Fatigue damage evolution using NDT techniques for Health Monitoring of CFRP laminates

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Abstract In this work, an experimental method based on ultrasonic measurements with piezoelectric transducers (PZTs) was proposed for monitoring the evolution of fatigue damage on a batch of carbon fabric Open Hole specimens. The amplitudes of the recorded ultrasonic sinusoidal waves in packets were evaluated with pitch-catch modality during the different phases of the fatigue life and correlated to the applied loads. The examination of the ultrasonic data showed high sensitivity of the UT signal respect to stiffness decay and to fatigue damage associated with delamination near the hole. Occasional ultrasound measurements with the consolidated pulse-echo Phased Array technique were carried out by the authors at regular time intervals during the tests to evaluate the state of damage in relation to the degradation of the signal detected with the PZT sensors. The results have shown the potential capability of the applied experimental technique for real-time detection of delamination on composite elements subjected to time-varying loads.

Keywords: CFRP, fatigue, damage, Non-Destructive Evaluation.

1. Introduction
Damage due to fatigue is one of the main problems of aeronautical structures. This phenomenon is more pronounced in areas of stress concentration such as the connection of components by means of bolts or rivets \cite{1, 2}. For the study of these structures, specimens with different geometric configurations of the hole are used. The possibility of real-time monitoring of composite aeronautical structures subject to fatigue, to assess the state of health in service, is a very important objective to be achieved in a logic of Structural Health Monitoring SHM \cite{3, 4}. Therefore, it is essential to develop structural health monitoring methods to detect fatigue damage within composite structures and continuously monitor its evolution \cite{5-7}.

In the literature there are several methods to investigate the presence of damage inside the materials and components: for example, the variation of the ultrasound propagation speed \cite{8, 9} was used to determine the fatigue damage; alternatively, the variation of the electrical resistance of a material subjected to cyclic fatigue loads \cite{10-12} has been proposed; these methods could be useful for a variety of SHM purposes.

A further technique is linked to the use of Lamb waves, which are ultrasound waves that propagate on the surface of the component and are generated by specific kind of excitations \cite{13, 14}. This method is based on the emission of ultrasonic wave packets in the component to be analysed and on the reading, at a position of the receiver, of the value of the received ultrasound signal. Lamb waves were used as NDT in the studies conducted by Kessler et al. \cite{15}, who used this technique to investigate the damage
within composite materials. Most of the current active structural monitoring systems based on the phenomenon of guided wave propagation describe the changes in the characteristics of the signal in time domain with respect to the basic signal [16].

The present work proposes one experimental method, based on ultrasonic measurements with piezoelectric transducers (PZTs) for monitoring fatigue damage evolution on a batch of carbon fabric Open Hole specimens. The ultrasonic signals acquired in wave packets with pitch-catch mode, during the different phases of the fatigue life, were exported and processed in Matlab with an appropriate analysis algorithm, based on the Fast Fourier Transform (FFT) and correlated to the applied loads. The examination of the ultrasonic data showed high sensitivity of the UT signal respect to stiffness decay and to fatigue damage associated with delamination near the hole.

The results showed the effective capacity of the applied technique for real-time detection of delamination on composite elements subjected to time-varying loads.

2. Materials and methods

2.1. Ultrasonic measurements on CFRP with countersunk hole

Three series of carbon fabric Open Hole Tension (OHT) specimens named S, T and V with different countersunk fastener hole geometry (Figure 1a) were considered. The specimens consist of carbon/epoxy prepregs with different woven patterns built with twenty-layer laminates for a total nominal thickness of 6.55 mm and stacking sequences symmetrical with respect to the mid-plane $[+45°/−45° | 0°/90° | 0°/90° | 0°/90° | +45°/−45°]_{2S}$. The nominal mechanical properties of each lamina are summarized in Table 1.

![Figure 1](image)

Figure 1. (a) Geometries of the specimens used for the fatigue tests (dimensions in mm); (b) Load versus displacement curve of the specimen 1T.

| Table 1. Mechanical properties of pre-impregnated fabric lamina. |
|---------------------------------------------------------------|
| E₁ [MPa] | 71000 |
| E₂ [MPa] | 67900 |
| E₃ [MPa] | 7100 |
| υ₁₂ | - | 0.1 |
| υ₁₃ = υ₂₃ | - | 0.34 |
| G₁₂ = G₁₃ = G₂₃ [MPa] | 4600 |
| Ply thickness [mm] | 0.327 |

A preliminary static test was carried out on a specimen of the T series according to the ASTM D5766 M standard (Figure 1b), which allowed to evaluate an ultimate load equal to 67.6 kN and used as reference value for fatigue tests.
The set-up adopted during the fatigue tests includes a signal generator (HAMEG Instruments HMF 2550), a commercial Control Unit OmniScan® MX, two piezoelectric ceramic discs 7 x 0.2 mm and a servo-hydraulic testing machine - INSTRON Model 8850 with a load cell of 250 kN (Figure 2). This measurement system allowed to record and to analyse the ultrasonic signals in transmission and reception (Pitch-Catch method) without removing the specimen from the testing machine.

![Testing machine](image1.png)
![Function generator](image2.png)

**Figure 2.** (a) Experimental set-up of fatigue test and UT measurements devices; (b) piezo disks transducers bonded on the specimen surface.

The application of continuous sinusoidal Lamb wave during fatigue test was performed using the two piezoelectric sensors (PZTs) bonded to the surface of the specimen from the countersink side, as previous tests indicated this area is subjected to delamination around the countersunk seat of the hole.

The sensors used in this work have a resonant frequency centered at 300 kHz ±10 kHz (radial mode vibration). The position of the two sensors is shown in Figure 3 where the transmitter sensor T1 and the receiver R1 have been positioned on the longitudinal axis of the specimen at a distance of 40 mm between them to cover the entire area where the countersunk hole is present. A block diagram of the connections is shown in Figure 3a.

![Block diagram](image3.png)

**Figure 3.** (a) Block diagram of ultrasonic measurements systems (dimensions in mm); (b) location of PZT sensors on the specimen.
The input signal supplied to the T1 transmitter at 300 kHz (in accordance with the resonant frequency of the sensor) has a voltage of 20V
(peak-to-peak voltage). The signal received in real time by the sensor R1, amplified by 40 dB and averaged 16 times with the OmniScan® MX unit, was recorded at predetermined time intervals, according to the expected fatigue life and exported in Matlab for data processing with a specific routine based on the Fast Fourier Transform (FFT) to obtain the amplitude of the fundamental frequency.

The batch of the specimens for the fatigue tests are subjected to both tension-tension and tension-compression loading in force-controlled fatigue tests with a sinusoidal waveform, frequency of 9 Hz and stress ratio of \( R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = 0.1 \) and \( R = -0.5 \). Seven different load levels were considered. Table 2 shows the experimental parameter used and the resulting number of cycles to failure (\( N_f \)). If no failure occurred before \( 10^6 \) cycles, test was interrupted.

Table 2. Scheduled experimental parameters for each fatigue tests.

| ID Specimen | Frequency of load (Hz) | Stress ratio (R) | Max load level (% UTS) | Mean load (kN) | Amplitude load (kN) | Number of cycles to failure (\( N_f \)) |
|-------------|------------------------|-----------------|------------------------|----------------|---------------------|---------------------------------------|
| OHT 4T      | 9                      | 0.1             | 90.18                  | 33.55          | 27.45               | 732673                                |
| OHT 5T      | 9                      | 0.1             | 93.86                  | 34.92          | 28.57               | 318797                                |
| OHT 2S      | 9                      | 0.1             | 87.22                  | 32.45          | 26.55               | 10^6 (run-out)                        |
| OHT 3S      | 9                      | 0.1             | 91.66                  | 34.1           | 27.9                | 737481                                |
| OHT 2V      | 9                      | -0.5            | 44.35                  | 7.5            | 22.5                | 10^6 (run-out)                        |
| OHT 3V      | 9                      | -0.5            | 66.52                  | 11.25          | 33.75               | 45012                                 |
| OHT 4V      | 9                      | -0.5            | 59.14                  | 10             | 30                  | 138167                                |

Further ultrasonic ND analysis was implemented on specimens 2S, 4T and 5T with the purpose to analyze composite delamination evolution during fatigue life. The equipment used for conventional ultrasonic technique consist of a Control Unit OmniScan® MX and one flat Phased Array probe with 64 elements and a frequency of 2.25 MHz, which is optimized for investigating composite laminates with a total thickness of 3-8 mm [17-20] (Figure 4a-b). These ultrasonic measurements required to interrupt the fatigue test at regular intervals, to remove the specimen from the testing system and to record UT data of the S-scan maps (0°) at different probe positions (Figure 4b). Conventional ultrasonic technique presents the limitation of difficult development of real-time measurements on specimens due to induced cyclic deformation state of specimen during fatigue.

![figure](image_url_1)

(a)

![figure](image_url_2)

(b)

Figure 4. (a) Experimental set-up during fatigue test for conventional Non-Destructive damage control.; (b) Probe location on the specimen’s surface.
Particular attention was paid to the presence of secondary lobes in addition to the main ones displayed on the A-Scan during the specimen ultrasound scans. These lobes are generated by the diffusion of the acoustic energy from the probe with angles different from the main path (Figure 5), they can be reflected by the surfaces of the element being inspected and be the cause of spurious indications in A-Scan or S-Scan analysis.

![Figure 5. Example of main lobes and secondary lobes.](image)

To identify the cause of the presence of the secondary lobes it is necessary to change the number of active elements of the probe, the pitch of the elements, the depth/distance of focus point and the position of the first and last active element (and various combinations of these parameters).

From the analysis of the A-Scans and S-Scans acquired the investigation was carried out keeping active all the elements of the Phased Array probe (16 x 64), a depth of focus equal to 2 mm and a pitch of 0.5 mm scan to obtain the best possible definition for the type of probe used. Measurements were conducted by varying the beam opening angle by acting directly from the "focal law" section of the Phased Array instrumentation adopting, after appropriate checks inspection, to use a linear beam with at 0° also in virtue of the fact that possible defects were orthogonal to the surface being inspected.

3. Results and discussion

3.1. UT monitoring results – Analysis of damage
This section describes the ultrasound results performed on the different types of specimens subjected to fatigue. The amplitude of the received signal $\Delta A_{pp}$ and the fundamental frequency were selected to monitor the fatigue damage initiation and evolution. Amplitude changes in recorded signals are widely used to detect damage [8].

Before fatigue tests, the effects of the static load in tension-tension and tension-compression mode on the received signal were experimentally verified. The results show that the UT signal approximately linearly depending on the static load in the range of 0-12 kN and 2-16 kN in tension and compression test respectively (Figure 6a-b). The amplitude received signals at 300 kHz showed this linear dependence on the applied load (and then on the stress) both in traction and in compression load. This result is also confirmed in the literature [21].
Figure 6. Effect of tension static load (a) and compression static load (b) on ultrasonic signal amplitude for specimens 4T and 2V.

Figure 7a shows an example of signals received in time domain at various fatigue steps for specimen 2S. The graph shows interesting variations in the amplitude of the UT signal which is reduced respect to baseline signal in intact specimen, due to continuous and early damage evolution. From Figure 7a, a time shift of the signal was observed at 960000 cycles. The raw data acquired in the time domain were subsequently converted into the frequency domain by means of an appropriate analysis routine based on the Fast Fourier Transform (FFT). Figure 7b shows the fundamental amplitude of the signal recorded at 300 kHz, highlighting an evident frequency attenuation of the reference signal of the undamaged specimen at 0 cycles with the progressive increase of fatigue cycles.

By processing fatigue data, recorded with a frequency of 9 Hz, the stiffness of the tested specimens was determined by varying the number of load cycles. Figure 8 show the variation of the normalized stiffness with respect to its maximum value as the number of cycles varies, normalized with respect to the total of cycles (N / N_{tot}) both for the tests with R = -0.5 and for those with R = 0.1.

From the general trend of the curves, a decrease in stiffness of 5-8% compared to the initial value can be observed. The specimens stressed with R = -0.5 showed a stiffness reduction of 12% for the 3V specimen and 20% in the case of the 4V. The 2V specimen shows a stabilized trend and only a slight reduction in the final phase before the interruption of the test at 10^6 cycles.
Figure 8. Normalized stiffness against number of cycles, normalized respect to total cycles for each specimen tested with stress ratio $R = -0.5$ (a) and $R = 0.1$ (b).

The peak-to-peak amplitude of the received signal was related to the stiffness of the material as the number of load cycles varies. To make a comparison between the data collected for the tested specimens, the UT signal of each of them was normalized respect to the reference signal relative at 0 cycles. From the general trend of the curves of Figures 9 and 10, a marked behaviour on the material is observed for the specimens stressed in tension-compression with $R = -0.5$. In particular, the specimens tested with the load levels indicated in Table 2 are damaged earlier and their fatigue life is reduced compared to those tested in tension-tension ($R = 0.1$).

Figure 9a shows a considerable sensitivity of the ultrasound signal to detect delaminations in the initial phases of fatigue affecting the first plies near the surface, on the side where the countersunk hole is present, while the stiffness slowly decreases with the progressive increase of the number of load cycles.

Figure 9. Normalized peak-peak amplitude and stiffness vs. number of cycles (a); (b) normalized fundamental frequency and stiffness vs. number of cycles for all specimens during fatigue life with stress ratio $R = 0.1$.

The highest reduction of the signal with respect to the reference signal at 0 cycles was obtained for specimen 5T, which was subjected to load cycles with a maximum load of 63 kN. Due to the high level of the applied load the change of the signal started from the first cycles and were originated by the delamination phenomena on the first layers. Specifically, from 0% (0 cycles) to 26% (84000 cycles) of the fatigue life, the amplitude of the signal is reduced from 110.59% to 96%. Starting from approximately 50% of the fatigue life, the signal is reduced in amplitude ($\Delta A_{pp} = 75.29\%$) due to the
progressive damage accumulation and delamination propagation. Subsequently, the amplitude is further reduced ($\Delta A_{pp} = 52\%$) at approximately 63% of the fatigue life. In the final stages, at 94% of the fatigue life, before the final failure of the specimen, the signal decreases rapidly ($\Delta A_{pp} = 10.2\%$); it is interesting to note that these relevant changes of the ultrasonic signal does not correspond to mechanical stiffness changes, which seems to vary with a quite uniform trend.

The specimen 3S, which fatigue cycles are characterized by a maximum force of 62 kN, showed a decrease in the amplitude of the UT signal from 0% (0 cycles) to approximately 20% (144500 cycles) of the fatigue life from 85.49% to 35.29% respectively, due to accumulation of damage in the laminate located around the hole on the countersunk side. At 60% of the fatigue life, the amplitude of the signal is reduced ($\Delta A_{pp} = 39.93\%$). Subsequently, starting at approximately 74% of the fatigue life (544500 cycles), the signal rapidly reduces from 24.31% to 19.6% before final failure. The specimen 4T, which fatigue cycles are characterized by a maximum load level of 61 kN, presents an initial amplitude reduction of the recorded signal from 101.17% to 0% of the fatigue life (0 cycles) to 70.6% at 22% of the life (160000 cycles). Starting from about 35% of the fatigue life (260000 cycles) up to 41% of the life, the amplitude is rapidly reduced from 65% to 54.1%. This quickly reduction of the signal is consistent with the experimental reduction of the stiffness of the sample due to the fatigue progressive damage.

The specimen 2S, unlike the other specimens tested with $R = 0.1$, did not show a final failure due to the low level of load applied ($F_{max} = 59$ kN). However, delaminations were observed in the first plies from the side of the countersunk hole which obviously did not affect the entire thickness of the laminate. The amplitude of the recorded signal is reduced from 51.7% at 0 cycles to 22% at 80000 cycles. Subsequently it presents a stable trend up to 560000 cycles ($\Delta A_{pp} = 21.2\%$) (Figure 9a). In the final phase, before the interruption of the test occurred at $10^6$ cycles, the UT signal is rapidly reduced to 17.2% at 700000 cycles, in accordance with a more rapid decrease of the stiffness.

A similar behaviour was observed also considering the trend of the fundamental frequency, normalized with respect to its initial value, as the number of cycles varies (Figure 9b). The comparison shown in the graph allows to observe, also in this case, that the attenuation of the fundamental frequency, such as the amplitude of the signal, is higher than the decrease in the stiffness of the material; ultrasonic measurements with Lamb waves are therefore a very sensitive tool for damage monitoring. The greater attenuation of the UT signal and the fundamental frequency with respect to the reduction of stiffness is due to delaminations that occur during the first phases of fatigue, which affect approximately a thickness of 3-4 mm of the total thickness of the specimen, and this determines a lesser influence on the decrease in total stiffness of the sample.

Figure 10a shows the results of the specimens subjected to tension-compression load ($R = -0.5$).

![Normalized UT signals and normalized stiffness vs. number of cycles (R = -0.5)](image1)

![Normalized frequency and normalized stiffness vs. number of cycles (R = -0.5)](image2)

**Figure 10.** Normalized peak-to-peak amplitude and stiffness vs. number of cycles (a); (b) normalized fundamental frequency and stiffness vs. number of cycles for all specimens during fatigue life with stress ratio $R = -0.5$. 


By the graph, it is possible to observe that the amplitude of the sine wave packet decreases rapidly for specimen 3V, subjected to a maximum load of 45 kN compared to the other two tested specimens 2V and 4V, due to delaminations that occur starting from the first plies near the countersunk hole and which subsequently affect an increasingly larger area until the failure. Specifically, from 0% (0 cycles) to 38% of the fatigue life (170000 cycles), the amplitude of the signal is reduced from 50.19% to 40.78%. Subsequently, at about half of the useful life of the sample (66% of the fatigue life), the detected amplitude of the signal is equal to 18.82%, reduced by 47.18% compared to the previous measurement. At 95% of the fatigue life (43000 cycles), the amplitude is further reduced before the final failure, in accordance with the rapid decrease in the stiffness of the sample.

The specimen 4V, stressed with a lower load ($F_{\text{max}} = 40$ kN), has a lower decay of the signal amplitude associated with the damage which is less than specimen 3V. The amplitude of the signal is reduced from 0% (0 cycles) to 40.53% (56000 cycles) from 84.7% to 71.37% respectively. Subsequently, at 87% of the useful life (120,000 cycles), the amplitude is reduced to 27.44%. In the final phase of failure (97% of the fatigue life), the signal is significantly reduced in amplitude ($\Delta A_{pp} = 18.03\%$) due to accumulation of damage with the number of load cycles. This result is coherent with the rapid decay of the stiffness of the material.

Specimen 2V did not show a final rupture. However, the sample was damaged and the delaminations observed affected the first plies near the countersunk hole. The amplitude of the signal decreases from 0 cycles ($\Delta A_{pp} = 49.4\%$) to 156000 cycles ($\Delta A_{pp} = 24.31\%$). Subsequently a reduction is observed to 221000 cycles ($\Delta A_{pp} = 21.7\%$) and finally, at 556000 cycles, before the interruption of the test occurred at $10^6$ cycles, the amplitude decreases further ($\Delta A_{pp} = 10.19\%$) caused by large delaminated area. The reduction in stiffness was found to have little effect on specimen damage. The same behaviour was observed by plotting the fundamental frequency versus fatigue cycles (Figure 10b).

To achieve a quantitative evaluation of the progressive fatigue damage, in which $\Delta A_{pp}$ is the peak-peak amplitude of the signal recorded in the different phases of the test and $\Delta A_{pp0}$ is the amplitude of the signal referred to the intact specimen, a Damage Indicator (DI) was defined by the following equation:

$$DI = \frac{\Delta A_{pp} - \Delta A_{pp0}}{\Delta A_{pp0}}$$

Figure 11a-b show the trends of the damage indicator for $R = 0.1$ and $R = -0.5$ of the tested specimens as a function of the number of cycles. From the graph in Figure 11a, the specimen 5T, stressed with a maximum load of 63.5 kN, has a damage index that rapidly increases to about 51% of the fatigue life, compared to the increase in damage observed at 22% of the useful life in the specimen 4T, stressed with a maximum load of 61 kN.

![Figure 11. Trend of Damage Indicator (DI) for specimens with stress ratio R = 0.1 (a) and R = -0.5 (b) against number of cycles.](image-url)
For the specimens 2S and 3S, the damage indices increase most rapidly in the initial stages of the test up to approximately 20% of the fatigue life for the 3S specimen and approximately 10% for the 2S specimen. Subsequently, they show an almost constant trend with the number of cycles and then further increase to about 60% of the fatigue life with a greater increase observed in 3S specimen compared to 2S.

From general trend of the curves relating to the samples stressed in tension-compression (Figure 11b), a higher increase in the damage index is observed as the applied load increases, as the number of load cycles varies.

Figure 12a show an example of damaged section of specimen 2S with clearly visible delaminations after fatigue test observed with the stereo microscope, while Figure 12b shows an example of delamination during the test for the specimen 2V.

In order to confirm the reliability of the technique, authors monitored at regular intervals the specimens 2S, 4T and 5T with conventional UT control acquisitions. Figure 13 shows an example of delaminations for the specimen 5T, according to probe position 1 on the specimen surface (Figure 4b), involving the first plies from the side of the countersunk hole in accordance with what was detected in real-time with the PZT sensors by the degradation of the signal during the fatigue test.

Figure 12. (a) Example of damaged section analysis observed by stereo microscope after $10^6$ fatigue cycles for specimen 2S; (b) Example of delamination during fatigue test for specimen 2V.

Figure 13. (a) Example of delamination in S-scan map ($0^\circ$); (b) amplitude profiles along directions 1, 2 and 3 for the specimen 5T.
From figure 13a, it is evident that the extent of the damage showed in the grey scale image is higher on the right side of the S-scan than on the left. The amplitude of the ultrasonic signal relating to line 1 is less high than that line 2, due to the greater extension of the delaminated area (see figure 13b).

Before fatigue test, UT scans was performed on the intact specimen 5T. Figure 14 shows the S-scan map (0°) where in the upper part the signal due to surface of the specimen from the no-countersunk side is observed, instead in the lower part, the signal of the back wall echo of the surface where is evident the countersunk hole. Between the signals of the two surfaces, in the thickness of the specimen, no pre-existing defect is observed.

![Figure 14](image)

**Figure 14.** (a) Example of S-scan map (0°) on un-damaged specimen before fatigue test; (b) amplitude profile along direction 1 for specimen 5T.

4. Conclusions

In this work, an experimental procedure for the progressive monitoring of fatigue damage of CFRP elements, based on the ultrasonic propagation of Lamb waves, was applied to monitor in real-time the onset and the progressive evolution of the damage up to failure. The acquired ultrasound signal was compared with the reference signal at the beginning of the fatigue test. From the measurements carried out on the batch of tested specimens, the attenuation of the wave packet amplitude of the received signal and of the fundamental frequency are much more sensitive than the reduction of stiffness. This result was explained by the fact that the Lamb wave received, in the pitch-catch mode configuration, can be sensitive to detect the first delaminations occurring on the side of the countersunk hole and affecting the first plies. This determines a signal degradation already from the initial stages of the fatigue life, while the stiffness is reduced very slowly with the number of fatigue cycles until the swiftly failure, due to the considerable thickness of the sample. The comparison with conventional ND monitoring methods were employed for damage analysis during the tests. The results obtained are satisfactory, though the first phases of damage affecting the first plies are not easily detectable because of noise and other factors. In conclusion, with reference to the parameters studied in this work, the results demonstrated the effective potential of the technique adopted for real-time detection of the delamination onset at the interface and its evolution to predict fatigue damage.

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