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Cluster analysis of acoustic emission signals and deformation measurement for delaminated glass fiber epoxy composites

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ABSTRACT

Understanding the failure mechanisms of the buckling process of glass fiber composites based on acoustic emission (AE) signals is a challenging task. In this work, a method combining AE with digital image correlation (DIC) was used to monitor compressive buckling behaviors of delamination composites. The analysis of AE signals is based on the k-means algorithm and principal component analysis (PCA). According to PCA, three characteristic parameters of AE signals like amplitude, peak frequency, and RA value (rise time divided by amplitude), are selected for cluster analysis by k-means algorithm. The results show that the AE signals of the compression process can be divided into three clusters. The three clusters correspond to three kinds of damage modes such as matrix cracking, fiber/matrix debonding, delamination and fiber breakage. The characteristic frequency of each mode is found by cluster analysis. Besides, the size and position of delamination defects result in the reduction of mechanical properties of the glass fiber composites. The complementary technology combining AE with DIC is effective for damage monitoring of the composites. Clear changes of the displacement fields can accurately detect the damage location and degree of the specimen.

1. Introduction

Because of a series of excellent characteristics such as light texture, high strength and better fatigue resistance than other materials, glass fiber reinforced polymer composites have been used in a wide range of applications such as automobile, aerospace and wind power [1–3]. However, some defects like delamination and void might appear during manufacturing and service processes. Therefore, characterization and monitoring of the delamination damage and evolution play an important role in studying failure behaviors of the composites [4,5].

In the case of the delamination damage, Juhasz et al. [6] established a progressive finite element model to simulate the effect of delamination growth on the critical budding load of uni-axial compressed plates and the simulations agreed well with the experimental results. Szekrényes [7] utilized second-order laminated plate theory to analyze the delamination damage of composite plates. The comparison of the numerical and analytical results showed that the second-order plate theory captured very well the mechanical fields.

Acoustic emission (AE) technology can monitor the damage process in real time and provide useful information for understanding the damage evolution of the composites [8,9]. Alander et al. [10] utilized AE technology to study the flexural properties of fiber-reinforced composites and it was found that AE activity in composite specimens started at a 19–32% lower stress level than occurred at final fracture. Kumara et al. [11] studied the ageing effect of glass/epoxy composite laminates exposed to seawater environment for different periods of time by AE monitoring. The flexural strength of the seawater treated composite specimens showed a decreasing trend with increasing exposure time. The degradation effects of seawater were obtained based on the changes in AE signal parameters for various periods of time. Nikbakht et al. [1] used AE data analysis and microscopic imaging methods to investigate the sequence of initiation and evolution of different damage mechanisms during the DCB standard test procedure on specimens with different interface fiber orientation. The results showed that the initiation and evolution process of matrix cracking as the first activated damage mechanism greatly depends on the interface fiber orientation, which proved that AE technique is a useful nondestructive technique for monitoring the damage behavior. Similarly, Yousefi et al. [12] presented AE and Cohesive Zone Modeling (CZM) approaches to study initiation and propagation of mode I delamination in glass/epoxy composite materials. The results established a reasonable correlation between delamination initiation and propagation and resultant AE features. Furthermore, Fotouhi et al. [13] used AE technique to track the actual occurring modes of delamination damage in glass/epoxy

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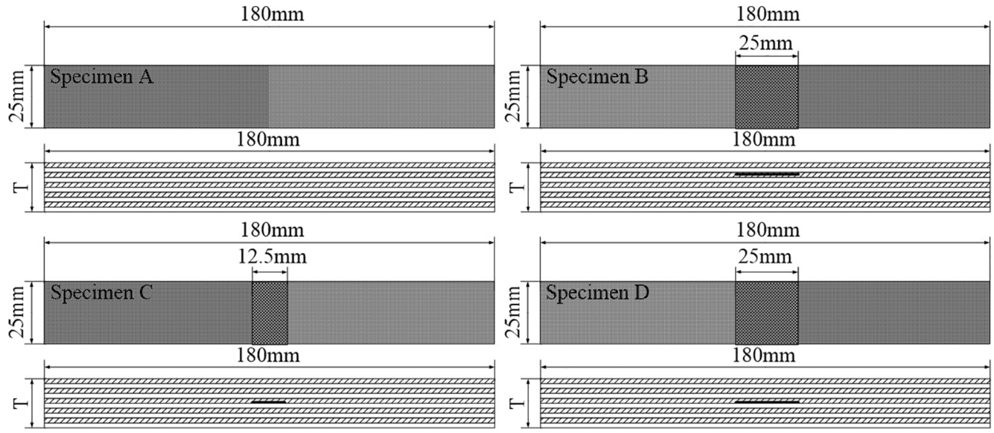

Fig. 1. Sketch map for four types of composite material specimens.

composites. The results indicated that different interface lay-ups and different GII/GT modal ratio values (ratio of mode II strain energy release rate per total strain energy release rate) are correlated with different AE signals and mechanical behaviors. It was demonstrated that AE technology could improve automatic techniques for health monitoring of the real composite structures. Saeedifar et al. [14] investigated the crack tip position during propagation of delamination. The crack tip location was identified by using localization of the AE signal source and the cumulative AE energy. It was found that the novel AE-based methods are more applicable than conventional methods for characterization of the delamination.

Compared with single AE technology, complementary monitoring technology can provide abundant results. Munoz et al. [15] utilized AE and infrared thermography (IT) to identify damage evolution in carbon fiber reinforced composites. The results showed that a spatial and time analysis of heat sources and AE events was developed and correlation ranges in the AE and IT events amplitude were identified. Zhou et al. [16] proposed combining AE with digital image correlation (DIC) method to simultaneously monitor the buckling process of multi-delaminated composites under compression. The results indicated that AE parameters were correlated with the damage process of composite specimens, while the critical damage deformation of delamination regions was clearly exhibited from DIC results. Therefore, the complementary characterization and monitoring technologies combining AE with DIC are beneficial for studying the damage and evolution of the composites.

With respect to the analysis of AE signals, Li et al. [17,18] found a result that the cluster identification creates a framework for analysis of a link between damage mode and AE parameters of the corresponding AE events by cluster analysis of AE signals for woven glass/epoxy composites. The analysis was based on the k-means+ + algorithm and principal component analysis. It was found that the number of AE events agreed well with the number of groups of fibers that fail simultaneously. This finding may provide a new way to explain why the Weibull distribution predicts much more fiber breaks than measured by AE. Monti [19] et al. utilized AE technique to study the mechanical characterization of composite consisting of a thermoplastic matrix reinforced by flax fibers under uniaxial tensile loading. The AE signals were post processed by the k-means unsupervised pattern recognition algorithm. It was demonstrated that three or four classes of AE events could be obtained and a correlation between these AE events classes and the damage mechanisms observed was proposed. K-means cluster analysis is an algorithm based on Euclidean distance. The changes of amplitude and rise time due to signals propagation will affect the Euclidean distance between parameters, and then affect the cluster results. However, the change of parameters is little during signals propagation process, which has little effect on cluster results. Hence, cluster analysis is an effective method to analyze multi-parametrical AE signals, which classifies signals by clustering multi-parametrical descriptors such as amplitude, frequency and signal rise time.

In this study, a complementary technology combining AE with DIC is used to monitor compressive buckling behaviors of the delaminated glass fiber epoxy composites. Meanwhile, cluster analysis based on the k-means algorithm and principal component analysis (PCA) is proposed for analyzing AE signals during buckling process of the composite specimens.

2. Experimental procedure

2.1. Materials and specimens

Four types of composite specimens were prepared with 10 layers of unidirectional glass fiber (ECW 600-1270, 600 g/m^2) which were placed orthogonally and manufactured by vacuum assisted resin infusion (VARI) method. The mass ratio between the Araldite LY 1564 SP epoxy resin and the Aradur 3486 curing agent is 100:34. The as-prepared composites were cured for 48 h at room temperature. Afterward, the laminates were put in drying for 8 h at 100 °C. After falling to the room temperature, the composite laminates with the thickness of 4.8 ± 0.1 mm were cut into specimens with the size of 180 mm × 25 mm by cutting machine. In order to simulate the delamination defects, Teflon film with a thickness of 0.05 mm was embedded in composite laminates. Sketch map for four types of composite material specimens is shown in Fig. 1. There is no delamination defect in Specimen A. Teflon film with the size of 25 mm × 25 mm is sandwiched between the 2th and 3th layers in Specimen B. Teflon films with the size of 25 mm × 12.5 mm and 25 mm × 25 mm are sandwiched between the 5th and 6th layers in Specimen C and D, respectively. Finally, in order to obtain the deformation fields, black/white paints were randomly sprayed on the middle side of the specimens about 40 mm. A total of five specimens of each type of composite laminates were employed.

2.2. Compressive testing

The compressive buckling tests of the composite specimens were carried out at a crosshead speed of 0.5 mm/min by a CMT5305 machine. The length of each grip is 60 mm and the effectively gage length of specimens is 60 mm. The compressive tests of composites were performed according to ASTM standard D3410 partly. At the same time, the AE signals and speckle images during the damage and evolution process were captured by AE instrument (DS-2A) and CMOS camera (MER-500-14U3M), respectively. Maillet [20] proposed an energy-based approach by using two sensors, which can effectively achieve the accurate location and selection of AE signals originating from damage in composites. Nevertheless, because of testing conditions (e.g.