Damage detection method for composites based on laser vibrometer

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Abstract
This paper contains results of research in the topic of damage detection based on propagation of elastic waves. Elastic waves that propagate in thin-walled structures are called Lamb wave or guided waves. Their propagation follows the structure curvature. These waves interact with discontinuities (rivets, holes, thickness change, damage) within the structural element. After registering the wave propagation in the form of time signals the information contained in the signals can be efficiently used for damage detection. In reported research authors used a method based on a piezoelectric transducer for wave excitation and a laser vibrometer for wave sensing. The method was tested on different CFRP (Carbon Fibers Reinforced Polymer) composite samples. The damage in composite sample was introduced thanks to laser shocks. Indeed, the high power laser irradiation of a composite surface results in a shock wave propagation into the composite target. These shock waves generate tension inside the target, which could damage or not the material depending on the laser parameters. Therefore, the laser parameters were adjusted to create different levels of damage inside the composite samples. Various locations and number of defects in the samples were considered. This allowed to study the influence of damage severity on the investigated NDT method.

The results showed that the damage position can be indicated by the proposed method. However in the case of multiple defects, the results are influenced by the distance from the wave source to damage. It does matter if a wave has to travel through one damaged region in order to reach the other damaged region.

Keywords: Laser vibrometry, guided elastic waves, laser shocks, damage detection

1. Introduction

The application of Carbon Fibre Reinforced Polymers (CFRP) in aeronautics and other industry branches has been increasing. This causes the researcher to seek for effective damage detection, localisation and identification methods. One of the promising techniques is based on elastic guided waves (Lamb wave or plate waves in isotropic materials) propagation [1]. Traditional ultrasonic testing methods are classified as either pitch-catch [2] or pulse-echo [3]. The former utilise wave scattering from damage. Wave propagating from the generation site reflects form damage site and is recorded by receiver. Pitch-catch methods utilise changes of wave characteristics (e.g. energy, amplitude, propagation velocity, wave mode conversion) on the direct path between transmitter and receiver. These methods are based on point wise sensing using transducers or laser beams. Methods that are developed in parallel are based on measuring full field of wave propagation using tools such as laser vibrometers. One of the approaches utilizes Root Mean Square (RMS) value. The RMS value is proportional to square root of normalised mean kinetic energy associated with the measurement point. The RMS value is used as a tool for damage localisation [4]. Obtained results are depicted as colour map that are a basis for damage detection and localisation. In order to improve the RMS approach, the measured signals are filtered in order to pick only the reflections from damage [5]. For this aim Fourier transform is used, enabling transition from space-time domain to
wavenumber-frequency domain. Another indicator similar to RMS is cumulative kinetic energy [6]. This indicator is proportional to square of RMS. In this particular work full field method was used to detect damage induced by a laser source in CFRP samples. A signal processing tool based on energy approach (RMS) was tested.

2. Materials and experimental techniques

2.1 Studied materials

In the presented research Carbon Fibre Reinforced Polymers (CFRP) samples were investigated. Two aeronautical composite materials are compared. The first one is the T300/914 unidirectional composite material. It is composed of several pre-impregnated plies of carbon fibers and epoxy matrix (approximately 150 µm thick). The second one is a T800/M21 unidirectional composite, qualified by aeronautical companies as an enhanced version of T300/914. Indeed, it is still made of carbon fibers and epoxy matrix, but thermoplastic nodules are added in the M21 matrix in order to increase the shock resistance of the material. The pre-impregnated plies are thicker (about 250 µm). A comparison of the two composite microstructures is given in Figure 1. One can see in these micrographs the presence of thermoplastic nodules in T800/M21 material.

2.2 The laser shock wave technique

In this study, damage in composite samples was introduced thanks to laser shocks. The laser shock wave technique consists in a high power laser irradiation of a surface. When focused on a material, it transforms the surface into an intense plasma gas. The plasma expansion produces a shock wave into the material by mechanical reaction (see in Figure 2, a). The created incident shock wave is then propagating through the thickness according to properties depending on the material characteristics and geometry. When reaching the sample back face, the reflection of this incident shock wave creates a release wave propagating backward (see Figure 2, b, time t1). This release wave is crossing the incident unloading wave coming from the front face and initiated by the end of the loading (back to the initial state). Since the laser pulse is really short, the unloading occurs right after the shock wave propagation, which enables the two release waves to intersect inside the material (see Figure 2, b, time t2). This crossing of two release waves can lead to a local high tensile stress area which could damage or not the material depending on the laser parameters (see in Figure 2). Indeed, the generated tensile stress level is directly linked to the laser shock energy, whereas its location mainly
depends on the material properties and the pulse characteristics. Therefore, the defect creation for a given material can be controlled by changing the laser source parameters.

The laser shocks have been performed in PPRIME Institute (Poitiers, France). The laser source used in this study generates laser gaussian pulses whose duration full width at medium height lasts about 25 ns and whose beam energy can be adjusted in the range [0J – 25J]. This laser source is generally used to test thick samples (millimeters) and can create sizeable inside damage (millimeters) in case of composite materials [7-9]. The laser shocks were made in water confinement configuration to increase the pressure.

2.3 The NDT method

2.3.1 Experimental set-up

The used method is based on a piezoelectric transducer for wave excitation and a laser vibrometer for wave sensing. It is available in IFFS, Gdansk, Poland. In the conducted research the Lamb wave source position was fixed (placement of the piezoelectric transducer). However, the laser vibrometer allowed measuring the response in various points using the scanning property of the vibrometer. In this way, the response from whole sample surface could be gathered. Next the signal processing procedure was utilized in order to convert the registered time signals into spatial information about the damage position.

Samples were excited with a piezoelectric transducer bonded to the surface using a wax for mounting the accelerometers. The excited wave was measured in by the one head of scanning vibrometer (Fig. 3). The measurements were realised at defined points at the sample surface. The response was an out-of-plane velocity of the vibrations registered thanks to Doppler Effect.
2.3.2 Signal processing for damage detection

The proposed algorithm for damage detection was based on signal energy calculation [4, 6, 10-11]. The signal registered at certain point at the sample surface contain wave directly propagating from the source (a piezoelectric transducer), waves scattered at the boundaries, rivets, holes and, the most important, waves scattered by the damage. So if a measurement point is in the damage region one should see a difference in signal energy in comparison to the undamaged region. After registering the time signals $S_{ij}$ ($i=1,2,\ldots,N$) in $N$ points the following index is calculated:

$$E_i = \log_{10} \sqrt{\frac{1}{N} \sum_{j=1}^{N} S_{ij}^2}$$

The $E_i$ value is assigned to measurement points and presented graphically in colour scale in order to localise anomalies that can be related to damage.

3. Results

3.1 Damage mechanisms created by laser shock in composites

Firstly, laser shocks with several energy levels have been performed on the two studied composites in order to analyse the created damage mechanisms. Cross section observations perpendicularly to the fiber direction were made (see in Figure 4). The laser shock intensities
are the same for the sample on the same line, and increase from bottom to top. For all the presented microographies, the 4 mm diameter laser impact area is represented on the bottom of each sample; it is meaning the front face. They are separated in two by the laser shock loading axisymmetric axis which is also defining the symmetric plan of the samples since they are all unidirectional. On one side only, the observed damage such as delaminations or cracks is highlighted by red lines. On both materials, the damage is located close to the back face, around 250 µm deep. This is due to the pulse duration of the laser source used as previously explained. A direct correlation between the laser intensity level and the damage extent can be observed. Long transverse cracks due to the flexural component of the loading can also be seen on the microographies. They are more obvious for T300/914 samples than for T800/M21 samples, especially for the highest intensity value. In that last loading case, the T300/914 sample was broken in two by the laser shock, when the T800/M21 sample was still in one part. The laser irradiation is also responsible for the delamination which can be observed on almost all the microographies. Delaminations and associated transverse cracks are due to the local tensile stresses induced by the laser shock wave propagation. In case of the highest intensity value, the T300/914 sample has been peeled off, and a few plies were ejected under impact. The corresponding T800/M21 sample is completely delaminated too, but all the plies remained on the sample (see the first two images in Figure 4). In case of the lowest intensity value, the T800/M21 is not delaminated, but the T300/914 is on a small distance. These results show that T800/M21 material seems stronger.

Figure 4. Comparison of the inside damage for two set of samples: T300/914 and T800/M21 – All the samples were shocked with various intensity laser irradiances.

The microographies allow analysing the damage mechanisms created by the laser shock inside the composite materials, but this technique is destructive, since it requires cutting the sample in the middle of the impact location. Therefore, the NDT method based on laser vibrometer has been used in order to detect the impact damages in composite materials. Moreover, it is interesting to test the technique sensitivity for small damage.
3.2 Damage detection by NDT method

The two unidirectional samples investigated with the technique were made of T300/914, 2 mm thick. The first one was shocked at 8 locations. The locations were numbered and indicated on sample surface as shown in Fig. 5a, and the laser shock parameters are given in Table 1. The second sample was shocked in 8 different positions but severe damage occurred only at three locations, numbered 2, 3 and 5. In these three positions, the damage is close to the one observed at medium intensity in Fig 4, on T300/914 sample. In the other five positions in sample 2 (shock 4, 6, 7, and 8), the damage threshold of the laser shock loading has not been exceeded (see in Fig. 6). Thus, at these locations, no damage should be detected. This sample has been painted afterwards (before sending it to Gdansk for NDT measurements) so the locations were unknown as one looked at the surface to be measured (see in Fig. 5b). This way, a blind test could be performed and the observations made in the following section were not influenced by the information given in Fig. 6.

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Spot diameter (mm)</th>
<th>Pulse duration (ns)</th>
<th>Energy (J)</th>
<th>Intensity (GW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.2</td>
<td>29.6</td>
<td>18.62</td>
<td>4.54</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
<td>29.6</td>
<td>1.40</td>
<td>0.34</td>
</tr>
<tr>
<td>3</td>
<td>4.2</td>
<td>29.6</td>
<td>1.73</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
<td>29.6</td>
<td>2.49</td>
<td>0.61</td>
</tr>
<tr>
<td>5</td>
<td>4.2</td>
<td>29.6</td>
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<td>0.61</td>
</tr>
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<td>3.40</td>
<td>0.85</td>
</tr>
<tr>
<td>7</td>
<td>4.2</td>
<td>29.4</td>
<td>7.36</td>
<td>1.81</td>
</tr>
<tr>
<td>8</td>
<td>4.2</td>
<td>29.8</td>
<td>14.06</td>
<td>3.41</td>
</tr>
</tbody>
</table>

Figure 5. Investigated CFRP samples; a) sample no. 1 (approx. 284 x 16 x 2 mm³), b) sample no. 2 (approx. 75 x 5 x 2 mm³, not rectangular)
Specific conditions have been applied in order to optimize the use of the NDT method. In case of sample no. 1 the disc was placed at the middle of the sample span, between damage no. 6 and 7 (Fig. 5a). In case of sample no. 2 the disc was placed at the unpainted lower right corner (Fig. 5b). In this way the whole area with assumed damage (silver painted) could be inspected and it was not possible that the transducer is attached just at the damage location. Firstly it was decided to use a 15 kHz excitation and the sample no. 1 was tested as the first. Due to dispersive nature of guided elastic waves that propagate in thin-walled structures a 5-cycle tone burst signal was chosen for excitation (Fig. 7). This type of signal has a relatively narrow frequency band. The 15 kHz wave was too long and did not give proper spatial resolution. Second experiment was with a 30 kHz excitation. The result was presented in Fig. 8. Measurements showed deviation in both directions (leftward and rightward from the piezoelectric transducer) along the specimen. Local circular increase in wave energy indicates the laser caused defects. Straight line of higher damage index indicates damaged fibres. Defects that are farther away from the piezo disc are not detected so well due to wave attenuation. Moreover, the wave in order to reach this region has to travel the region of remaining defects.
The same approach was applied for sample no. 2. However, as it was described in experimental set-up section the disc was attached in the corner not at the middle of the surface. Looking at the snapshot from wave propagation (Fig. 9) one can see disturbance in wave field related to damage no. 2 and 5. Next, the damage detection signal processing was utilized. The result is depicted in fig 10. One can see small indication of damage no. 2. Damage no. 5 is not clearly visible.

![Figure 9](image1.png)
Figure 9. Elastic wave propagating in the sample for 30 kHz at 64.5µs after excitation, arrows indicate the disturbance in wave field due to damage

![Figure 10](image2.png)
Figure 10. Damage detection result for sample no. 2; 30 kHz excitation; displayed range: (-80dB, -60 dB)

In order to improve the result a higher frequency was tested that ensure shorter wavelength and possible sensitivity to smaller damage. The sample was excited with 100 kHz. At 39.1 µs after excitation there is an interaction with damage no. 5. The wave splits in two at it (fig. 11). When the wave reaches damage no. 2 at 72.7 µs there is a clear interaction (Fig. 12). After calculation of the damage index both defects (no. 2 and 5) were indicated – fig. 13. The increase of the frequency improved the results and better sensitivity was achieved.
Figure 11. Elastic wave propagating in sample no. 2 for 100 kHz at 39.1 µs after excitation. The elastic wave splits at damage no. 5; arrow indicate interaction with damage.

Figure 12. Elastic wave propagating in sample no. 2 for 100 kHz at 72.7 µs after excitation; arrow indicate interaction with damage.

Figure 13. Damage detection result for sample no. 2; 100 kHz excitation displayed range: (-90 dB, -75 dB)

5. Conclusions

Two CFRP composites were investigated in reported research: one with a classical epoxy matrix: T300/914, and one with an epoxy matrix containing thermoplastic nodules: T800/M21. Laser shocks have been performed on these two materials. At first, a destructive technique, by micrography, has been used in order to analyse the damage mechanisms created inside these materials when impacted by the laser source. Then, a NDT technique, based on
laser vibrometer, has been applied to detect impact damage in composite plates. It was shown that an energy based damage index allowed to detect multiple damage induced by a laser. The frequency of excitation had to be adjusted in order to achieve damage sensitivity. In the case of sample no. 2, only two defects (no. 2 and 5) were found out of three that were above damage threshold. It can be concluded that the laser vibrometer technique can detect damage above 2.8 GW/cm² laser irradiations, which result in strong delamination. The shock performed at 1.5 GW/cm² could be close to the detection limit of the technique. It was also noticed that the surface condition has influence on the results. This can be seen on results for sample no. 1 (Fig. 8). The unpainted circular areas are indicated in the results similarly like the damaged fibres indicated by straight lines.

The research will be continued especially focusing on higher wave frequencies in order to achieve sensitivity to defects caused by low power irradiation.

References