heated in the heating chamber, the gap between the plate and the ring decreased due to the differences of the coefficients of thermal expansion (CTEs). The contact temperature (ΔT_{cont}) is defined using following equation:

$$\Delta T_{cont} = \frac{GAP}{R_{AL} \times \alpha_{AL} - R_{TI} \times \alpha_{TI}}, \tag{1}$$

where R_{AL} is the radius of the aluminum plate, R_{TI} is the inner radius of the outer ring, GAP is the initial gap between the plate and the outer ring, α_{AL} is the CTE of aluminum, and α_{TI} is the CTE of titanium. Assuming that a CTE temperature dependency does not exist during the temperature increase, the contact temperature is $\Delta T_{cont}=51.4$ °C based on Eq. (1).

After contact, the aluminum plate and titanium ring will deform together. However, due to the aluminum plate having a larger CTE, it will expand faster than the titanium ring. Hence, the aluminum plate will push the titanium ring, which leads to a reaction force that acts on the aluminum plate. It is assumed that the force (P) is in-plane and uniform, and the governing equation of motion for the aluminum plate can be express as

$$D\nabla^4 w = P\nabla^2 w, \tag{2a}$$

$$\nabla^4 = \nabla^2\nabla^2, \tag{2b}$$

$$\nabla^2 = \frac{\partial}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2}{\partial \phi^2} + \frac{1}{r}\frac{\partial}{\partial r}, \tag{2c}$$

where r and ϕ are radius and angle in a polar coordinate system, respectively, w is the transverse plate deflection, and $D=Et^3/[12(1-\nu^2)]$ is the flexural rigidity of the plate. Additionally, E is the elastic modulus, ν is Poisson's ratio, and t is the thickness of the plate. For certain critical values of the in-plane load, the plate will buckle transversely even though external transverse loads may not be present. Finally, the critical load (P_{cr}) is obtained using following equation [29,30]:

$$P_{cr} = k\frac{D}{r^2}, \tag{3}$$