STUDY OF THE EFFECTS OF ENVIRONMENTAL PARAMETERS AND IMPACT IN THE COMPRESSIVE STRENGTH OF LAMINATE COMPOSITES.

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Abstract

The aim of this work is to study the influence of the effects of water absorption and high temperature in compressive strength of carbon-fibre-reinforced epoxy laminates before and after low velocity impacts. Specimens were immersed in room temperature water for over 50 h and 100 h and the dry specimens subjected at temperatures of 80 ºC. The laminates were manufactured with sixteen unidirectional carbon layers with two stacking sequences $[0,90,0,90]_{2s}$ and $[0,90]_8$. Results show that the temperature and the water immersion have significant effect on the compression after impact (CAI) strength of laminates. CAI tests are conducted using an INSTRON 4206 tensile testing machine. Validation of the CAI tests is tried using an ultrasonic C-scan method and Lamb waves. Results show that the water absorption and temperature effects produced minor changes on the compression strength of the studied laminates.

Keywords: Laminate composites, Compression strength, Lamb waves, C-Scan, Delamination.

Introduction

Laminate composite materials have been increasingly used in structural components because of their high specific strength and stiffness, good fatigue performance and corrosion resistance. The sensitivity of composite laminates to impact loads in the thickness direction [1] is however a serious obstacle to more widespread use, since in this class of materials the energy dissipated during impact is mainly absorbed by a combination of matrix damage (intralaminar and interlaminar cracks), fibre fracture and fibre–matrix debonding, thus leading to significant reductions in the capability of the material. These kinds of composites are used in components to sustain large stress like in structural parts exposed to aqueous medium involving submarine structures. The degradation of the carbon-epoxy laminates can occur when exposed to the environment such as wet conditions. The absorbed water can influence not only physical features but also the compressive strength, before and after low velocity impacts. According Kishore and Kumar [2] the absorption into epoxy resin occurs in two ways: (i) absorption by the free volume of polymer depending on the cross-link density and (ii) hydrogen bonding of water molecule into hydrophilic sites present in the polymer network. To evaluate the effects of water absorption, the samples should be tested in dry and immersion conditions. The structures made of composite laminates, however, are susceptible to impact damages such as delamination and transverse crack [3]. These damages are barely visible from outside but cause a severe reduction of compressive performance of the structure. For this reason, the CAI strength is one of the most crucial factors to determine the design load in aircraft structure and material screening for new composite systems. CAI is a method to determine the degradation in the compressive strength of the composite plate prior and after impact loading. Under this type of loading, strength reduction is the largest [4]. Ultrasound techniques, like Lamb waves and C-scan are frequently used to check the structural integrity of laminates.

Lamb waves or plate waves are composed of a superposition of longitudinal and shear modes and are available in thin plates. Their propagation characteristics vary with entry angle, excitation, structural geometry and material properties. Due to its high susceptibility to interference on a propagation path, e.g. damage or a boundary, Lamb waves can travel over a long distance even in materials with a high attenuation, such as carbon fibre-reinforced composites, and thus a broad area can be quickly examined [5]. The entire thickness of the laminate can also be interrogated by various Lamb modes, affording the possibility of detecting internal damage as well as that on surface. Lamb waves can be excited and collected by a wide variety of means. Su et al [6] grouped these methods under five categories: (1) Ultrasonic probes can generate and collect single mode signals using angle adjusted wedges or Hertezain transducers with high controllability and accuracy; (2) Laser-based ultrasonics can be adequate when contact coupling is not possible and high precision is demanded; (3) Piezoelectric lead zirconate titanate (PZT) have very good performance in Lamb wave generation and are an interesting solution for integration in the structure under test; (4) Interdigital transducers such as PVDF can also produce Lamb waves with controllable wavelength by adjusting the space between electrodes. This kind of transducers are flexible and have other advantages such as higher dimensional stability, more stable piezoelectric coefficients over time and greater ease of handling, when compared with conventional PZT ceramics; (5) Optical fibre together fibre Bragg grating filter connected with a photodetector can be used for capturing static or quasi-dynamic strain in some applications with good results. Optical fibres have several advantages such as: light weight, immunity to electromagnetic interference, wide bandwidth, good compatibility, long life and low power consumption and cost.

Manufacturing of the composites plates

Carbon epoxy laminates were prepared in the laboratory from high strength unidirectional carbon pre-preg (Texipreg HS 160 REM from SEAL™, Legnano, Italy) and processed in agreement with the manufacturer recommendations, using the autoclave/vacuum-bag moulding process. After making the bag several steps are accomplished, like apply 0.05 MPa vacuum; heat up to 125º C at a 3–5º C/min rate; apply a pressure of 0.5 MPa when a temperature of 120 – 125º C is reached; maintain pressure and temperature for 60 min; cool down to room temperature maintaining pressure and finally get the part out from the mould. The laminates were manufactured with sixteen unidirectional carbon layers with two stacking sequences $[0,90]_8$ and $[0,90,0,90]_{2s}$. The overall dimensions of the plates were 300 x 300 x 2.4 (mm) and the quality control of the plates was performed by C-Scan, to evaluate the eventual presence of defects resulting from manufacturing process.

Experimental procedure

Low velocity impact tests were made using a drop weight-testing machine IMATEK-IM10. The impacts were produced on samples of 100x150 (mm) using a hemispherical impactor of 20 mm diameter with a mass of 2.545 kg. The impact energy used for whole tests was 3 J, which corresponds to an impact velocity of 1.72 ms^{-1}. The compression after impact test was carried out using the compression test fixture according to the ASTMD3410 standards, (see Figure 1).

Fig. 1 – Compression-after impact (CAI) test fixture.

The CAI testing and the tests to determine tensile strength in the plates without defects, are conducted using the INSTRON 4206 tensile testing machine illustrated in Figure 2, with a 50kN load capacity. Compressive load is applied under stroke control at a displacement rate of 1.5 mm/min. During the CAI test, a data acquisition system collects the force versus displacement history. The failure load is obtained from the force-displacement curve. The compressive strength (σ_c) of the specimen is calculated by using Eq. 1.

$$\sigma_c = \frac{F_{\max}}{b\,t} \tag{1}$$

where F_{max} denotes the maximum failure load, *b* the width and *t* the thickness of CAI specimen, respectively. For the test specimens, *b* = 25 mm and *t* = 2.4 mm.

Fig. 2 – Compressive strength testing machine.

The goal with this work is the evaluation of the composite laminate compressive strength in the following conditions: dry plates at room temperature; immersed plates in plain water for 50 hours and 100 hours also at room temperature, and plates subjected to high temperature (80ºC), with and without damage, for the considered times. The major delamination damage occurs at the back face of the laminate and progressively becomes smaller toward the impact face [7]. Testing was made considering damage zones oriented vertically according to the loading direction as illustrated in Figure 3.

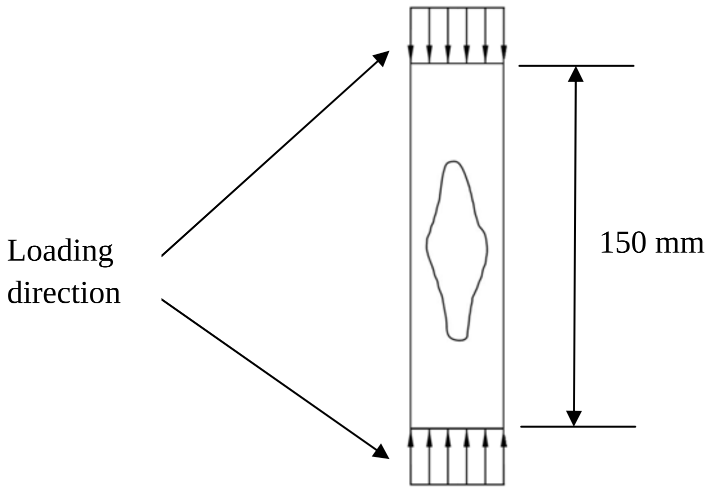

Fig. 3 – Vertical damage according the loading direction.

Ultrasound Lamb waves and the C-Scan technique were also used to validate the CAI results. The experimental setup used in this work to generate and detect *Lamb waves* is shown schematically in Figure 4. A Panametrics pulser/receiver acting as a pulsing system and two immersion transducers with central frequency of 500 kHz working in a pitch and catch configuration, were used. Each transducer was connected to a rotation stage to control the angular inclination. Signals were obtained with a digital oscilloscope and saved into a computer. The use of an immersion method is related to the necessity of guarantee the same coupling between the transducers and the plate, thus maintaining the reproducibility in the measurements.

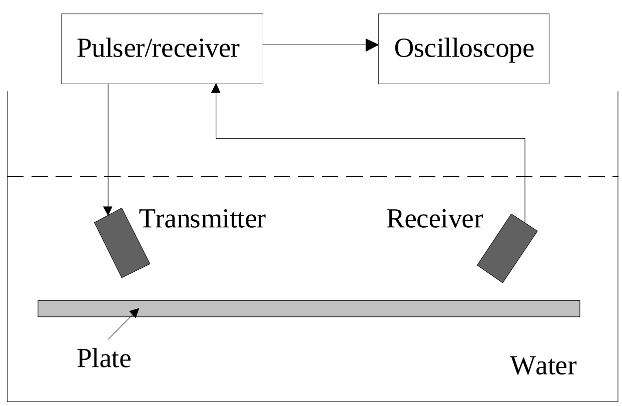

Fig. 4. Experimental setup for Lamb wave evaluation

Controlling the frequency range of excitation is very important when we work with Lamb waves. If the excitation signal has a large bandwidth we could obtain more than a single mode, which is not generally desirable. Then, typically, toneburst excitation is used due to its reduced bandwidth [8]. However pulse excitation can also be used if the bandwidth includes no more than one single mode. It is, also, important to identify a particular propagation mode from guided waves. Due to their dispersive behaviour, frequency domain techniques are demanded in order to get a correct velocity evaluation. The phase spectrum method is extensively used. In this method, the phase velocity is given by

$$C_p = \frac{2\pi f L}{\Delta\varphi} \tag{2}$$

where f is the frequency and $\Delta\varphi$ the difference in the phase spectrum of the two signals far from each other a distance L [9]. In this study the S0 propagation mode was selected due to its low dispersion and spatial separation from other modes within the used frequency range, leading to easier amplitude measurements. Figure 5 shows the experimental S0 mode phase velocity for one of the samples, obtained with phase spectrum method. As expected and according to the theory, the phase velocity is nearly constant for the range of frequencies used in our study. It was not verified remarkable differences in phase velocity behaviour for both $[0,90]_8$ and $[0,90,0,90]_{2s}$ tested samples. This is expectable due to the samples structure similarity in the propagation direction. The C-Scan technique was used to evaluate the integrity of the several samples, prior and after damage, used in the compressive strength testing.

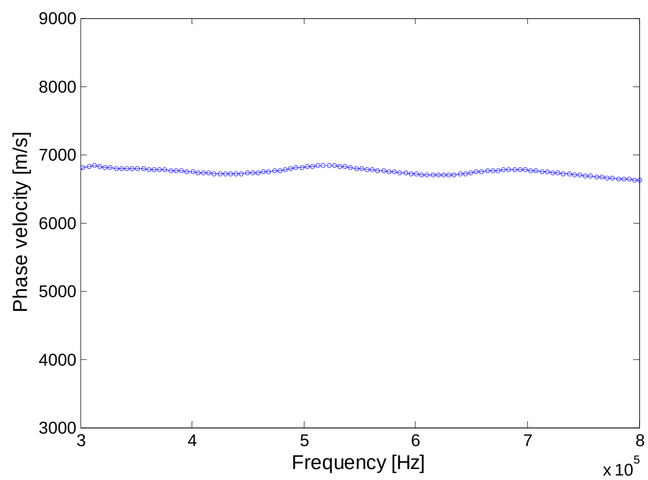

Fig.5. Experimental dispersion curve for the fundamental propagation mode S0

Results and discussion

It is expected the compressive strength presents lower values for samples immersed 50 hours in plain water compared to the unexposed case, at room temperature. This compressive strength reduction tendency should be observable for samples sunk for 100 hours. That behaviour is due to the higher energy absorption feature presented by immersed samples compared with the dry samples. At 80ºC, due to matrix resin property degradation and the development of cracks in the interface matrix/fibre, the compressive strength will decrease. After low velocity impact, the samples present some defects like delamination, being expected the compressive strength shows lower values when compared to the undamaged samples. That can be explained by the fact that samples absorbing more energy originate higher damaged areas and consequently a decreasing in the compressive strength value. Table 1 illustrates the experimental averaged results obtained by the compression testing for undamaged samples in dry and immersion conditions. From this table it is clear that for the $[0,90,0,90]_{2s}$ samples, the heating led to a reduction of about 17.3% on the compressive strength compared to the test made at room temperature. Also, for samples in water bath the compressive strength presented a reduction of 6.2% and 7.5%, relatively to dry condition, for 50 hours and 100 hours, respectively. For the $[0,90]_8$ tested samples, it was observed a decreasing on the compressive strength around the 10.5% due to the heating, and a 10% reduction in water bath condition for 50 hours. Table 2 presents the experimental averaged results for compressive strength obtained from impacted samples in the same conditions: dry and water bath. Thus, for the $[0,90,0,90]_{2s}$ samples submitted to the water bath, it was observed a reduction on the compressive strength of 5% and 6.6% for 50 hours and 100 hours, respectively. Also, for the $[0,90]_8$ stacking, it can be observed a decreasing on the compressive strength of about 17% for samples submitted to 80ºC, and 5.6% for samples immersed 50 hours in water.

Table 1 – Compressive strength (MPa) without defect.

Plate	Dry	Dry (80ºC)	Immersion (50 h)	Immersion (100 h)
$[0,90,0,90]_{2s}$	457.4	378	429	423
$[0,90]_8$	459.5	411.2	413.7	-

Table 2 – Compressive strength (MPa) after impact, with defect.

Plate	Dry	Dry (80ºC)	Immersion (50 h)	Immersion (100 h)
$[0,90,0,90]_{2s}$	230.5	-	219	215.4
$[0,90]_8$	288.2	239.4	272	-

A simple analysis of data shown in tables 1-2, lead us to conclude that the stacking sequence has almost no influence on the compressive strength for the undamaged laminate composites. However, it observed that, for almost all situations, the $[0,90]_8$ stacking presents higher compressive strength than the $[0,90,0,90]_{2s}$ one. Yet, the compressive strength has not suffered relevant changing in the immersion process. This can be explained by the small difference obtained in the water absorption parameter *M*, which is given by equation 3, [3]:

$$M = \frac{W_t - W_0}{W_0} x\,100 \tag{3}$$

where, W_0 is the weight of the dry samples and W_t is the weight of the wet samples. In this study, the value obtained for *M* is about 6% for the two stacking sequences and for the considered immersion times. Such can be explained by the relative proximity of these two times and the low permeability of the analysed samples, thus giving rise to similar compressive strength values.

Table 3 presents the results for the compressive strength extracted from laminate composite samples with and without defects. It is clear that the presence of the defects reduces the compressive strength considerably. That reduction is about 49% and 38% for the $[0,90,0,90]_{2s}$ and the $[0,90]_8$ stacking sequences, respectively, for all testing conditions: dry, heating and water immersion.

Table 3 – Compressive strength (MPa) comparison

Plate		**Dry**	**80ºC (Dry)**	**Immersion (50 h)**	**Immersion (100 h)**
$[0,90,0,90]_{2s}$	No defect	457.4	-	429	423
	Defect	230.5	-	219	215.4
$[0,90]_8$	No defect	459.5	411.2	413.7	-
	Defect	288.2	239.4	272	-

All inspected damaged samples presented embedded defects having areas of about 340 mm^2. Figure 6, outlines a damaged composite sample with $[0,90,0,90]_{2s}$ stacking sequence.

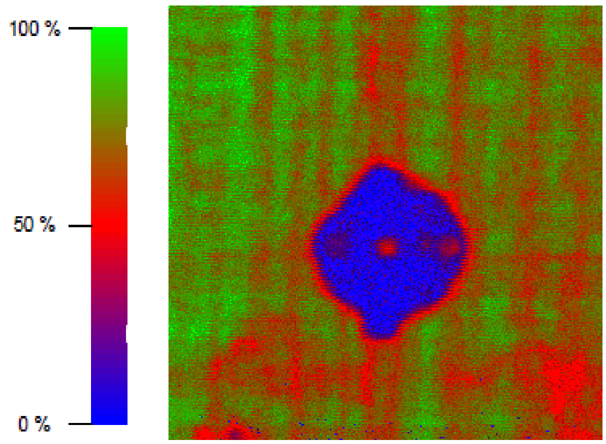

Fig. 6. C-Scan image (4x4cm) of a damaged composite sample with stacking sequence $[0,90,0,90]_{2s}$

Lamb waves technique was also used in order to evaluate the laminate composite compressive strength behaviour. The study was based on the experimental setup presented in Figure 4. The laminate composite samples were subjected to the same testing conditions before being tested by Lamb waves. For each undamaged sample it was measured the phase velocity (about 6800 m/s) and amplitude of the S0 mode. The results led to similar values for the phase velocity, meaning that there was no structural changing in the samples in accordance with the results shown in tables 1 and 2. The waveform amplitudes appeared also almost unchangeable.

The analysis of the impacted samples revealed that only for the ones with extent defects was possible to observe a clear amplitude decreasing and a wide spread of the spectral response, as illustrated in Figures 7 and 8. Thus, as an important conclusion, it can be referred that the Lamb wave method based on the used experimental set up is unable to detect defects of small size due, essentially, to the large beam width of the used transducers, which probably masks the signal amplitude variations. However, an empirically relationship between the damage size and frequency response can be established, in spite of the produced error in the detection of small defects.

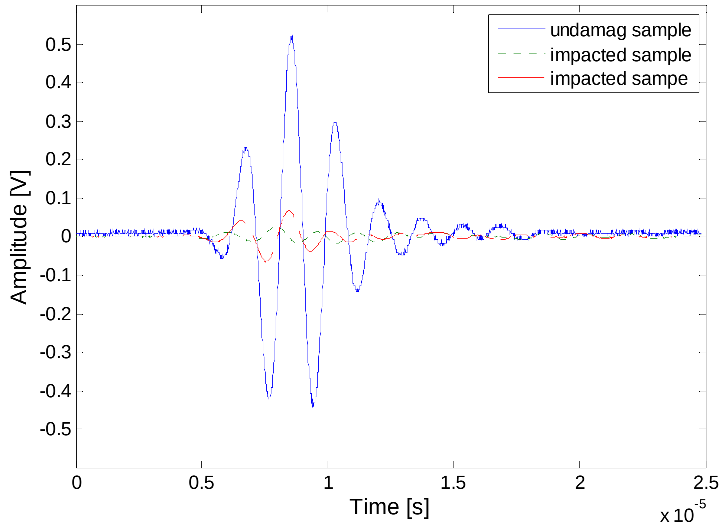

Fig. 7. Time domain signals related to one undamaged sample and two damaged samples (1.5 J).

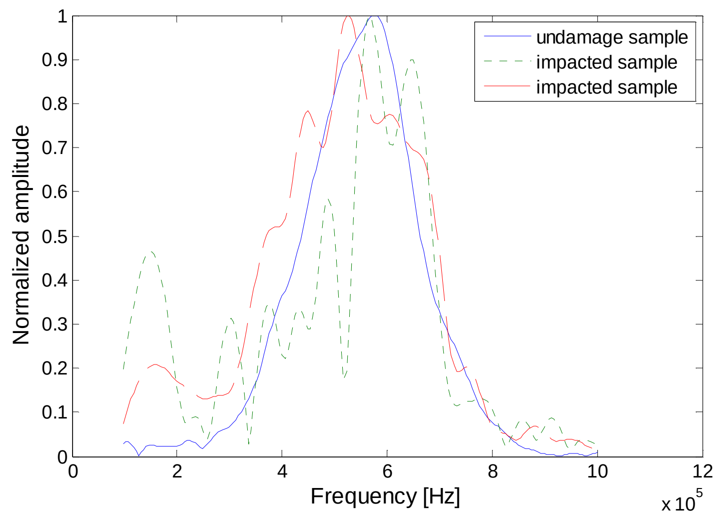

Fig. 8. Frequency features of the signals shown in figure 7.

Conclusions

In this paper, two techniques were proposed to evaluate the compressive strength parameter in laminate composites: the compression testing and the Lamb wave method. Several laminate composite samples with and without damages, were inspected in different environmental conditions. The defects were produced by low velocity impact at room temperature. The compression testing was accomplished using the INSTRON 4206 tensile testing machine. The results provided the following conclusions: (1) the compressive strength values are affected by heating and immersion effects; (2) the compressive strength obtained by $[0,90,0,90]_{2s}$ plates are smaller than the $[0,90]_8$ ones, for all the studied situations; (3) The effect in the compressive strength, of the defects produced by low velocity impact for the laminates with the $[0,90,0,90]_{2s}$ stacking, is superior to that observed in the $[0,90]_8$ laminates; (4) The heating effect produced a major decrease in the compressive strength than the water bath, for both stacking sequence; (4) It was not observed remarkable changing in the compressive strength values for the samples submitted to 50 hours and 100 hours.

A Lamb wave method was also used in order to establish some correlation among the phase velocity and/or frequency response, and the compressive strength. The results were not satisfactory since only samples with large defects led to important variations on the amplitude and frequency spectrum of the signals. As an important conclusion, it can be referred that the used Lamb wave configuration is unable to locate all states of damage, thus needing some refining in future developments.

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