Available online at www.sciencedirect.com
ScienceDirect
Computers and Structures 86 (2008) 367–373
Computers & Structures
www.elsevier.com/locate/compstruc

Health monitoring of FRP using acoustic emission and artificial neural networks

R. de Oliveira [a,*], A.T. Marques [b]

[a] *INEGI, Rua do Barroco, 174, 4465-591 Leça do Balio, Portugal*
[b] *Departamento de Engenharia Mecânica e Gestão Industrial (DEMEGI), Faculdade de Engenharia da Universidade do Porto (FEUP), Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal*

Abstract

In this study, a procedure is proposed for damage identification and discrimination for composite materials based on acoustic emission signals clustering using artificial neural networks. An unsupervised methodology based on the self-organizing map of Kohonen is developed. The methodology is described and applied to a cross-ply glass-fibre/polyester laminate submitted to a tensile test. Six different AE waveforms were identified. Hence, the damage sequence has been identified from the modal nature of the AE waves.

Keywords: Composite materials; Health monitoring; Damage; Acoustic emission; Waveform analysis; Artificial neural networks; Clustering

1. Introduction

Composite structures integrity is sensible to service life. Their application in the aeronautical and space engineering implies the necessity to insure their integrity through non-destructive evaluations. An on-line health monitoring procedure capable to detect, acquire, and identify damage in fibre reinforced polymer composite materials will permit to guarantee the structure safety. Among the different non-destructive techniques, acoustic emission (AE) was chosen for its ability to detect progressive defects during in-service life of structures.

When loading a material, it starts to deform elastically. Elastic strain energy storage is associated with this deformation. Part of the elastic strain energy is rapidly released, at local stress redistribution such as that caused by growing cracks, in the form of elastic waves (AE). The analysis of AE waves permits to continuously monitor the structural integrity throughout its service life, and to control, in real-time, the full structure with few sensors.

AE waves can be detected from mounted surface piezoelectric transducers or embedded sensors such as fibre optic sensors [1]. The health monitoring method described in this paper is based on the application of piezoelectric transducers.

The interpretation of AE signals and the separation of "true" damage sources from spurious noise is still a major problem of this method. Until recently, AE analysis relied on the conventional AE features (e.g. peak amplitude, rise time, counts, duration of the signals etc.). The simultaneous study of various AE features has permitted to obtain more reliable information for identification of AE source mechanisms especially when associated to pattern recognition algorithms [2–4]. The analysis of the frequency content of the AE signals revealed also to be useful for damage discrimination [5]. An alternative treatment consists of considering the AE signals as mechanical waves (modal AE), which has demonstrated to provide more quantitative information about the mechanisms sources [6].

In this study, a hybrid processing of AE signals is implemented based on transient signals and frequency content analysis. Due to the large amount of AE signals acquired,

---

[*] Corresponding author. Address: INEGI, UMEC, Rua do Barroco, 174, 4465-591 Leça do Balio, Portugal. Tel.: +35 1229578713; fax: +35 1229537352.
E-mail address: rcosta@inegi.up.pt (R. de Oliveira).

0045-7949/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruc.2007.02.015

their analysis is not straightforward. Artificial neural networks (ANN) are used for their capacity to process a huge amount of data in a short time. An unsupervised classification methodology was developed for its capacity to discover patterns among the input data without any a priori knowledge. This permits the application of the classifier in any case.

A two-level approach is considered for data clustering. AE data set is first clustered using the self-organizing map of Kohonen (SOM), and then, the SOM is clustered using *k*-means. This approach facilitates the interpretation of the clustering made by the SOM and increases the processing speed. The methodology was applied to the AE signals detected when submitting cross-ply glass-fibre/polyester laminates to a tensile test.

2. Experimental procedure

Glass-fibre/polyester $[0/90_n]_s$ ($n = 1, 2, 3$) cross-ply composite laminates were submitted to tensile tests. Monotonic tensile tests were performed using an INSTRON® Model 4208 universal testing machine, according to the ISO 527 standard. The speed test was controlled by displacement to 1 mm min^{-1}. In addition to the AE acquisition, an acquisition system spider 8, from HBM®, collected the load applied to the material and the strain values obtained by an electric strain gage, mounted on the test specimen.

Composite plates were produced, by manual stratification assisted by vacuum, in the form of plates of dimension 30 cm × 30 cm. Rectangular specimens with dimensions of 25 mm × 250 mm were cut from the plates. The edges were polished with silicon carbide paper to avoid premature initiation of cracking. Aluminium tabs were mounted on the specimens to limit grip signal noise.

A two-channels AMSY-5 AE system from Vallen-System GmbH was used. The signals were digitalized by an analogue/digital converter having a dynamic range of 16 bit using a sampling rate of 10 MHz. Two piezoelectric transducers were used for AE waves detection: a resonant piezoelectric transducer and a broadband B1025 piezoelectric transducer of DigitalWave Corporation, with a near flat frequency response from 150 kHz to 2 MHz. Only the AE signals detected by the broadband transducer were considered. The resonant transducer was used to trigger the acquisition and for localization of AE sources, from the arrival time difference of AE waves at the transducers. The transducers were mounted on the specimen surface using a tape. Silicone grease was used as coupling agent between the sensor and the composite surface.

3. Clustering procedure

A two-level approach was considered for data clustering. AE data set was first clustered using a self-organizing map of Kohonen (SOM), and then, the SOM was clustered using *k*-means. This approach is a variant of the one adopted by Godin et al. [4]. This procedure permitted a considerable computational load decrease, making possible the clustering of large data sets. Signal processing was performed using MATLAB software. Clustering programmes were developed based on the freeware SOM toolbox for MATLAB of Kohonen's group at Helsinki University of Technology [7].

3.1. Features selection and pre-processing

The signals clustering from the entire signal time and frequency representation would be time consuming. Features were thus calculated from the AE signals in the time and frequency domain. A floating or adaptive threshold was used in order to remove the part of the signal due to reflections at specimen edges. Threshold value was fixed to 10% of the signal amplitude.

Fourteen features were extracted from the AE signals in the time and frequency domains. In the time domain, besides the traditional AE parameters (the amplitude in mV, the counts number, the counts to peak, the duration, the rise time and the energy), other features were chosen related to the signal waveform. Selected features are summarized in Table 1.

The selected features revealed to be correlated. In order to optimize the clustering procedure, new more independent features were then calculated using the principal component analysis. This was done without losing significant information.

3.2. The self-organizing map

The self-organizing map [8] is the most popular artificial neural network algorithm in the unsupervised learning category. It solves difficult high-dimensional and nonlinear problems, such as feature extraction and classification of patterns. Besides, it is one of the most realistic models of the biological brain function [8]. Self-organizing map is unique in the sense that it can be used at the same time both to reduce the amount of data by clustering, and to construct a nonlinear projection of the data onto a low-

Table 1
Selected features of the AE signals

Selected features	Unit
Amplitude	mV
Rise time	μs
Duration	μs
Energy	1e^{-7} V^2 s
Counts	–
Counts to peak	–
Amplitude ratio 1	–
Amplitude ratio 2	–
E/F	–
Counts/duration	kHz
FFT peak frequency 1	kHz
FFT peak frequency 2	kHz
FFT amplitude	–
Spectrum's centre of gravity	kHz