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The study of buckling and post-buckling behavior of laminated composites consisting multiple delaminations using acoustic emission

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ABSTRACT

This study introduces a comprehensive set of designed and tested glass/epoxy composites, AE monitoring and signal processing techniques; (i) to investigate the effect of multiple delaminations on buckling and post-buckling behaviors of laminated composites and (ii) to evaluate Acoustic Emission (AE) technique ability to monitor the buckling delamination growth and to classify the occurred damage mechanisms. The pre-delaminations were made by inserting a Teflon film at the plies interfaces during fabrication. Three different types of specimens were fabricated and subjected to compression loading to study the effects of the location, the number of delaminations, and the thickness of the Teflon film on buckling and post-buckling behaviors of the specimens. The mechanical results showed that the number of delaminations has a major effect on the critical and maximum loads and the location of delamination and the thickness of the Teflon film have minor effects on the critical and maximum loads. The AE signals of the specimens were then classified using Gaussian Mixture Model (GMM) and the evolution of different damage mechanisms was investigated. The AE results showed that AE is a robust technique to classify damage mechanisms in buckling of laminated composites and could identify delamination propagation earlier and with a lower standard deviation, compared with the conventional methods.

1. Introduction

Fiber Reinforced Polymer (FRP) composites are utilized increasingly in many industries due to their high specific strength and stiffness [1–3]. Despite their advantages, these materials suffer from different damage mechanisms such as matrix cracking, fiber breakage, and delamination [4–6]. Delamination is the most common damage mode in laminated composites that significantly reduces the stiffness of the structure [4]. Delamination is particularly critical when the structure is subjected to in-plane compressive loading. In this situation, complex interactions between buckling, post-buckling, and delamination evolution can occur [7].

Delamination usually occurs at the interior layers of laminated composites, thus it is not visible to the eye from the outside. In order to detect delamination in composite structures, different Non-Destructive Evaluation (NDE) methods have been used [8–11]. Among the NDE techniques, Acoustic Emissions (AE) have a good applicability for in-situ monitoring [12–15].

Some researchers have investigated the buckling and post-buckling behavior of laminated composites consisting of one or multiple delaminations using experimental, analytical and numerical methods [16–19]. Hosseini Toudeshky et al. [20] studied the effect of composite lay-ups on the delamination propagation in specimens under in-plane compression loading. They showed that delamination propagation could be controlled by changing the composite's lay-up. They also stated that delamination propagation rate decreased by increasing the vertical displacement of the specimen. Gu and Chattopadhyay [21] investigated the effects of the location and the length of delamination on buckling and post-buckling behavior of carbon/epoxy composite plates using analytical and experimental methods. The results showed that the buckling mode was closely dependent on the location and length of the delamination.

In recent years, some research has been conducted to investigate the behavior of delamination in laminated composites under tensile, mode I, mode II and mixed-mode I&II loading conditions using AE method [22–27]. Saeedifar et al. [22] predicted the propagation of delamination in glass/epoxy specimens under mode I loading using AE cumulative energy parameter. Some researchers used AE technique to

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Table 1
The specifications of the specimens.

Specimens	Delamination location	The thickness of Teflon film that serves as the artificial delamination (μm)	Lay-ups
S_P	Without pre-delamination	–	$[0^{\circ}/90^{\circ}]_6$
S_2	2nd interface	250	$[0^{\circ}/90^{\circ}]_6$
S_4	4th interface	250	$[0^{\circ}/90^{\circ}]_6$
S_6	6th interface	250	$[0^{\circ}/90^{\circ}]_6$
$S_{M\text{-}K}$	2nd, 4th, and 6th interfaces	250	$[0^{\circ}/90^{\circ}]_6$
$S_{M\text{-}N}$	2nd, 4th, and 6th interfaces	150	$[0^{\circ}/90^{\circ}]_6$

classify different damage mechanisms in laminated composites under in-plane compression loading. Mohammadi et al. [25] classified different damage mechanisms in Open Hole Tensile (OHT) composite specimens under compression load. They quantified different damage mechanisms by analyzing the AE signals with wavelet transform and fuzzy clustering methods. However, as the manufactured specimens were unidirectional lay-up ($[0]_{10}$) delamination did not occur. McCrory et al. [28] classified damage mechanisms in carbon/epoxy composite plates without any pre-delamination under in-plane compression loading. They classified damages in the specimens by three methods: Artificial Neural Network (ANN), Unsupervised Waveform Clustering (UWC), and Measured Amplitude Ratio (MAR). Debski et al. [29] determined the buckling load of a thin-walled carbon/epoxy channel using experiments and Finite Element Method (FEM). They utilized AE energy parameter to determine the initiation of buckling, without further analysis of the AE data. Zhou et al. [30], studied the state of damage during buckling of delaminated composites using Digital Image Correlation (DIC) and AE techniques. They investigated the global state of damage, but no discriminating and detailed attention were done regarding the damage evolution and the occurred damage types such as delamination, matrix cracking and fiber breakage separately.

Based on the literature review, it was discovered that there is a lack in comprehensive AE-based study of buckling and post-buckling behavior of the delaminated composites. Therefore, the main objective of this study is to utilize AE to investigate buckling and post-buckling behavior of glass/epoxy laminated composites with multiple pre-delaminations. To this aim, three different types of specimens, with and without pre-delaminations and with different numbers and locations of the delaminations were subjected to in-plane compression loading and the tests were monitored by AE technique. The mechanical results showed that the number of delaminations has a major effect on the critical and maximum loads and the location of delamination and the thickness of the Teflon film have minor effects on the critical and maximum loads. The AE signals of the specimens were then classified using Gaussian Mixture Model (GMM) and the evolution of different damage mechanisms was investigated. The AE technique is able to identify the propagation of delamination and the type of damage in laminated composites under in-plane compression loading and it can be used to investigate the integrity of composite structures.

2. Experimental procedures

2.1. Description of the materials

The specimens were fabricated from epoxy resin EPL1012, which was mixed with EPH112 hardener and reinforced with E-glass unidirectional fibers with density of 1.17 g/cm^3 and 400 g/m^2, respectively. The laminates were prepared by Vacuum Infusion Process (VIP) method. Inserting a Teflon film at the interface of different plies during manufacturing was used to create the artificial delaminations. The specification of the specimens is represented in Table 1 and Fig. 1.

2.2. Test method

As illustrated in Fig. 2, the specimens were subjected to compression loading. Compression loading was applied at a constant feed rate of 0.5 mm/min in displacement control mode and at a temperature of 25 °C. The applied load and the vertical displacement were continuously recorded during all the tests by a universal compression/tensile machine (DARTEC). The load cell capacity was 50,000 N with 10 N resolution.

In addition, the lateral deflection of the specimen was recorded by two digital dial indicators with resolution of 0.01 mm, located at the left and right sides of the specimen. In order to record the AE signals, two AE sensors were placed on the specimen surface at a distance of 40 mm from the specimen center. The test process was monitored using a digital video camera. Three coupons of each type of specimen were tested to check the tests repeatability.

2.3. AE system

PICO which is a single-crystal piezoelectric transducer, from Physical Acoustics Corporation (PAC) was used as the AE sensor. It is a broadband, and resonant-type sensor with the resonance frequency and optimum operating frequency range of 513.28 kHz and [100–750 kHz], respectively. The AE events were recorded by the AEWin software and a data acquisition system PAC-PCI-2, with a maximum sampling rate of 40 MHz. Vacuumed silicon grease was used as acoustical coupling. The recorded AE signals were enhanced by a 2/4/6-AST preamplifier. The gain selector of the preamplifier was set to 40 dB. The threshold of

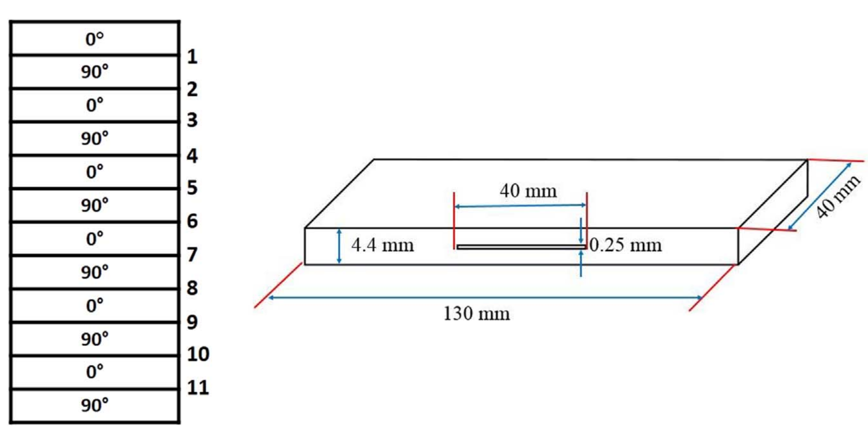

Fig. 1. The schematic of the specimens.