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Material Properties

Effect of thermal cycling and open-hole size on mechanical properties of polymer matrix composites

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ABSTRACT

This paper investigates the effects of thermal cycling on mechanical degradation of polymer matrix composites (PMCs). Un-notched and open-hole specimens are tested using developed thermal cycling apparatus and tensile test machine. In addition, the hole-size effect of open-hole tension glass/epoxy composite laminates is investigated. The tensile strength, mass loss and surface degradation of the specimens were obtained during 250 cycles. Experimental results showed that the holes diameter is the main parameter to control the thermal cycling effects on open hole structure. Also, it is found that laminates with smaller holes have higher tensile strength variation than those with larger holes. The results showed that increment of the hole diameter and number of cycles decreases the tensile strength.

1. Introduction

Degradation of mechanical properties is one of the weaknesses of polymer matrix composites (PMCs) during thermal cycling. This weakness limits applications of this light and strength material in aerospace industry. During the past decades, different studies are done to identify thermal cycling effects on the PMCs specimens [1,2]. An earlier work in this area is done by Eselun et al. [3]. They found that resin micro cracks generated by thermal cycling affected gas permeability, fatigue life, tensile strength, modulus and interlaminar shear stresses. Also, the coefficient of thermal expansion (CTE) and coefficient of moisture expansion could change. They employed [0/±60/0] and [±30] tubes made from GY70 carbon-fiber and 934 epoxy resin. These samples were cycled six times between 248 °C and −120 or 140 °C at a rate of 3.68 °C/min and the performance monitored by X-rays, acoustic emission, mechanical testing and microscopy analyses. But the effects of the CTE in their results were not clear, because of the low number of thermal cycles and relatively low-temperature drop used.

An attempt to emulate the effect of a space environment on carbon/epoxy (T300/5208) specimens were made by Adams et al. [4]. Various symmetrical cross-ply laminates were used as $[0/90_3]_s$, $[0_2/90_2]_s$, $[0_3/90]_s$, $[90/0_3]_s$, $[90_2/0_2]_s$ and $[90_3/0]_s$ that were subjected up to 500 cycles between −157 °C and 121 °C at a rate of 5.68 °C/min. Transverse cracks were first detected at −46 °C though many specimens remained crack free at the lowest temperature. In no case was crack saturation observed even after 500 cycles.

One of the important factors affecting in design of composite structures is the load carrying capability of the composite joints. Holes are intentionally created to reduce structural weight or to facilitate joining and access. However, hole also undergoes high stress concentration during loading, and consequently, damage is often initiated from the hole area. During flight, aircraft structure is certainly subjected to fatigue loading. If the structure is made of composite laminates and some parts are reinforced with stitching thread, it is imperative to investigate the fatigue characteristics of stitched laminates [5].

Recently, Ghasemi et al. [6–8] are used Taguchi method to consider a comprehensive experimental analyses to find main effective factors and fracture behavior of specimens on glass/epoxy composite components subjected to the thermal cycling. Statistical analysis of the experimental results showed that long splitting fiber breakage, lateral fiber breakage and angled breakage are dominate failure mode of the $[0]_8$, $[0_2/90_2]_s$ and $[0/\pm45/90]_s$ layups, respectively.

Also, different study is accomplished to consider the hole effects on mechanical properties of composites [9–11]. The effects of open hole on the strength and fatigue life of carbon/epoxy composite laminates have been studied [9]. Also, the tensile behavior of unidirectional glass fiber reinforced polymer laminates with drilled

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holes was investigated [10]. Salleh et al. reported the effect of drilled hole on the mechanical behavior of long kenaf composite with and without fiber glass reinforcement. The surface fracture, residual tensile strength and stiffness of natural fiber/glass fiber hybrid composites were investigated. Since the drilling induced damage is inevitable, this article will provide useful information on the damage progression and its influence on the strength of hybrid kenaf/glass reinforced epoxy composites [11].

Shimokawa et al. [12] evaluated the effect of isothermal aging on the ultimate strength of composite materials. The hole-notched and un-notched panels, before being machined to specimens, were isothermally aged at 120 °C and 180 °C for up to 15,000 h. Static tests at room and elevated temperatures before and after thermal aging provided the open-hole tensile, open-hole compressive and short beam shear strengths. Moreover, the effects of five oxidation resistant treatments on open-hole compressive strength at 180 °C were investigated after isothermal aging of 5000 h at 180 °C. The test results clarified the effects of isothermal aging on ultimate strengths and oxidation resistant treatments on the open-hole compressive strength.

However, despite the extensive studies on mechanical behavior of open-hole laminates, authors found very limited publication on thermal cycling effects on the open hole laminated composite materials. Nakamura et al. [13] considered the thermal cycling tests up to 10,000 cycles on the two kinds of carbon fiber/thermoplastic-polyimide composite, and up to 1000 cycles on a carbon fiber/bis-maleimide composite for use in the structures of the next-generation supersonic transport structures (SST). The laminates had a quasi-isotropic stacking sequence of 32 plies, $(45/0/-45/90)_{4S}$. The open-hole compressive (OHC) specimens were short only in length in comparison test and the size of the hole was 6.35 mm. The number of microcracks initiated was counted and the OHC strength investigated by static mechanical tests at room temperature before and after thermal cycling tests. The study discussed the relationship between the number of thermal cycles, number of microcracks initiated, and OHC strength. The results showed that the OHC strength before and after thermal cycles did not change. Therefore, thermal cycles and the initiation of transverse microcracks did not affect the OHC strength within their studies. However, this work did not present any data on the strength degradation variation of the laminates during thermal cycling loading.

There are no reports however dealing with the quantitative relationship between mechanical degradation by thermal cycling for different open-hole size polymer matrix composites. In this research, the hole-size effect of open-hole tension glass/epoxy composite laminates is investigated. Glass fiber and epoxy resin were used to prepare the required specimens. A two-chamber apparatus and a tension test machine were used for thermal cycling and tension test on the specimens, respectively. Also, the tensile strength of glass/epoxy laminated composite materials was obtained using tensile test during 250 cycles. A correlation between the hole size and thermal cycles on the tensile strength was established. Then fracture analysis and surface degradation changes as a function of the hole diameter and the number of cycles are studied.

2. Material and experimental conditions

All tests and observations described in this paper were performed on glass/epoxy composites which used the ML506 epoxy resin and polyamine hardener (HA-11) as the matrix of composites. This resin has good mechanical properties and low viscosity that makes it a suitable material for the composite applications. Also, unidirectional E-glass fibers (supplied by Gurit™) have been used as the reinforcing material (Table 1). Laminates were prepared with $[0_2/90_2]_s$ stacking sequence. The composite laminates are fabricated using hand lay-up method and are allowed to cure for seven days at room temperature. The test specimens were cut from laminates according to the standard ASTM D3039 [14]. The fiber volume fraction of the composites was 53%.

Table 1
Mechanical and physical properties of epoxy resin and glass fiber.

Material properties	Units	ML506 Epoxy	E-Glass
Tensile modulus	GPa	2.79	71
Shear modulus	GPa	15.24	15.24
Poisson's ratio	–	0.35	0.3
Density	g/cm^3	1.11	2.48
Coefficient of thermal expansion (CTE)	$10^{-6}/°C$	62	4.9

Three specimens were fabricated for each test. The specimens are in form of the rectangular cubic shape with 25 ± 0.5 mm width. The thickness of each layer was 0.2 mm and the thickness of the specimens was 1.6 ± 0.1 mm as shown in Fig. 1. The cross-ply glass/epoxy tabs were locally bonded on each side of the specimens. The size of the hole was 5 and 10 mm and also the un-notched specimens were considered to compare with the open hole results.

A thermal cycling apparatus consisting of heating and cooling chambers and a rail system for specimen motion was assembled to provide the temperature cycle of the specimens [6]. The thermal cycling tests consisted in 250 triangular thermal cycles, the maximum and minimum temperatures being, respectively of 100 and 0 °C with constant cooling and heating rates of 17 °C/min. Temperatures were measured with four thermocouple gauges; two sensors for measurement of the heating and cooling chamber temperature and two sensors for the two sides temperature of the specimens. An example of a temperature record is given in Fig. 2. The specimens were subjected to 0, 50, 100,150, 200 and 250 thermal cycles.

The mechanical tests were conducted on a 50 kN hydraulic universal testing machine (Fig. 3), and each data point indicated in the results is an average of three separate specimens. Tensile tests are done on the proposed specimens with 2 mm/min crosshead velocity.

3. Results and discussion

3.1. Results of tensile test

Three specimens groups were fabricated for each test. Tensile tests were performed on the specimens and the average results and standard deviations values (SDV) of the tensile tests are reported in Table 2. The tensile strengths of the laminates are measured using $S_f = \frac{F}{wt}$ that F is the maximum force, w is the samples' width, and t is the samples' thickness. All the open hole samples have been failed in the net tensile section due to the high stress concentration coefficient.

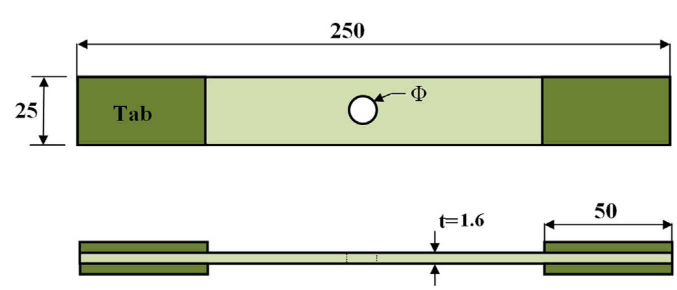

Fig. 1. Tension test specimens with open hole.