Comparative evaluation of NDT techniques for high-quality bonded composite repairs

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Abstract

Adhesively bonded composite repairs exhibit significant advantages in terms of mechanical efficiency compared to those achieved using mechanical fasteners. However they are sensitive to process parameter variations. In order to reliably use this patch repair, NDT assessments need to be performed. A European project COMPARE (SPI-JTI-CS-2010-01) funded under the Clean Sky program seeks to contribute via a comparative evaluation of three different NDT techniques: conventional ultrasound, laser ultrasound and laser shearography on carbon fibre reinforced polymer. The work being presented will show a comparison between conventional and laser ultrasound techniques, using samples with artificial delaminations. Conventional ultrasound used a pulsed echo method to detect delaminations and laser ultrasound interrogated sample via surface wave interaction delaminations. Laser ultrasound has the advantage over conventional ultrasound of being non-contact and has the potential for higher scanning speeds due to the larger coverage of surface wave. C-Scans were produced and compared using both methods. Additional analysis was performed in the time domain to help understand effects that the flaws have on the surface wave, which aided defect characterisation.

1. Introduction

Even though adhesively bonded composite repairs exhibit significant advantages in terms of mechanical efficiency compared to mechanically fastened ones, they are at the same time very sensitive to variations in process parameters. Small deviations against the repair specifications and subsequent flaws, could lead to disproportionally larger consequences to the final mechanical performance of the repair and to the integrity of the
structure. Consequently, the existence of reliable and easy to apply NDT techniques is of capital significance to the repair reliability and the safety of flight. For this reason existing NDT principles need to be adapted to the specificities of bonded composite repairs, in order to guarantee high-quality and highly durable bonded repairs, thus achieving certification of their flightworthiness.

The scope of the COMPARE project is to contribute to this need with a comparative evaluation of three different NDT techniques, conventional ultrasound (CU), laser ultrasound (LU) and laser shearography (LS). Desirable detectable flaws include delaminations, debondings, and foreign object inclusion. This paper shows preliminary results comparing CU and LU in carbon fibre reinforced polymer (CFRP) samples with a unique way of creating artificial delamination features and a novel way to detect them using LU. Some works have used LU to detected delamination on CFRP (1) and material degradation in glass FRP (2) using the frequency domain of generated guided waves and Rayleigh waves, our work exploits the time domain information extracted from surface waves to characterise delamination features accurately. Additionally, C-scans were generated and compared using both CU and LU methods.

2. Sample detail

A squared CFRP panel with dimensions 300X300 mm was manufactured by means of prepreg/autoclave technology. The material used was Hexply M21 268/35%/T800S, a pre-impregnated carbon fibre produced by Hexcel, with an areal weight of 268 g/m² of carbon fibre. The plates had the following layup [0°,0°,45°,0°,-45°,90°]ₙ, resulting in a fibre volume content of approximately 60% for thickness of 3 mm after the usual curing cycle.

Interlayer induced flaws were produced during the lamination of the plate, in order to calibrate different non-destructive inspection methods. Detectable flaws must present a significant density difference compared to the healthy material, and must be located at defined positions and have controlled sizes in order to be useful as validation samples. The approach followed to achieve this was the inclusion of objects of defined sizes at predefined positions during the laminating operation. The intercalated objects must be able to undergo the exigent temperature and pressure conditions of the autoclave process (180°C and 7 bar, respectively) and maintain their position during the cycle.

The method chosen is the intercalation of plastics bags containing small amounts of ammonium carbonate during the laminating process. The ammonium carbonate transforms in ammonia and carbon dioxide gases when reaching temperatures about 80°C, equation 1, increasing its volume and producing a local delamination during the curing process.

\[ \text{NH}_4\text{HCO}_3 \overset{80^\circ\text{C}}{\longrightarrow} \text{NH}_3(g) + \text{H}_2\text{O}(l) + \text{CO}_2(g) \]  

Using this method, the plate was made with artificially induced delaminations at predefined places. The plate was made with artificially produced defects of different sizes
at the mid-plane of the laminate, Figure 1. The bags were filled with different amounts of this salt and were located at the mid-plane in places as shown in figure.

![Figure 1. Location and relative size of inserted features at mid-plane of laminate on sample.](image)

3. Experimental details

Although this project will compare three methods previously mentioned, CU, LU and LS, at this moment in the project we have only performed the first two methods. Using the representative sample with features as described on previous section, CU and LU results are presented.

3.1 Conventional ultrasound

A conventional ultrasonic scan was performed in a raster scan manner with a step of 0.5 mm. An immersion tank was used with a single 5MHz probe in a pulse-echo configuration. Receiver amplification was set to 44 dB using Hilgus software. After scanning the sample, which took over one hour, a time of flight C-scan was generated. To remove DC a high-pass filter was set to 0 MHz and to remove high frequency noise a 20MHz low-pass filter was used. Scan results are shown in Figure 2, where (a) shows the intended position and size of features and (b) is the time-of-flight C-scan. Separation distances of features (in mm) on Figure 2a where extracted from C-scan images. Reasonable identification of features I to III are shown on the C-scan, where features I, II and III are approximately 10mm, 30mm and 20mm wide. Feature IV was either lost in the detection limit of this system or delamination did not materialize as intended. The circular features at the corners are the mounting supports. The additional triangular feature was accidental produced, probably from a layer being bent or an additional material insertion. Nevertheless, it was a very identifiable featured, which had base and height dimensions of 50mm.
3.2 Laser ultrasound

The scan was repeated with a laser ultrasound technique, using surface waves to identify inserted features in material. Laser ultrasound generation was performed using a Q-switched Nd:Yag laser, with 1064 nm wavelength, 10 ns pulse duration, energy ~20mJ/pulse and repetition rate of 20Hz. The laser light was fed through an optical fibre and focused into approximately a 10X1mm line to enhance surface wave amplitudes in a normal direction to the line and increasing the frequency content of such waves \[^{3,4}\]. To avoid material damage the thermoelastic regime was chosen, where laser energy densities of about 2 mJ/mm\(^2\) were used \[^{5}\]. A state-of-the-art laser ultrasound system from IOS was used for detection.

Each A-scan covered a distance defined by the generation and detection distance (varying from 15 to 20 mm), therefore this method has a potential to be faster for large area scans, although it is makes it difficult to identify the location between these two points.

A motorised scanning system was used for the horizontal axis and was controlled by a PC, generating a series of A-scans which in turn generated B-scans. The vertical axis scan location was positioned manually, and in total 12 positions (12 B-scans) where capable to cover desired area of sample. The total scanned area covered was 252X215mm, and the total scan time was comparable to CU, but the scanning system has the potential to be much faster if both axes were automated and through the use of a laser with a higher repetition rate.
Figure 3 illustrates a B-scan, where the distinctive red line labelled R is the Rayleigh surface wave, when the measuring system is away from the any features. When the measuring system is over the feature, a very different response is detected. Mainly the Rayleigh wave is delayed, reflected and mode converted due to reduction on sample thickness as previously shown \(^{(6,7)}\). Although some measures were taken to avoid the generation of Lamb waves at this sample thickness (3mm) and ultrasonic wavelength (2.4mm), zero order Lamb wave modes were expected \(^{(8)}\). This is shown on B-scan as the blue area as a low frequency high amplitude signal. Nevertheless, this distinct Rayleigh wave disturbance corresponds to the area where generation detection covered the triangular feature previously detected with CU.

![B-scan figure](image)

**Figure 3.** B-scan performed over the triangular feature on sample, where R indicates the Rayleigh wave.

Using the time delay on Rayleigh waves as shown on Figure 3, C-scans were generated. To accomplish this, it is necessary to precisely measure the Rayleigh wave time-of-arrival. And, to improve the measurement accuracy for time-of-flight difference between affected and unaffected, Rayleigh waves, cross correlation was used. The cross correlation of two time signals is defined by:

\[
C_{fg}(t) = \int_{-\infty}^{\infty} f(\tau) g(t + \tau) d\tau
\]

where \(C_{fg}\) has a maximum when there is an optimum match of \(f(t)\) and \(g(t)\), the location in time of this maximum was used. A reference Rayleigh wave was taken as a windowed section of an unaffected A-scan. In order to calculate the time delay, \(\Delta t\), between affected and unaffected waves, a reference/initial time was calculated using the location of the
autocorrelation maxima of an unaffected wave, $t_{\text{maxCu}}$, which was subtracted from the location of the autocorrelation maxima of an affected wave $t_{\text{maxCa}}$:

$$\Delta t = t_{\text{maxCa}} - t_{\text{maxCu}}$$  \hspace{1cm} (3)

Figure 4 shows the results of these data calculations, generating a C-scan of the sample, compared to the intended location of features. Results show a high intensity area where the triangular feature was previously detected by CU, which dominate the image. And similarly to CU, features I to III were identified. Unlike CU which used a localised inspection area, using pulse-echo, LU used surface waves covering a large area. This LU method had the advantage of covering a larger area but it identified other location of features due to surface wave reflection from features. These indications are seen in the C-scan above the actual location of features. An indication was found above where feature IV was intended which was not possible with CU.

![Figure 4. Sample intended location of features, (a) and laser ultrasound time of flight C-scan results (b). Arrows show corresponding indication of features.](image)

Additional analysis was performed on these data using the assumption that the delay in time is due to an added path that the surface wave has taken, either by following the feature contour or in fact the closest path. Equation 4 is therefore an estimate of the extra distance travelled by surface wave, and although it may not directly correspond to the actual dimension of the feature, nevertheless it was expected to give an indication of feature size. Rayleigh wave velocity ($v$) was calculated from generation detection distance and wave arrival time; average velocities were in the order of 1750m/s.

$$\Delta x = v\Delta t$$  \hspace{1cm} (4)
Figure 5a shows a B-scan of the section covering features I and II, where some visual indication of surface wave delay is detected. Figure 5a shows a better characterisation of the feature by applying time delay calculations and $\Delta x$. Horizontal dimension of both features agree well with CU scan and vertical indications ($\Delta x$) are distinctive but as expected it shows a relative size response. The triangular inclusion and feature III were also dimensioned using this technique and results are shown in Figure 6, where again both horizontal feature dimensions agree well with CU method and vertical responses have some relative proportional to feature height.

Figure 5. (a) B-scan over features I and II and (b) $\Delta x$ calculated features delays.
Figure 6. Calculated feature dimensions for triangular feature (a) and feature III (b).

4. Conclusions and further work

Conventional ultrasound was successful in identifying artificially created delaminations, but requiring a water media, when compared to laser ultrasound. Laser ultrasound technique using surface wave information showed good identification of same features with equivalent sizing capabilities in the horizontal axis and a relative indication on the vertical axis when compared to conventional ultrasound scans, although more understanding of their behaviour was required to interpret LU results. Additionally, an indication was found above where feature IV was intended which was not found with CU. Furthermore, LU has the advantage of being non-contact which may be a requirement for some of the actual measurements in the field.
Future work will apply these ultrasonic techniques to a patch repaired CFRP sample, where additional challenges are expected, such as different surface roughness between original sample and newly applied patch. This work will also include a comparison with an additional inspection technique, namely laser shearography.

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References