# PHYSICAL AND MATHEMATICAL SCIENCES

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## WAVELET ANALYSIS OF IMPACT-INDUCED DELAMINATIONS IN COMPOSITES

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**Introductions.** Carbon fiber reinforced structures have been widely used in the aerospace industry in recent decades due to their outstanding advantages over other conventional materials in terms of high strength and stiffness, light weight, corrosion resistance, and the ability to fabricate complex shapes are among the advantages of using carbon fiber reinforced composite structures in various industries. However, during the service life of structural elements made of carbon fiber, the latter may be subject to delamination. The cause of such delamination may be, in particular, a low-velocity impact [1]. The presence of delamination in the volume of the composite leads to a deterioration in the structural characteristics throughout the service life. As a result, the problem of implementing a fast and reliable damage identification procedure is currently quite pressing [2]. Impact damage can cause a combination of different types of mechanical damage. Accordingly, matrix cracking, delamination and fiber rupture can cause a serious reduction in the stiffness and strength of the carbon fiber composite material [3].

Non-destructive testing methods are widely used to detect, localize and assess the extent of damage. The most commonly used are those based on acoustic emission, thermography and vibration testing. They, in particular, use the information included in the dynamic response of the structure in terms of mass, stiffness and damping properties. The analysis of the monitoring result of a possible local damage network is often implemented based on wavelet transforms [4]. The wavelet technique consists of decomposing the vibration time domain signal into a combination of shifted and scaled type of the so-called mother wavelet. Detection of data discontinuities and breakpoints that indicate the presence of localized damage is successfully performed by both the continuous wavelet transform approach and the packet wavelet transform approach. Damage analyses based on wavelet transform have proven to be quite effective for the case of a laminated composite structure.

**Aim**. This paper analyzes the efficiency of detecting mechanical delaminations in carbon fiber composite plates. A finite element model for the composite plate is implemented to obtain modal curvatures of the laminates, which will be used in the optimal placement of sensors for wave packets of mechanical shear and stress. The model experiment assumed the presence of three low-speed impacts with different energies. The results of time-varying deformation responses of the laminates before and after the impacts were analyzed. In the subsequent stages, identifiers of various damaged and undamaged configurations were successively used based on wavelet transforms.

**Materials and methods**. Most composite materials are actually brittle, so only a small amount of energy can be absorbed through elastic deformation. This results in large fracture zones, causing both strength and stiffness loss. The failure modes used in the model experiment relate to various physical phenomena, the identification of which provides information about both the impact event and the residual strength of the target. A characteristic development of deformation is the expansion of the delamination area. Therefore, the analysis of the onset and shape of delaminations is of great interest. The effect of transverse load on composite plates leads to a variation in their bending moment due to their orthotropy. To maintain the constancy of the deformation field, normal and shear stresses arise. Delaminations are also a source of possible destruction of the composite sample in the presence of a compressive load.

**Results and discussion**. Wavelet transform-based damage detection is proposed to overcome the limitations of the damage monitoring procedure relying only on the resonance frequency analysis of samples. The obtained time histories are used to construct a tree of wavelet packets with the corresponding wavelet packet energy. Two cases were considered in which each standardized time signal is decomposed into 32 and 64 packets, with the modulation parameter taking the value of n = 5 and n = 6, respectively. The wavelet function used in this paper is Daubechies 4 (db4). Based on the comparison of intact and damaged configurations of three composite samples, a structural diagram was constructed. The classification results of this diagram are expressed in terms of the correct identification percentage, which was increased to 92%.

**Conclusions**. Statistical processing of impact energies using linear discriminant analysis allows separating different structural damage configurations in the wavelet energy space. It was found that the initialization phase, characterized by the identification of a known damaged configuration, was necessary for training the used algorithm. The proposed identification procedure showed a high success rate for delamination damage in composite plates. This method is particularly suitable for large-scale applications and for certification and testing of high-performance materials. Extending such a procedure to lower impact energies, determining the location where the impact occurs, and selecting optimal wavelet functions to extend the developed procedure to larger full-scale composite structures are promising directions for this technique.

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