Composite Structures 116 (2014) 670–681

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental study on the low velocity impact responses of all-composite pyramidal truss core sandwich panel after high temperature exposure

Jiayi Liu [a,*], Xiang Zhu [a], Tianyun Li [a,*], Zhengong Zhou [b], Linzhi Wu [b], Li Ma [b]

[a] School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
[b] Center for Composite Materials and Structures, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Article history:
Available online 14 June 2014

Keywords:
Composite
High temperature exposure
Sandwich panel
Impact behavior

ABSTRACT

The effects of high temperature exposure on the low velocity impact behaviors and damage mechanisms of all-composite pyramidal truss core sandwich panels were investigated by experiment in this paper. The composite sandwich panels were manufactured from unidirectional carbon/epoxy prepreg and exposed to different temperatures for 6 h. The impact tests of exposed specimens were performed at three different energy levels, and the effects of exposure temperature and impact energy level on the damage mechanism, absorbed energy and maximum impact force were analyzed. The impact-damaged specimens were subsequently subjected to in-plane compressive tests in order to investigate the effect of exposure temperature and impact energy level on the compressive failure load. The results have shown that the high temperature exposure has a significant effect on impact properties and damage mechanisms of specimens. The fiber fracture, node failure, delamination and buckling were observed during low velocity impact tests and the extent of damage area was significantly affected by exposure temperature. In addition, the absorbed energy increased with increasing exposure temperature, while the maximum impact force and compressive failure load after impact decreased with increasing exposure temperature due to the degradation of the matrix properties and fiber–matrix interface properties at higher temperatures.

1. Introduction

Lightweight composite sandwich panel with lattice truss cores are currently being designed and implemented for the load-bearing structures in aircraft [1–3]. Significant research has been conducted to understand their static mechanical behaviors at room temperature [4–7], and the superior mechanical properties such as high specific stiffness, high specific strength and potential multifunctional advantages have been revealed [8]. In addition to the static loading, composite sandwich panel is often subjected to thermal loading due to the environment and significant dynamic loading due to foreign object impact [9]. Tools dropping on the surface of composite materials and a flying fragment with low velocity hitting the military aircraft panels can create impact scenarios. The resultant damage of such impacts is usually in the form of delamination, fiber fracture and matrix failure [10]. With increasing use of composite sandwich panel in aircraft structures, a great deal of research should be done to better understand the impact responses of composite sandwich panel under extreme environmental conditions.

During their service life, the degradation of mechanical properties of composites by various environmental effects such as high temperatures and moisture absorption will occur [11–14]. Especially, history of exposure to high temperatures can seriously influence the mechanical properties. Mass loss, matrix cracking, reduction in failure strength and changes in fracture behavior have been shown to occur after high temperature exposure [15]. The residual tensile strength of carbon fiber reinforced polymer composite materials after exposure to high temperatures of 100 °C, 200 °C, 300 °C and 400 °C for 3 h has been investigated. The results showed that the tensile strength did not experience obvious reduction with temperature up to 300 °C, but that there were severe reductions at 400 °C [16]. The residual performances of glass fiber reinforced polymer composite materials after exposure to high temperatures of $0.5T_g$, $1T_g$, and $2T_g$ for 0.5 h, 1 h, and 3 h have been studied. The results showed that the specimens exposed to a temperature of $2T_g$ for 3 h experienced severe reduction in axial

* Corresponding authors. Tel.: +86 13628663509.
E-mail addresses: liujiayi@hust.edu.cn (J. Liu), ltyz801@hust.edu.cn (T. Li).

http://dx.doi.org/10.1016/j.compstruct.2014.06.005
0263-8223/

compressive strength compared to those subjected to a temperature of $0.5T_g$ [17].

Although the static behavior of composites after high temperature exposure has been extensively studied, the dynamic response of such materials is also equally important [18]. A few studies have reported the effects of high temperature exposure or fire on the impact response of composite laminates and sandwich panels [18–21]. The effects of high temperature exposure on failure mode and impact performance of composites have been revealed. Akay et al. [22] studied the effects of long-term exposure to high temperature on the impact behaviors of composite laminates. The results showed that the failure modes changed with exposure time from a brittle transverse tensile failure to a failure where the fibers fracture by buckling, following delamination and excessive deflection. Badawy [23] investigated the impact behavior of glass fibers reinforced composite laminates after exposure to temperatures of 20 °C, 50 °C and 80 °C for 1 h and 3 h. They found that the impact strength decreased as exposure temperature increased for both 0° unidirectional and cross-ply laminates. Ulven et al. [24] evaluated the low velocity impact responses of fire exposed composite sandwich panels. The results showed that the initial stiffness, peak load and energy to peak load decreased with increasing fire exposure. All of the above studies were concerned with composite laminates and sandwich panel with balsa wood core or honeycomb core. However, no work has been conducted to evaluate the effects of high temperature exposure on impact behaviors of all-composite pyramidal truss core sandwich panel. Hence, an attempt is needed to investigate the impact properties loss associated with high temperature exposure, which can aid the design and application of the composite pyramidal truss core sandwich panel.

In this paper, the composite pyramidal truss core sandwich panels were exposed to different temperatures for 6 h. After high temperature exposure, the low velocity impact tests at three different impact energy levels (10 J, 20 J, and 30 J) were conducted to investigate the impact damage behaviors, fracture mechanisms and energy absorption mechanisms of composite sandwich panels. Finally, the in-plane compressive tests were performed to determine the compressive failure load after impact.

2. Experimental

2.1. Panel fabrication

Carbon fiber composite pyramidal truss core sandwich panels were fabricated from unidirectional carbon/epoxy prepregs by the molding hot-press method. The detailed fabricate process is as follows. Firstly, the carbon/epoxy prepregs were cut into the required dimension. Then the prepregs were made into composite struts as truss members. In the manufacturing process, all the continuous fibers of composites are aligned in the direction of truss members. In this case, the truss structure can fully exploit the intrinsic strength of the fiber-reinforced composite. Secondly, the composite struts were inserted into the holes of the molds, both ends of the struts were dispersed and embedded gradually into 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 face sheets were interconnected with pyramidal truss cores, and the face sheets and truss cores were fabricated in one manufacturing process without bonding. Prior to producing pyramidal truss core sandwich panel, a release agent was brushed on the mold surfaces in order to separate the structures from the mold easily after the curing of resin. Finally, the preformed sandwich panels were cured at 125 °C under constant pressure of 0.5 MPa for 1.5 h. The resin was melted and redistributed in the curing process. Then the composite pyramidal truss core sandwich panel was obtained by removing the mold after curing. The schematic of the manufacturing method of sandwich panel is shown in Fig. 1, and the fabricated pyramidal truss core sandwich panel is presented in Fig. 2a. The schematic of the pyramidal unit cell with the truss diameter d, the truss length l, the inclined angle ω, and the distance k between two closest struts is shown in Fig. 2b. The pyramidal core presented in this paper has $d = 2.5$ mm, $k = 7$ mm, $l = 21.2$ mm, $\omega = 45°$.

2.2. High temperature exposure

In order to investigate the effects of high temperature exposure on low velocity impact behaviors and damage mechanisms, the sandwich panels were exposed to the prescribed temperature for the prescribed time. For this purpose, a programmable insulated temperature-controlled air oven was used to provide high temperature environments. Thermal exposures were accomplished by placing the specimens in the oven and heating to the desired temperature. A constant temperature was maintained for 6 h. The thermal exposure time of 6 h was determined according to the thermal exposure time for the service life of a specific aircraft. The exposure temperature is 20 °C (room temperature), 100 °C, 200 °C, 250 °C, and 280 °C, respectively. This temperature regime may be experienced by the composite sandwich panel during their service life. After each thermal exposure, the specimens were cooled at room temperature for a period more than 24 h.

2.3. Mechanical tests

Fig. 3 shows the schematic of the procedure used to evaluate the effects of high temperature exposure on low velocity impact behaviors and compressive failure load after impact. After high temperature exposure, low velocity impact tests at three different energy levels were conducted at room temperature. The low, medium, and high impact energies were selected to be 10 J, 20 J, and 30 J, respectively. These values were chosen such that the low impact energy caused partial penetration of the top face sheet, the medium impact energy caused complete penetration of the top face sheet, and the high impact energy caused nearly complete penetration of the entire specimen. An Instron Dynatup drop tower (Model 9250HV) was used to conduct the impact tests as shown in Fig. 4. In this paper, all specimens were impacted with a 12.1 mm diameter striker with a hemispherical nose. During tests, the different impact energies were obtained by adjusting the drop height. The top face sheet of sandwich panel was taken as the zero reference point for the height measurements. A pneumatic clamping fixture was used to secure each sample during impact. The impact position on a sandwich panel was located in the center of the specimen, as shown in Fig. 5. The dimension of the test specimen was $180 \times 90 \times 16.92$ mm^3. The impact data such as time, deflection, load and energy was recorded and stored by computer using data acquisition software. Three repeat tests were conducted at each of the impact energy and thermal exposure combinations in order to gauge the level of the experimental scatter.

The compression tests of impact-damaged sandwich panels were performed to analyze how the compressive failure load was reduced by the low velocity impact. The compression tests were conducted on INSTRON 5569 according to ASTM C364/C364M-07 with the displacement rate of 0.50 mm/min [25]. In order to give the baseline failure load for the sandwich panel, the nonimpacted sandwich panels (denoted as the 0 J impact category) were also tested under in-plane compressive load.