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Damage-induced acoustic emission source monitoring in a honeycomb sandwich composite structure

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ABSTRACT

A coordinated semi-analytical, finite element, and experimental analysis of damage induced acoustic emission (AE) wave propagation and source monitoring in a honeycomb sandwich composite structure (HSCS) have been carried out. Towards this, a global matrix method based two-dimensional (2D) semi-analytical formulation is first applied to obtain the AE response and dispersion characteristics in the HSCS. The finite element simulation of AE-wave propagation in the HSCS is then carried out using different AE-sensor network configurations. Eventually, the damage source locations are efficiently identified by applying a source localization algorithm, which uses the registered AE signals from the sensor networks. In order to verify the robustness of the proposed damage source monitoring technique, the localization is further broadened for randomly selected multiple damage source locations for each sensor network configuration. The obtained results distinctly represent the efficiency of the proposed online monitoring strategy for localizing the damage-source in such complex and advanced structures. Moreover, it is shown that the proposed damage source monitoring technique is reliable and independent of sensor positions.

1. Introduction

Honeycomb sandwich composite structures (HSCSs) are extensively used as advanced lightweight construction materials in the Aerospace, Aeronautical, and Automobile industries due to their good fire resistance, water/moisture resistance, acoustic insulation, construction flexibility, high stiffness-to-weight ratio, and high load-bearing capacity [1–3]. Despite many such advantages, the HSCSs are prone to damages, like fatigue cracking, indentation, debonding, matrix failure, and crushing of core that may lead to a sudden structural failure [3,4]. Therefore, a fast and efficient online structural health monitoring (SHM) strategy is required to detect such damage symptoms in advance. Several SHM techniques, such as-acoustic emission (AE), guided wave propagation, scanning laser vibrometry, active infrared thermography, ultrasonic goniometric immersion tests, X-ray computed tomography, amongst others have been described by many authors [5–8]. The AE based monitoring techniques are widely used for real-time damage-source localization in metallic/composite structures [5,9–15]. AE is the phenomenon in which elastic waves are emitted by a sudden release of strain energy during the initiation and extension of cracks or other flaws in structural solids. The AE wave propagation based SHM techniques offer in-service large area monitoring potential with a minimal instrumentation required, giving a proper idea about the damage initiation [15]. In this monitoring technique, the AE-sensors record the elastic-wave motion that follows damage initiation as well as existing damage propagation events within the materials and transforms them into electric waveforms. The study of these registered waveforms can help in understanding the nature of damage and deterioration level. This technique has the capability of global monitoring, requires energy only from the damage-source and does not require any externally supplied energy [16].

Many AE based inspection techniques are proposed for damage detection in multi-layered composite structures [17–25]. The time of arrival (TOA) technique, based on identifying the arrival-time of an AE signal at the sensors for a particular wave mode is used to locate damage sources in isotropic and homogeneous structures [18–20]. Several other AE based damage inspection techniques, such as short-term average (STA) and long-term average (LTA) window, delta-T mapping (DTM), modal acoustic emission (MAE), and the two-step hybrid techniques are also proposed [21–28]. The STA-LTA technique compares the average wave energy in a short-term window with the average wave energy in a long-term window prior to a point in a propagating AE-signal [21]. In MAE technique, the AE wave modes in thin isotropic structures are predicted from the dispersion curve [21–23]. In the DTM

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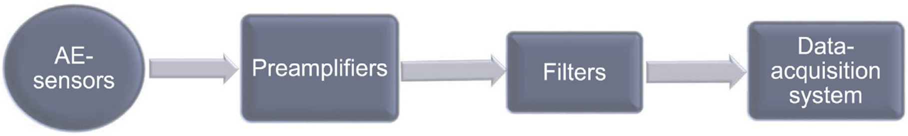

Fig. 1. Schema of GAE instrument configuration for AE signal registration.

technique, the artificially generated AE-sources in the target structure are used to map complex geometries [24,25]. A parameter correction technique (PCT) to derive empirical relationships between varying AE wave amplitudes and other AE wave parameters from different locations on a structure was proposed in Ref. [26]. A fatigue damage detection strategy for metallic structures with complex geometries under noisy environments was presented in Ref. [27]. The strategy combines various signal processing techniques to tackle the monitoring limitations. A tomography approach was also proposed for the detection of possible AE source locations in heterogeneous structures [28].

Various type of damage sources (fatigue damage, impact-damage, lead break, amongst others) are adopted as artificial AE-source by many researchers [14,23,26,27] and among them, the pencil lead break (PLB) damage source is widely considered as the reproducible artificial AE-source for laboratory experimentations. Various functions for rise-times of PLB source like linear-function, step-function, and cosine bell-function are proposed for numerical simulation of PLB loading, and the best understanding between numerical simulation and analytical results was found for the cosine bell-functions [29–31]. The relationship between the surface response and micro-fracture modes in composite laminates is studied extensively to establish the theoretical background for waveform analysis of AE signals [29]. Later, Banerjee [30,31] proposed a semi-analytical method for the calculation of the elastodynamic field generated by localized dynamic loads in a relatively thick multi-layered composite plate using PLB-source located on the surface and a localized shear-delamination excitation within the interior of a relatively thick multi-layered composite plate. The obtained waveforms are found to be comprised of both flexural and extensional modes, and the modal amplitudes showed a strong dependency on the direction of propagation. The results obtained from the two different loading methods (PLB and shear-delamination) shown good agreement in the low-frequency ranges. Sause et al. [32] proposed a two-step hybrid technique to locate the impact sources in anisotropic plates. In the first step, AE wave propagation in a straight line is assumed to find the initial damage source location and an optimization technique is applied in the second step to improve the accuracy of the impact source location. Application of a particular sensor-network to identify impact locations in composite structures with unknown material properties are described in Ref. [33]. Nonlinear Kalman Filtering algorithms with extended and unscented Kalman filters are also proposed as probability based damage source localization algorithms for anisotropic structures [34].

While the previous studies were mostly limited to thin anisotropic plates, in this paper, an in-depth analysis of AE-waves is presented and a robust AE source monitoring framework is proposed for the real-time monitoring of advanced sandwich composite structures, such as HSCS that involved structural complexities like extremely lightweight and relatively thick hexagonal aluminum honeycomb-core bonded with epoxy adhesive-layer (HEXCEL 212NA) to eight-layer carbon-fibre reinforced composite face-sheets. A detailed theoretical, numerical, and experimental analysis of AE-wave propagation and real-time damage-source identification in an HSCS is presented using a network of sophisticated piezoelectric AE-sensors. A two-dimensional (2D) semi-analytical model of AE wave propagation in the HSCS is applied to study the AE-wave response characteristics. A series of 3D finite element simulations of AE-wave propagation in HSCS have been carried out in commercially available finite element software ABAQUS. Laboratory experiments are then conducted on a sample HSCS using various networks of broad-band AE-sensors. In the process, the semi-analytical model is used to obtain the dispersion curves and theoretical time-domain response of the HCSS, in order to effectively predict different wave modes and to analyze the numerical and experimental AE signals. The numerical simulations are successfully validated with experiments, and based on the simulation results the experimental signals are effectively trained. An online SHM strategy is configured that uses a time of arrival (ToA) algorithm to locate damage source locations in the target HSCS.

2. Experimental analysis

A *General Acoustic Emission* (GAE) instrument along with AE-sensors and supporting devices is configured in the laboratory to perform the damage induced AE wave propagation based experiments, as schematically described in Fig. 1. In the experiment, the *AE-sensors* sense the damage induced mechanical vibrations from the attached target structure and convert them to corresponding electrical signals. The collected AE signals are amplified using *Pre-amplifiers* and then pass through *Filters* to remove the calibrated system noise before passing the signals to the *Data-acquisition system*, which processes the data and converts the electrical signals into user recognizable format.

The experimental setup for the AE based monitoring of a 13.5 mm thick 17-layer sample HSCS (450 mm × 600 mm) is shown in Fig. 2. An 8-channel *MISTRAS's Micro II Express* 8 AE-instrument (bandwidth: 1 kHz to 1.2 MHz and data transfer speed: 20 Mb/s) from *Physical Acoustic Corporation* (PAC) connected to a high-performance desktop computer has been employed for the experimental investigations (Fig. 2). In the setup, the *Preamplifiers* are configured with a gain choice of 20 dB, 40 dB, and 60 dB with built-in automatic sensor testing and in-line 20 mm diameter cylindrical shaped broad-band differential *AE-sensors* (*R6D*) with high-pass Filter (3 kHz) are used for identifying the artificial damage source-locations, propagation, and severity. The employed *DAQ* is an *Express*-8 AE system, which has an eight-channel AE board and bundled with AE-win software that enables the waveform processing and efficient real-time monitoring. The AE instrument settings are kept the same for all experimental study cases. All sensors are set to a fixed predefined threshold value of 49 dB to efficiently eliminate the system noise.

In the experiments, the PLBs are used as a reproducible artificial damage source, which also referred as the Hsu-Nielsen (H−N) source for the generation of damage induced AE signals in laboratory

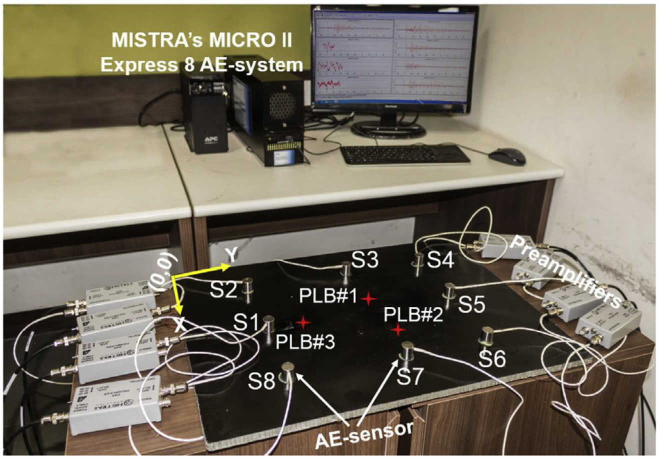

Fig. 2. Experimental AE setup for the monitoring of sample HSCS.