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Effects of thermal exposure on mechanical behavior of carbon fiber composite pyramidal truss core sandwich panel

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ABSTRACT

An experimental study was performed to investigate the effect of high temperature exposure on mechanical properties of carbon fiber composite sandwich panel with pyramidal truss core. For this purpose, sandwich panels were exposed to different temperatures for different times. Then sandwich panels were tested under out-of-plane compression till failure after thermal exposure. Our results indicated that both the thermal exposure temperature and time were the important factors affecting the failure of sandwich panels. Severe reductions in residual compressive modulus and strength were observed when sandwich panels were exposed to 300 °C for 6 h. The effect of high temperature exposure on failure mode of sandwich panel was revealed as well. Delamination and low fiber to matrix adhesion caused by the degradation of the matrix properties were found for the specimens exposed to 300 °C. The modulus and strength of sandwich panels at different thermal exposure temperatures and times were predicted with proposed method and compared with measured results. Experimental results showed that the predicted values were close to experimental values.

1. Introduction

A number of studies on carbon fiber composite sandwich panel with lattice truss cores have been conducted. Such work is very important because lightweight sandwich panels are being developed for structures that require high specific stiffness or strength [1–4]. Various carbon fiber composite sandwich panels have been designed, fabricated and tested over the past few years [5–13]. Finnegan et al. [14] fabricated carbon fiber composite pyramidal truss core sandwich panel using a snap-fitting method. The delamination and buckling failure of truss member were revealed under compression. Xiong et al. [15] manufactured carbon fiber composite pyramidal truss cores sandwich panel using the hot-press molding technique. The mechanical properties of sandwich panel were investigated under axial compression. Fan et al. [16] developed a new method to manufacture a carbon fiber-reinforced three-dimensional lattice sandwich panel by intertwining. However, these studies on carbon fiber composite sandwich panel with lattice truss cores mainly focused on the failure and strength at room temperature. They have not investigated the high temperature behavior of composite sandwich panels themselves. Nor have these studies examined the residual mechanical properties of composite sandwich panels after exposure to high temperature. Thus further work is required to fill the gaps in knowledge. The aim of this paper is to fill some of the gaps in understanding the residual mechanical properties of composite sandwich panel after thermal exposure.

Carbon fiber composite sandwich panels have potential naval and aeronautical applications due to their lightweight attributes as well as potential multifunctional advantages. The mechanical properties of fiber reinforced polymer composites are significantly dependent on temperature. Thermo-mechanical effects due to softening may occur at temperatures around the glass transition temperature of the resin matrix [17]. At higher temperatures, mechanical properties are also dependent on decomposition and delamination cracking of the matrix [18,19]. The mechanical properties degrade more rapidly when the material is heated in an oxidising environment. In aircraft structures, some composite parts adjacent to a hot air source are exposed to high temperature and cooled down to room temperature when the hot air source is removed [20]. Mechanical properties of the composites will be influenced by the thermal environment [21–23]. Matrix cracking, delamination damage and decomposition have been revealed after thermal exposure by some authors [24–26]. Saafi and Romine [27] investigated the residual performance of GFRP-wrapped concrete cylinders after exposure to elevated temperatures of 0.5 T_g, 1T_g, and 2T_g for 0.5, 1, and 3 h. They found that the specimens exposed

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to a temperature of 2 T_g for 3 h experienced severe reduction in axial compressive strength compared to those subjected to a temperature of 0.5 T_g Cleary et al. [28] studied the residual compressive strength of GFRP-confined concrete cylinders after exposure to high temperature. The results showed that the GFRP-confined concrete cylinders lost about 2%, 4%, 13% and 18% of their initial room temperature ultimate strength after exposure for 90 min at temperatures of 120 °C, 135 °C, 150 °C and 180 °C respectively. The T_g of the resin system used in this study was quoted as 121 °C. Thus, in order to prevent catastrophic failures, the effects of high temperature exposure on mechanical properties of composite sandwich panel should be investigated before they are used in load-bearing structures in aircraft and ships.

The present investigation aims to study the effect of high temperature exposure on mechanical behaviors and failure mechanisms of carbon fiber composite sandwich panels with pyramidal truss cores. First, the composite struts were exposed to different temperatures for different times. After high temperature exposure, specimens were tested at room temperature under axial compression till failure. In order to provide insight into the effect of high temperature exposure on failure mechanism, the specimen surfaces and fiber–matrix interfaces were examined by scanning electron microscope (SEM). The thermal behavior of the epoxy resin matrix was studied using thermogravimetric analysis (TGA) as well. Second, carbon fiber composite sandwich panel with pyramidal truss cores were exposed to different temperatures for different times. After high temperature exposure, composite sandwich panels were tested at room temperature under out-of-plane compression till failure. The effects of thermal exposure temperature and time on mechanical behaviors were investigated. Then, analytic models were presented to calculate the residual compressive modulus and strength of sandwich panels after high temperature exposure.

2. Materials and experimental methods

2.1. Materials

Sandwich panel with pyramidal truss cores presented in this paper was fabricated from unidirectional carbon/epoxy prepreg by the molding hot-press method. The fabricate process of composite sandwich panel is as follows. First, the unidirectional carbon/epoxy prepregs were cut to the required size, and made into composite struts as truss members. In order to fully exploit the intrinsic strength of the fiber reinforced composite by the truss structure, all the continuous fibers of composite are aligned in the direction of truss members. Second, the composite struts were inserted into the holes of the mold, both ends of the struts were embedded into eight layers of the top and bottom face sheets. The face sheets were made from 8-plies unidirectional carbon/epoxy prepreg with the stacking sequence $[0/90/0/90]_s$. The sandwich face sheets and truss cores were manufactured in one manufacturing process without bonding. Finally, the sample was cured at 125 °C under pressure of 0.5 MPa for 1.5 h. Then the carbon fiber composite sandwich panel was detached from the molds after the solidification of the resin. The schematic of the manufacturing method of composite sandwich panel is shown in Fig. 1. Fig. 2 shows an example of the manufactured carbon fiber composite sandwich panel with pyramidal truss core. A Cartesian coordinate is established in order to facilitate the analysis as shown in Fig. 2: 1-axis is along the length direction, 2-axis is along the width direction and 3-axis is along the thickness direction.

Fig. 3 shows the schematic diagram of the pyramidal unit cell. The relative density of the pyramidal core depends on the diameter of truss d, length of truss l, inclined angle ω, and the distance k between two closest struts. The relative density of the cell is defined as the ratio of the truss volume to that of the unit cell. The relative density of the truss core is:

$$\bar{\rho} = \frac{\pi d^2}{\sin\omega\left(\sqrt{2}l\cos\omega + 2k\right)^2} \tag{1}$$

In the present paper, the pyramidal truss structure has d = 2.5 mm, k = 7 mm, l = 21.2 mm and $\omega = 45^\circ$, leading to $\bar{\rho} = 2.24\%$.

2.2. Test methods

As mentioned above, some composite struts and sandwich panels with pyramidal truss cores were exposed to different temperatures for different times. For this purpose, an insulated temperature-controlled air oven is used to provide high temperature environments. In order to investigate the effect of thermal exposure temperature and time on mechanical properties of composite struts, some of the composite struts were exposed to temperatures of 20 °C (room temperature), 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C for a period of 6 h, whereas other composite struts were exposed to temperatures of 200 °C and 300 °C for a period of 3, 6, 9, 12, or 15 h. This temperature regime was selected to simulate temperatures that might be experienced by the fiber reinforced polymer system in an actual fire situation [23]. After thermal exposure, the composite struts were cooled down to room temperature. Then composite struts were tested at room temperature according to ASTM D695-96 [29] under axial compression till failure. The diameter and gauge length of tested composite struts is 2.5 mm and 9 mm, respectively. The struts were sufficiently thick to prevent Euler buckling of the struts. The test schematic of composite strut is shown in Fig. 4a, and the molds in Fig. 4b are used to ensure the vertical state of the specimen under compression. In order to remove the bending effects from the tests, vernier caliper was used to guarantee that both ends of composite struts are along the loading direction. For truss core sandwich panels, some of composite sandwich panels were exposed to temperatures of 20 °C, 100 °C, 150 °C, 200 °C, 250 °C, and 300 °C for a period of 6 h, whereas other composite sandwich panels were exposed to temperatures of 200 °C and 300 °C for a period of 3, 6, 9, 12, or 15 h. After thermal exposure, composite sandwich panels were tested at room temperature according to ASTM C365 [30] under out-of-plane compression till failure. The dimensions of tested sandwich panel specimens are $80 \times 80 \times 17.4$ mm^3, the thickness of the face sheet is 1.2 mm. Fig. 4c shows the test schematic of composite sandwich panel.

3. Results and discussion

3.1. Thermal analysis of epoxy resin

Thermal decomposition of epoxy resin was measured by thermogravimetric analysis using a TA Instruments TGA Q50 thermogravimetric analyzer. TGA was performed in air at heating rate of 20 °C/min. The retained mass-temperature curve for the epoxy resin measured with TGA is presented in Fig. 5. The curve is used to determine the range of temperatures over which decomposition occurs. It can be seen that the epoxy resin decomposed in two stages. A first rapid degradation started from 250 °C and ended by a pseudo-plateau. The second stage resulted in the complete degradation of epoxy resin. The reduction in mass is mainly attributed to the burning off of the epoxy resin in the range of these decomposition temperatures.