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An innovative nondestructive perspective for the prediction of the effect of environmental aging on impacted composite materials

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ABSTRACT

In this work, three different types of laminates, each one realized with thirteen layers of fabric in epoxy matrix, have been inspected. In the first one, only aramid fiber is used, whilst the other two are hybrid laminates reinforced with basalt and aramid fibers disposed either in an intercalated or in a sandwich-like structure. All laminates were impacted with an energy of 12.5 J. Inspection of the impacted laminates has been performed by using different nondestructive testing (NDT) methods, such as infrared thermography (IRT), near-infrared reflectography (NIRR) and transmittography (NIRT) and ultraviolet (UV) imaging. Subsequently, impacted laminates were subjected to accelerated aging in an environmental chamber and then inspected again by IRT and digital speckle photography (DSP) using, in the latter technique, an innovative methodology of image speckle processing. Finally, a comparison between the Fast Fourier transform (FFT) and the wavelet transform (WT) techniques applied to the IRT data is reported along with a discussion about the optimal choice of the scales related to the complex Morlet wavelet. Combining these techniques, useful information was obtained to elucidate the structural changes on these laminates after accelerated environmental aging process.

1. Introduction

The fabrication of innovative types of hybrid composite materials has experienced an exponential growth in the last years thanks to the research conducted on the mechanical properties of plant-based and mineral fibers. A significant threat to in-service behavior of composite materials is represented by low velocity impact. As a consequence, the satellite defects that appear in the surrounding area of an impact event have been thoroughly investigated by using non-destructive testing (NDT) techniques (Banerjee et al., 2013; Sfarra, Ibarra-Castanedo, Santulli, Sarasini, et al., 2013b). An interesting research topic in the field of mechanics of composites is represented by the evolution over time of such subsurface defects after accelerated environmental aging (Akil, Santulli, Sarasini, Tirillò, & Valente, 2014; Martin, 2008). Indeed, the changes in strength and stiffness of composite materials after exposure to external environments can lead to a structural response considerably

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inferior to the predicted behavior. Therefore, the evaluation of the degradation of impacted composite structures induced by external environmental factors is necessary to predict their lifetime, so to schedule their replacement.

It is the authors′ opinion that this gap could be filled without using stochastic, probabilistic or statistic models, via a two step strategy: first, predicting aging effect by using environmental conditioning, second, localizing and characterizing subsequent subsurface defects by means of the combined use of NDT techniques. The first NDT technique used is infrared thermography (IRT) (Ibarra-Castanedo et al., 2009): IRT data were processed using the wavelet transform (WT), which appears suitable for the purpose of this study (Moreau, Gibert, Holschneider, & Saracco, 1997).

In the past, several works focused on the application of WT to this type of data have been published (Galmiche, Maldague, Valler, & Couturier, 2000; Olbrycht, Więcek, Gralewicz, Świątczak, & Owczarek, 2007; Vavilov, Shiryaev, & Khorev, 2011) but, up to now, none of these suggested a practical method for choosing the scales related to the complex Morlet wavelet.

By means of this work, it is possible to demonstrate that the scale range can be established working with the wavelet-averaged coherence (in the amplitude and in the phase domain) based on *n*-points linked to the sound area and *m*-points linked to the damaged areas, but only during the cooling phase, where each coherence is estimated using the procedure described in Grinsted, Moore, and Jevrejeva (2004).The coherence is normally used for identifying the correlation at a given frequency/scale between signals. Conversely, in this work, the incoherence trace is investigated that corresponds to a most evident difference response in the cooling phase energy transfer between damaged and sound areas. Subsequently, in this range, a scale-averaged wavelet power is performed obtaining a frame sequence. From this, the frame captured at the maximum thermal contrast, *i.e.*, the one showing a maximum/minimum ratio of amplitude corresponding to the most pronounced inflection, is determined. Finally, a binomial filter in two dimensions is applied to the final frame sequence to identify the emerging defects.

The comparison among the WT results obtained before and after the accelerated environmental aging can demonstrate that the thermal imprints of the laminates change around the impacted areas, *i.e.*, the satellite defects are more pronounced after the treatment, because they represent zones of weakness of the laminates (Bendada et al., 2013; Ibarra-Castanedo et al., 2013; Sfarra, Ibarra-Castanedo, Santulli, Paoletti, et al., 2013a).

In addition, ultraviolet (UV) reflectance imaging and near-infrared reflectography (NIRR)/transmittography (NIRT) techniques are used as non-thermal inspection, since the illumination source was supplied by light emitting diodes (LED) (Ebeid, Rott, Talmy, Bendada, & Maldague, 2010). The double inspection after non-natural aging process was avoided, considering the UV band merely useful to highlight the correct application of the external matrix layer. Instead, NIRR/NIRT technique used to define the extension of the impact damage beyond the visible spectrum is combined with a new image speckle processing method, working in transmission mode, which is not related to the application of digital gradient sensing (DGS) to semi-transparent materials (Periasamy & Tippur, 2012; Periasamy & Tippur, 2013a, 2013b, 2013c): a further innovation is the application of the Wiener filter, herein used for the first time to the best of our knowledge (Lim, 1990) among similar cases.

2. Theory – nondestructive testing (NDT) methods

The article is divided into three main parts; these offer theoretical background about the sensing techniques, information on materials and accelerated environmental aging process and a summary of the main findings, respectively.

2.1. Multispectral imaging: ultraviolet (UV) reflectance, near-infrared reflectography (NIRR)/transmittography (NIRT), infrared thermography (IRT)

Multispectral imaging is used to observe an object using selected ranges of wavelengths in the electromagnetic spectrum extending beyond the capabilities of the human eye. This study will concentrate on the wavelength range that can be observed using a modified commercially available camera, which typically employs silicon-based sensors sensitive from approximately 250 nm to 1000 nm. In addition, also the 7500– 13000 nm wavelength range has been explored using an infrared camera working in the long wave IR spectrum. A generic setup for multispectral imaging is composed of three main components: 1) incoming radiation, which is generated by a radiation source and travels towards the object, 2) the object, which interacts with the incoming radiation, and 3) outgoing radiation, which, following the interaction between the incoming radiation and the object, travels from the object to the recording device. Both the incoming and outgoing radiation are typically in one of three ranges: ultraviolet radiation (UV 200–400 nm), visible light (400–700 nm) or infrared radiation (IR 760–1700 nm).

The extent to which this radiation will penetrate the object under investigation is dependent on its wavelength and on the absorbance of the materials which compose the object, with longer wavelengths of radiation generally penetrating further into the material.

The radiation reaching any particular point in the object can be: a) absorbed, b) reflected, and/or c) absorbed and re-emitted as luminescence at longer wavelengths. Each outcome produces an image set which yields information specific to that points. Thus, by selecting particular combinations of illumination and detection ranges, it is possible to gain insight about the distribution of materials in the object under study. A complementary metal-oxide-semiconductor (CMOS) camera (22.2 × 14.8 mm, 10 MP, spectral band: 380–1000 nm) equipped with a visible cutoff filter to limit the spectrum from 700