ULTRASONIC EVALUATION OF PLIES' INTERFACE STRENGTH IN AFP THERMOPLASTIC COMPOSITES

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Abstract

The aim of this study is to assess the integrity of ply interfaces in aerospace-grade thermoplastic composite samples using high-frequency non-destructive ultrasonic methods. The analysis of the mechanical properties of the polymer adhesive layer situated between adjacent plies enables the evaluation of the adhesion quality in Carbon Fibre Reinforced Polymers (CFRP) manufactured by the Automated Fibre Placement (AFP) process. Indeed, interply adhesion in multilayered structures is strongly influenced by manufacturing parameters, such as deposition speed and consolidation conditions, which result in variations in the mechanical properties of the contact zones between plies. These regions, referred to as interphases, exhibit properties that differ from those of the plies themselves. Their characterisation therefore requires the use of Non-Destructive Testing (NDT) techniques, particularly ultrasonic methods. A numerical model based on the Debye Series Method (DSM) was used to reconstruct the experimental ultrasonic signal. The numerical response obtained from the model is obtained through an inverse-problem minimisation procedure, achieving a relative error of less than 1.5% compared with the experimental response.

Keywords: *automated fibre placement, non-destructive testing, debye series method.*

1. Introduction

Composite materials are increasingly used in aerospace industry. Compared with conventional materials such as steel and aluminium, they exhibit excellent mechanical properties while enabling significant weight reduction and maintaining the ability to withstand demanding environmental conditions. Carbon fibre-reinforced polymers (CFRP), and more specifically thermoplastic composites, offer several advantages over thermoset composites, including shorter processing times, higher strength, improved durability, easier maintenance and the possibility of recycling [1]. Advanced manufacturing methods and processes have recently been developed and are now widely used by major players in the composite industry. Amongst these processes, Automated Fibre Placement (AFP) has emerged as a promising manufacturing solution. In this process, shown in Figure 1, carbon fibre pre-impregnated tapes are laid onto a mould using a robotic tool. A heat source warms the tapes at the contact point, after which they are pressed onto the substrate by a compaction roller [2].

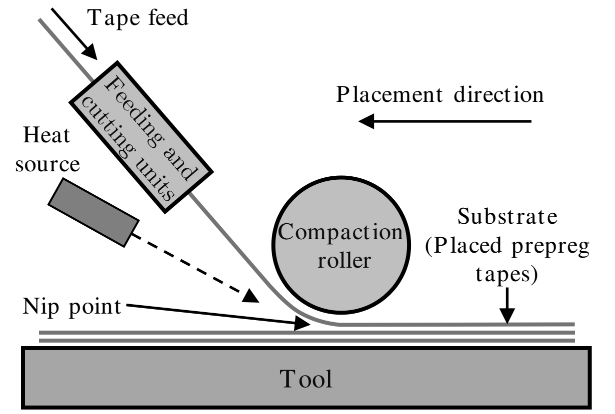

Figure 1 AFP process [2].

Regarding consolidation, two main methods are commonly used: autoclave consolidation and in-situ consolidation. Autoclave consolidation is the conventional process: the preform is placed on a mould, sealed in a vacuum bag and then consolidated in an autoclave. On the other hand, the in-situ method

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enables immediate consolidation after fibre placement using a tool that applies heat to the contact area between the substrate and the newly deposited fibre ply [3].

Safran Group, a major player in the aerospace industry, is evaluating and assessing the AFP process for the manufacturing of thermoplastic composite parts. Mechanical tests carried out by the group have shown that the adhesion quality between plies strongly depends on manufacturing parameters, particularly placement speed and consolidation conditions. The aim of this work is therefore to assess the integrity of the laminate interfaces. These interfaces exhibit mechanical properties that differ from those of the carbon composite plies, resulting in distinct acoustic properties that can be identified and characterised using high frequency ultrasonic non-destructive methods, such as acoustic microscopy [4].

2. Experimental study

In this study, a PVA TEPLA Scanning Acoustic Microscope, operating in pulse-echo mode is used [5], [6]. The sample is immersed in a container filled with deionised water. A 30 MHz planar transducer partially emerged in water emits an impulsion excitation. The wave propagates through the sample and generates a time-domain signal, known as an A-scan. This signal contains reflections from the different interfaces within the sample. Each echo corresponds to an acoustic impedance contrast between two media. The high impedance contrast between water and the sample produces a high amplitude echo, whereas the subsequent echoes decrease in amplitude over time due to attenuation.

The acoustic impedance is defined as:

$$Z = \rho . C_L \tag{1}$$

Where C_L the longitudinal wave velocity and ρ the density.

The sample used in this study is an 8-plies carbon fibre-reinforced Low Melt Polyaryl-Ether-Keton (LM-PAEK) thermoplastic composite [2] with a total thickness of 1.47 mm, resulting in an average ply thickness of 183 µm. The measured A-scan, shown in Figure 2, contains echoes from both the sample surface and the internal ply interfaces. The ply thicknesses were determined using Eq. (2), and the resulting values are listed in Table 1. In this sample, the echoes can be clearly and easily identified, indicating the existence of polymer layer between adjacent plies. These interphases are sufficiently thick to generate an acoustic impedance contrast.

$$e = \frac{C_L . \Delta t}{2} \tag{2}$$

Table 1 Measured plies thicknesses.

Ply	1	2	3	4	5	6	7	8
e(µm)	197	181	185	194	183	169	188	167

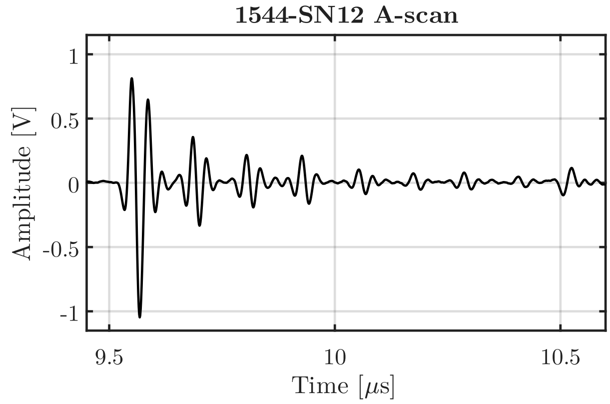

Figure 2 A-scan of an 8 plies sample.

3. Numerical model

3.1 Debye Series Method

The numerical model is based on the Debye Series Method developed by J.M.Conoir [7], and implemented by Marechal et al. [8]. This method uses local Fresnel reflection and transmission coefficients, defined in Eqs. (3) and (4), to describe wave interactions at the interfaces in the frequency domain. In the present study, a multilayer structure composed of N layers is considered. The method accounts for multiple reflections at the interfaces, as illustrated in Figure 3. The global reflection coefficient can then be calculated recursively (see Eq. (5)).

$$R_{n,n+1} = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n} e^{2j\varphi_n} \tag{3}$$

$$T_{n,n+1} = \frac{2Z_{n+1}}{Z_{n+1} + Z_n} e^{-j(\varphi_{n+1} - \varphi_n)} \tag{4}$$

$$R_g = R_{12} + \frac{T_{12} r_{23} T_{21}}{1 - R_{21} r_{23}} \tag{5}$$

Such that:

$$\begin{cases} r_{n,n+1} = R_{n+1,n} + \dfrac{T_{n,n+1} r_{n+1,n+2} T_{n+1,n}}{1 - R_{n+1,n} r_{n,n-1}}, for\ 2 \leq n \leq N \\ r_{N+1,N+2} = R_{N+1,N+2} \end{cases}$$

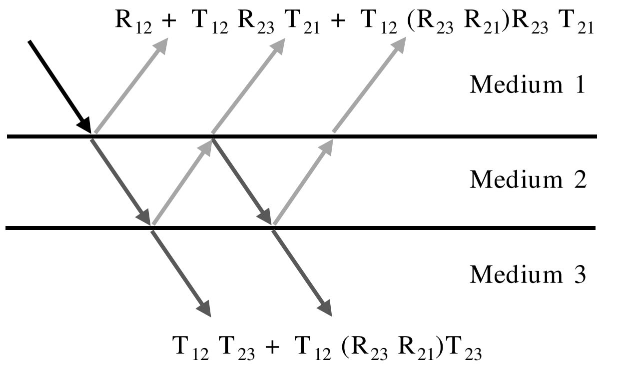

Figure 3 Wave propagation inside a multilayer structure.

The global reflection coefficient R_g enables to reconstruct the time-domain signal *s(t)*, which results from the echoes associated with each interface defining the layers of the sample. The global reflection coefficient is weighted by the Gaussian envelope of the transducer. An inverse Fourier Transform is then applied to obtain the numerical time-domain A-scan. Thus, the time domain response is given by:

$$s(t) = FFT^{-1}\left(BW_{f_0,\Delta f_6} . R_g\right) \quad (6)$$

Such that:

$$BW_{f_0,\Delta f_6} = e^{-\frac{1}{2}\left(\frac{f-f_0}{\sigma_f}\right)^2} \quad with \quad \sigma_f = \frac{\Delta f_6}{2\sqrt{2ln(2)}}$$

Where $BW_{f_0,\Delta f_6}$ is the Gaussian excitation spectrum, f_0 is the central frequency, Δf_6 is the bandwidth at -6dB and σ_f is the standard deviation.

Figure 4 shows DSM results superimposed on the A-scan experimental signal. By using the ply thicknesses measured from the experimental signal, the echoes obtained with the numerical model are accurately aligned in time. However, amplitude discrepancies are observed for several echoes, which can be attributed to changes in acoustic impedance between the different media. It was therefore necessary to introduce a thin layer of a different material in order to generate an impedance contrast between adjacent composite plies (Figure 5).

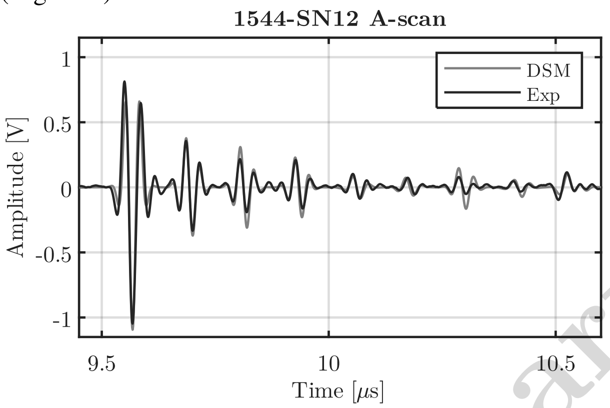

Figure 4 Reconstructed numerical result and experimental A-scans.

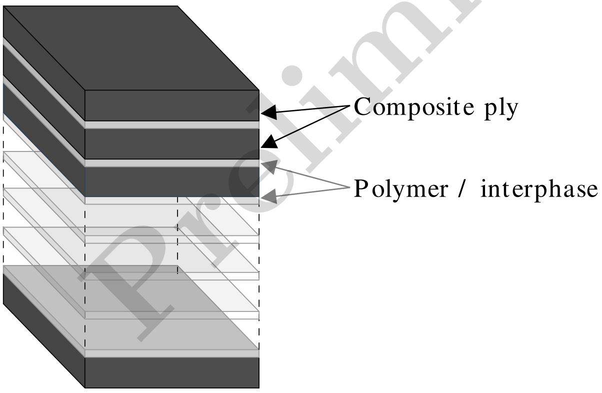

Figure 5 Structure used in the DSM.

This layer was modelled as a polymer interphase with a thickness equal to 5% of the thickness of the ply located above it, corresponding to the maximum value provided by the supplier. It should be noted that a first simulation was performed using a model limited to the eight carbon composite plies only. The resulting A-scan contained only the front-wall and back-wall echoes, with no information related to the internal structure of the sample.

3.2 Interphase model

In order to characterise and quantify the adhesion quality between two adjacent plies, an interphase model is considered. In this model, the coupling between the two substrates is represented by a very thin layer, referred to as the interphase Its thickness is of the order of a few micrometres and depends on both the nature of the substrates and the manufacturing process parameters, such as consolidation conditions and placement speed. The evaluation of the interphase is based on its mechanical properties, which are derived from the acoustic response, and compared with reference properties: those of the carbon composite, corresponding to perfect bonding, for which the structure behaves as a continuous medium; those of the polymer, representing acceptable bonding quality; and those of air, corresponding to interply delamination. Two metrics, α and γ, describing the mechanical properties of the interphases, were optimised using a grid-search minimisation algorithm, as illustrated for one layer in Figure 6.

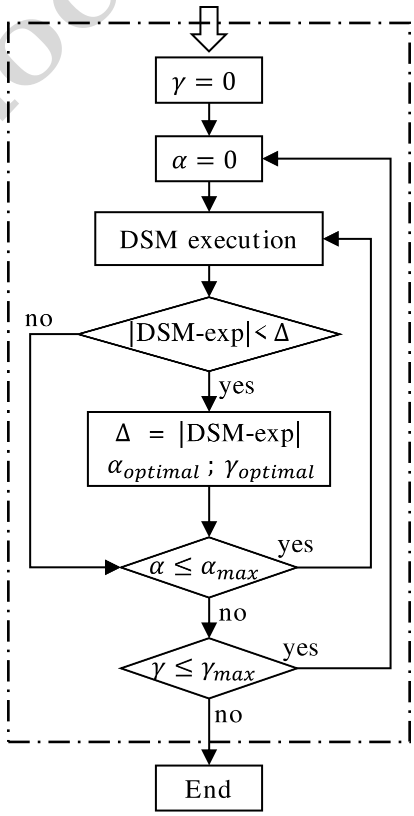

Figure 6 Grid search workflow.

The results of the optimisation algorithm indicate that the interphase properties lie between those of the composite and those of the polymer, reflecting good bonding quality at these interfaces. An average relative error of 1.46% was obtained between the numerical and experimental signals. As shown in Figure 7, the numerical and experimental signals, as well as their respective envelopes, are in good agreement.

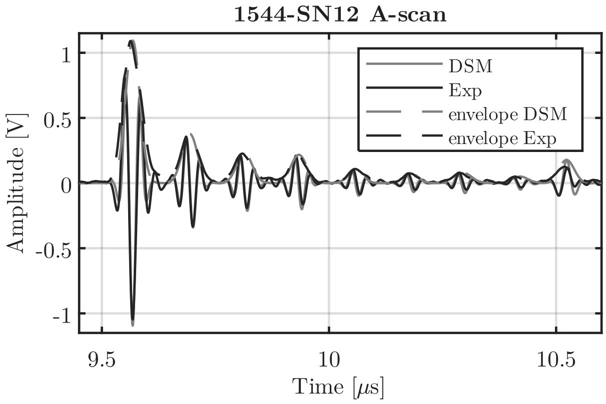

Figure 7 Reconstructed numerical and experimental A-scans.

4. Conclusion and outlook

The experimental measurements performed on the sample yielded an A-scan containing multiple echoes, each corresponding to a distinct ply interface. The numerical model, based on the Debye Series Method has successfully reconstructed the A-scan, and achieved good agreement with the experimental data, with a relative error of less than 1.5%. The mechanical properties of the interphases, derived from the optimisation process, indicate that the bonding regions are intact, with no evidence of defects such as porosities or delamination. Indeed, the amplitude analysis reveals that the echoes correspond to subtle impedance contrast at most interphases. This suggests that the interphases exhibit acoustic impedances close to those of the adjacent plies, while remaining between those of the composite and the polymer, confirming the presence of high-quality transition zones.

Further research could integrate more advanced characterisation metrics to improve the reconstruction of the experimental A-scans. This would enable a more precise interpretation of the interphase microstructure and potentially allow the detection of early-stage degradation. Ultimately, extending this approach to include probabilistic uncertainty quantification could provide a more robust framework for assessing the reliability of adhesion quality across large aerospace structures.

5. Acknowledgments

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