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Structural health of polymer composites: non-destructive diagnosis using a hybrid NDT approach



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A hybrid non-destructive testing (NDT) approach has been developed to characterize composites damage using simultaneously bulk and guided ultrasonic waves, acoustic emission, and passive and active infrared thermography. Combining multiple NDT techniques makes it possible to optimize the diagnosis of a material's structural health.

Non-destructive testing (NDT) methods have proved to be invaluable both in detecting initial defects and assessing the damage process of polymer composites [1]. Recent NDT applications for damage monitoring include the use of non-contact optical [2-4], thermal [5, 6] or acoustic-based [1, 7-9] techniques. Such methods have had some success in characterizing the damage behaviour of composite materials. However, a more global NDT approach is required to efficiently and reliably track and quantify both damage initiation and subsequent damage evolution [10], i.e. to go towards efficient structural health monitoring for preventive maintenance purposes. Therefore, Mines Douai suggested a hybrid NDT approach to evaluate composites damage under mechanical loading in a more comprehensive manner [11]. This approach uses five different NDT techniques in situ and in real time: bulk and guided ultrasonic waves [1], acoustic emission, passive [5] and active infrared thermography [6].

Composite materials

A cross-ply E-glass/epoxy laminate (prepreg) with a [0/90/90/0] stacking sequence and a 54% fibre volume fraction was chosen to implement the hybrid NDT approach. Plates were compression-moulded at 120°C for 60 min. Tensile tests were performed according to the ISO 527-5 standard.

Experimental setup for the hybrid NDT approach

Figure 1 shows the experimental setup including the five NDT measurements in situ and in real-time. Three piezoelectric probes were fixed to the composite sample, named AE1 and AE2 for the two iden-

tical acoustic emission (AE) sensors (125-750 kHz), and longitudinal waves (LW) for the bulk pulse-echo longitudinal wave transducer (5 MHz frequency and 13-mm diameter) placed for a normal beam incidence on the other face of the sample. For acoustic emission, the acquisition threshold of the acoustic events was fixed at 30 dB in order to avoid surrounding noises. The AE1 probe also acts as an emitter, when excited by a high-voltage function generator, in order to generate guided waves (GW), namely the S0 mode, at a frequency of 200 kHz, with the AE2 probe ensuring the reception of the GW. An IR camera (320x240 pixels with a temperature sensitivity of 10 mK) was

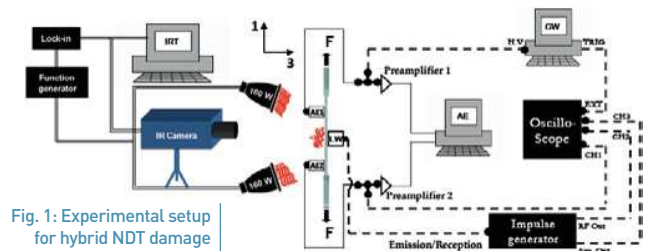


Fig. 1: Experimental setup for hybrid NDT damage monitoring

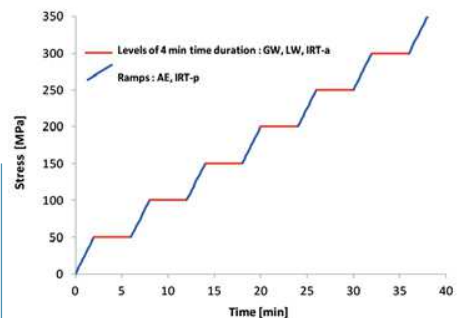


Fig. 2: Step-wise mechanical loading profile with the corresponding NDT techniques implemented during stress ramps or levels

placed in front of the specimen in order to measure its surface temperature in real-time during the mechanical loading (passive thermography, hereafter abbreviated IRT-p) as well as during the heating of the sample by two halogen lamps (320 W, with a three-cycle sinusoidal signal of 0.1 Hz), and then during its cooling (active thermography, hereafter abbreviated IRT-a).

The mechanical loading was applied at room temperature with a cross-head speed of 0.5 mm/min using a standard tensile machine according to the loading profile shown in Figure 2, which consists in a step-wise tensile test of 50 MPa each time (7 ramps and 6 levels of 4 min duration). The thermal scene (specimen under loading, lamps and IR camera) was isolated from the external environment using an opaque and insulating curtain. During the ramps, the AE and passive thermal activity of the composite specimen were acquired in real-time by, respectively, the AE1-AE2 sensors and the IR camera. The GW, LW and IRT-a measurements were applied sequentially (GW before LW, then IRT-a to avoid potential harmful interference) during the constant stress levels and before the first ramp. The sample cooling phase under constant stress, for 125 s after heating by the lamps, was monitored by the infrared camera and the cooling rate was measured for each constant applied stress.

Damage assessment

Raw data analysis

Glass fibre-reinforced plastics are not very heat-dissipative under static tensile loading (see Figure 3). During the first five loading ramps, almost no damage was detected on the thermal maps, which were uniform over the entire surface of the specimen. During the 6th ramp, three damaged areas were identified, labelled 1, 2 and 3 on the corresponding thermal map. Both areas 1 and 3 were rather large and diffused heat for a long time (over 102 seconds), while area 2 was thin with very brief heat diffusion (flash lighting for about 4 seconds). The two damaged zones 1 and 3 may be ascribed to localized delamination between the 0° and 90° plies, whereas the longitudinal damaged zone

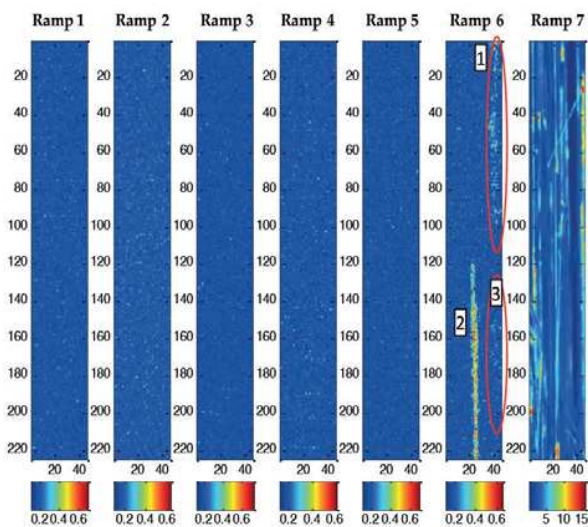


Fig. 3: Thermal maps under the applied tensile stress ramps

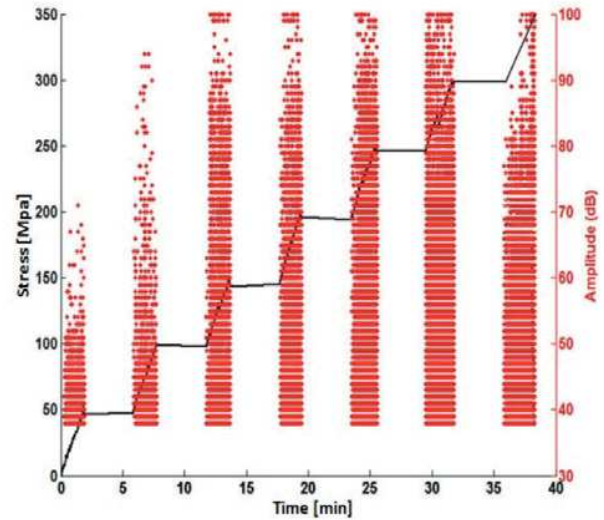


Fig. 4: Acoustic emission amplitude under the applied tensile stress ramps

2 corresponds to a fibre/matrix debonding area located on the 0° ply on the rear face of the specimen. During the 7th ramp, the final failure of the specimen gave rise to a very high heat emission.

The acoustic activity during the applied stress ramps is illustrated in Figure 4 in terms of amplitude vs time. Once loading started, the acoustic emission began with low amplitudes (38 to 50 dB) and gradually became denser and higher as the load increased. The growth of the acoustic emission events in terms of quantity and amplitude indicates that the damage induced in the material was heterogeneous, including different mechanisms such as matrix cracking, fibre/matrix debonding, delamination and fibre rupture [12].

The guided wave signals (S0 Lamb mode) are shown in Figure 5 for stress-free conditions and for the six applied stress levels. The signal amplitudes decrease sharply and continually until the transmitted ultrasonic energy at the highest stress level totally disappears. This amplitude decrease is due to the damage induced in the material, result-

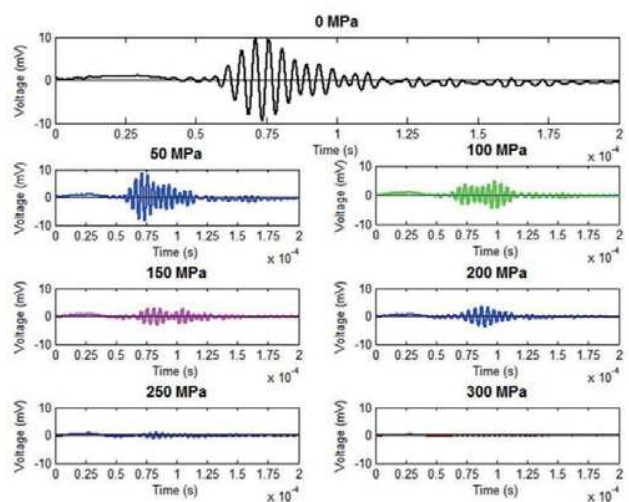


Fig. 5: Guided waves during the applied tensile stress levels

Tab. 1: Definition of the damage indicators associated to the NDT techniques used

NDT technique	Associated damage indicator
Acoustic emission AE]	$D_{EA}(\sigma_i) = 1 - \frac{NEA(50MPa)}{NEA(\sigma_i)}$ NEA[σi] is the number of acoustic events accumulated for each stress ramp to σi
Passive IR thermography [IRT-p]	$D_{IRT-p}(\sigma_i) = 1 - \frac{K_m(50MPa)}{K_m(\sigma_i)}$ K_m [σi] is the thermoelastic coefficient calculated for each stress ramp to σi
Active IR thermography [IRT-a]	$D_{IRT-a}(\sigma_i) = 1 - \frac{\dot{T}(0MPa)}{\dot{T}(\sigma_i)}$ \dot{T} [σi] is the cooling rate calculated at each stress level σi
Bulk pulse-echo longitudinal waves (LW)	$D_t^{LW-A} = 1 - \frac{A(\sigma_i)}{A_0}$ A[σi] is the maximum amplitude of the wave at each stress level σi $D_t^{LW-E33} = 1 - \frac{E_{33}(\sigma_i)}{E_{33}^0}$ E_{33} [σi] is the dynamic elastic modulus in the thickness direction at each stress level σi
Guided waves (GW)	$D_t^{GW-SE} = 1 - \frac{SE(\sigma_i)}{SE_0}$ SE[σi] is the spectral energy of the S0 mode at each stress level σi $D_t^{GW-E11} = 1 - \frac{E_{11}(\sigma_i)}{E_{11}^0}$ E_{11} [σi] is the dynamic elastic modulus in the axial direction at each stress level σi

ing in multiple scatters that certainly weaken the signals. A global characterization of the material damage and its quantitative monitoring under different mechanical loading further requires the calculation of certain damage indicators.

Definition and analysis of damage indicators

Table 1 defines seven damage indicators (dimensionless variables normalized between 0 and 1) representing a relative variation of certain physical characteristics of the material obtained from the five NDT techniques.

Figure 6 shows the evolution of the previously defined damage indicators versus applied stresses. Each damage indicator value corresponds to the mean of five measurements obtained on five samples with a maximum standard deviation of 1%. These damage indicator evolutions indicate the damage initiation from the same stress value (50 MPa), which can be considered as a damage threshold of the tested material. They also indicate that damage increases as the stress increases, but with different sensitivities, which are due to the anisotropic and multi-scale features of the induced damage.

Actually, the GW used in the axial direction is more sensitive to the damage that occurs parallel to the loading direction. This axial dam-

age was evaluated by measuring both the variations of the spectrum energy (D^{GW-SE}) and the axial elastic modulus (D^{GW-E11}), which reach respectively 100% and 60% at the material failure. The LW propagating in the through-thickness direction examines the material perpendicularly to the loading direction, where the variation due to the elastic constant (E_{33}) versus the applied stress is very small [12]. Therefore, this small variation may not reflect the real extent of the induced damage. However, the measured attenuation of the LW in the thickness direction becomes increasingly higher as the stress increases. This attenuation could be due to multiple reflections of the ultrasonic beam with the discontinuities created in the material, which grow more and more as the stress increases. Therefore, the defined damage indicator, D^{LW-A} associated with the maximum back-wall amplitude variation of the LW, allows a more realistic evaluation of the damage induced in the thickness direction.

On the other hand, the AE sensors can detect signals coming from any direction and take into account all damage mechanisms from the microscopic (matrix cracking, matrix/fibre debonding, fibre breakage) to the macroscopic (delamination) scale. These are the reasons why the associated damage indicator (D^{AE}) is higher.

At last, the thermography measurements are exploited differently when compared with previous conventional analyses (based on thermal images or temperature variation curves). Concerning passive thermography, the thermoelastic coefficient (K) is measured as well as its variation for each applied stress interval of 50 MPa up to failure. The associated damage indicator (D^{IRT-p}) increases continuously when the stress increases. Concerning the active infrared thermography measurement, the associated damage indicator (D^{IRT-a}) also increases continuously when the stress level increases. This means that the material cools more and more quickly when the damage increases.

Conclusion

The proposed hybrid NDT approach makes it possible to accurately characterize the mechanical damage of composite materials. Its benefit is a more efficient interpretation of the damage characteristics and their cross-validation in order to increase the reliability of the monitoring strategy, based on an original definition of damage indicators that provides a quantitative evaluation of the material's damage state.

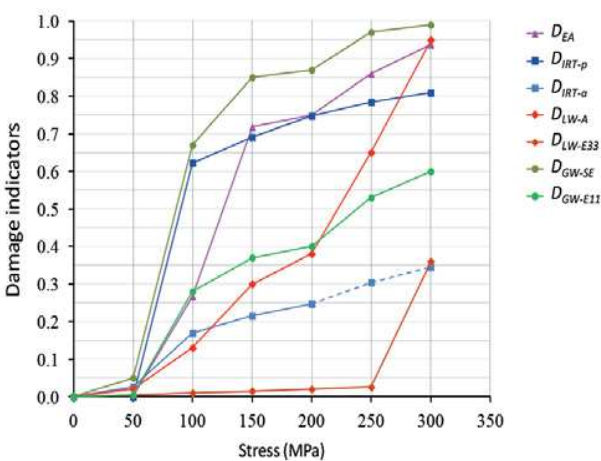


Fig. 6: Evolution of the damage indicators versus applied stresses

On-going work addresses the issue of data fusion (see figure 7), combining the results of the five NDT techniques in order to help users make decisions about the damage state of industrial composite structures. □

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