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INVESTIGATION INTO THE PRODUCTION FLAWS IN THIN SOLID CARBON LAMINATES BY USING THE ULTRASONIC PHASED ARRAY METHOD

Summary. Composites are used in a wide variety of markets, including the aerospace, architecture, automotive and military sectors. Along with the increased use of composites, multiple non-destructive testing (NDT) methods have been further developed specifically for inspecting them. Among them, one can single out ultrasonic phased arrays. Research described in this article focuses on the use of ultrasonic PAs for production flaw investigations into an aileron. The examined part was made of up to 16 layers of BAER 3068 epoxy carbon prepreg. The investigation was carried out by using the tap test, conventional ultrasonic measurement and phased array methods. The phased array method allowed us to thoroughly check the affected specimen and confirm the presence of a production flaw in the form of epoxy resin build-up. The results show how effective this method can be and emphasize its advantages over traditional ultrasonic inspections.
Keywords: carbon; composites; CFRP; non-destructive testing; ultrasonic phased array

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1. INTRODUCTION

Composite materials are made by combining two or more base materials with significantly different properties, which, after being combined, have unique properties different to those of base components. Despite being connected, when looking closely at the composite structure, one can still see the different materials as they do not blend or dissolve together. The new material may be preferred for reasons such as higher strength, lighter weight or lower cost when compared to traditional materials. Composites are used in a wide variety of markets, including the aerospace, architecture, automotive, military and household goods sectors. [1]. Along with the increased use of composites, multiple NDT methods have been further developed specifically for examining them. These inspections can range from the manufacturing process and continue with routine and non-routine inspections throughout the components' life [2]. Except for visual checks, which are commonly used in all industries, many other methods such as thermography, acoustic emission, eddy current and ultrasonic testing have been investigated and used for inspecting composites. The selection of investigation method can be dependent on multiple factors such as the physical properties of the reviewed specimen (size, shape etc.) or the manufacturer's instructions (for example, NDT manuals in aviation, which differ for each type of aircraft) [3-4]. Ultrasonic testing (UT) is a well-established technique based on the vibration of materials. It can be used for both composite and metal structures. The inspection of carbon fibre reinforced polymer (CFRP) components with UT is subject to strict requirements in terms of ensuring reliable and time efficient NDT. Examining composites carries some major technical challenges such as the attenuation, scattering and absorption of the signal and the shadowing effect of multiple damage can have an influence on the received results. The majority of these difficulties can be overcome by using phased array ultrasonic testing (PAUT), involving signal processing and correction with advanced algorithms, such as the threshold modified S-transform (TSMT), combined with multiple pulser-receiver elements working together [5-7,12]. Research described in this article has been done in order to determine whether visible irregularity in the composite skin structure of an aileron is a production flaw or another kind of defect. In order to do this, several methods have been used, as described in the following chapters.

2. BASICS OF ULTRASONIC PHASED ARRAY NDT METHOD AND EQUIPMENT

Traditional ultrasonic transducers used for non-destructive testing consist of a single active element or a pair of elements. Meanwhile, an UT phased array transducer consists of between 16 and 256 individual elements, which can be pulsed separately from each other. These elements are coordinated by a complex computer-based instrument, which is integrated into the array. This instrument is capable of driving the multi-element probe, receiving echoes and converting them into a digital format, as well as mapping the echoes in a variety of formats [8].

Phased array systems work, based on the wave physics law of phasing, which changes the time between a range of outgoing ultrasonic pulses. This is done in such a way that the separate wave fronts produced by elements in the array merge together, in turn increasing or decreasing the total energy in a desired way, which allows for the effective guidance of the sound beam. In order to realize such a situation, each of the individual probe elements is pulsed at different times. A focal law calculator calculates each group's firing time delays to achieve the desired beam shape. The beam shape is dependent on probe characteristics as well as the geometry and acoustical properties of the inspected element. The pulsing sequence is chosen by the instrument's operating software and introduces several wave fronts in the test material. Once inside, the wave fronts merge together and pass via the material to reflect off the back walls (back wall echo), as well as discontinuities, cracks and other boundaries, such as delaminations [9]. Measurements can be presented in A-scan, B-scan, C-scan and S-scan modes. The A-scan represents the amplitude and time of an ultrasonic signal. Additionally, the A-scan waveform denotes reflections from a single sound beam position in the tested material. The S-scan denotes a two-dimensional (2D) cross-sectional view obtained from a range of A-scans, which are mapped in accordance with the refracted angle and time delay. B-scan imaging examines the material with a sound beam moving along the preferred axis. A C-scan is a 2D presentation of data, which appears as a top view of a test piece [5].

3. DESCRIPTION OF EXPERIMENT

During the redelivery process of an Airbus A319, one of the technical representatives indicates his suspicion that two delaminated spots are present on the outboard edge of an aileron. To prove that these are not delaminated areas but production flaws, it is decided to probe them by using a tap test, conventional ultrasonic measurement and the phased array method. These methods are selected because they are approved by Airbus and the preferred methods for testing composite structures in NDT manuals. In the thickest area, the inspected component is made of 16 layers of epoxy prepreg carbon fabric (5H satin weave). This type of prepreg contains 45% epoxy resin and, during manufacture, is cured at 180°C. This material meets the requirements given in the BAER 3068 specification. Figure 1 depicts the section of the aileron that was inspected. The closer to the centre, the fewer the cloth layers present, thus the element thickness is reduced.

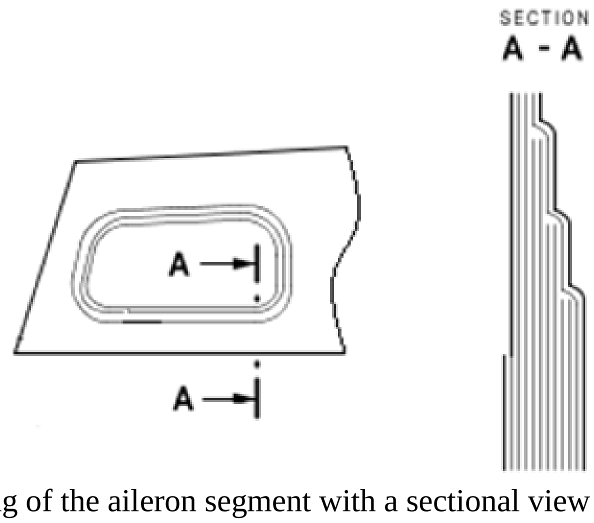

Fig. 1. Drawing of the aileron segment with a sectional view of carbon layers

In order to perform the examination, a plies layout is drawn on the aileron, along with 10x10 [mm] grid mapping over the areas where the production flaw is suspected. The first phase of this investigation is done by the tap test method [10] using a certified Airbus tap test tool. It is possible to notice a slight change in sound during the test; however, it is not typical and, as a result, it is insufficient proof to come to a conclusion. As such, further testing is required.

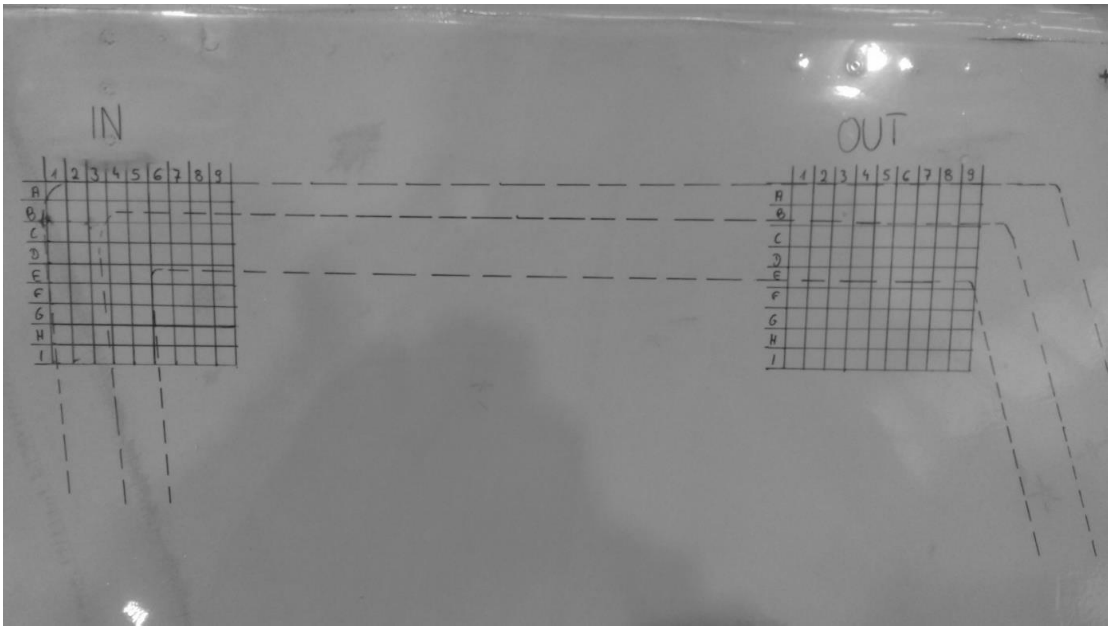

Fig. 2. Aileron segment with the drawn thickness change layout
and a grid over the suspected area

The next step requires the use of the PAUT method. Olympus Omniscan SX is used together with an Olympus RollerFORM-5L64-5 probe. In order to overcome the lack of calibration block, the equipment is manually set to the speed of sound in carbon (approximately 3,000 m/s) [11]. The remaining settings, such as gain, frequency and range, are set according to Chapter 51-10-06 of the *Airbus Non-Destructive Testing Manual* for phased array inspections of carbon monolithic components. The company where the experiment is performed does not have a proper calibration block for CFRP testing. However, in the case of this particular experiment, obtaining an exact thickness value is not of the highest importance; thus, an approximate value is satisfying. Water is used as a couplant. The alarm gate value is set at 1.5 and 3 mm. Arranging the gate values in this way causes the received image to clearly indicate any possible defects. Setting the gate values in a given manner is possible as it is not necessary to satisfy any requirements regarding minimum material thickness. The results of this investigation can be seen in Figures 3 and 4 below. After the PAUT measurements are finished, UT measurement of the previously prepared grid mapping is also been performed. The results of this measurement can be found in Table 1. Equipment for this measurement is calibrated using the same NTM chapter; however, the instructions are specific to the conventional UT of carbon composite monolithic structures.

4. ANALYSIS OF RESULTS

Figures 3 and 4 are screenshots taken directly from the Olympus scanner. Based on these figures, as well as Table 1, it can be easily determined that no damage is present at the inboard corner of the suspected area. There is no visible change in material thickness, which would indicate delamination or other damage both on the UT measurement and PAUT scans. In terms of the outboard edge, it can be seen that there is an irregularity (slightly brighter colour on the C-scan image in Figure 3). This irregularity has also been detected by traditional

UT measurement (cells E3-E6, F3-F5 and G3-G5, as seen in Table 1). It can be noticed that thickness values within these cells are around 0.05-0.12 [mm] lower than in the surrounding area. For further investigation purposes, it is necessary to refer to the A-S-scan image (Figure 4). In this picture, one can see that the composite layers are intact, as a good back wall echo has been received on the entire scan length. In turn, it is possible to confirm that no structural damage is present on the examined segment of the aileron. The final question that needs to be answered concerns why there is a change in thickness indicated on the outboard corner. In the middle C-scan image, as seen in Figure 3, one can notice a white area in the spot where we have observed a thickness change. This means that there was a lower dampening of ultrasonic signal, probably caused by a larger amount of resin. This accumulation of resin might have occurred during the manufacture of the aileron as it was made of epoxy prepreg material. Thus, it can be called a production flaw.

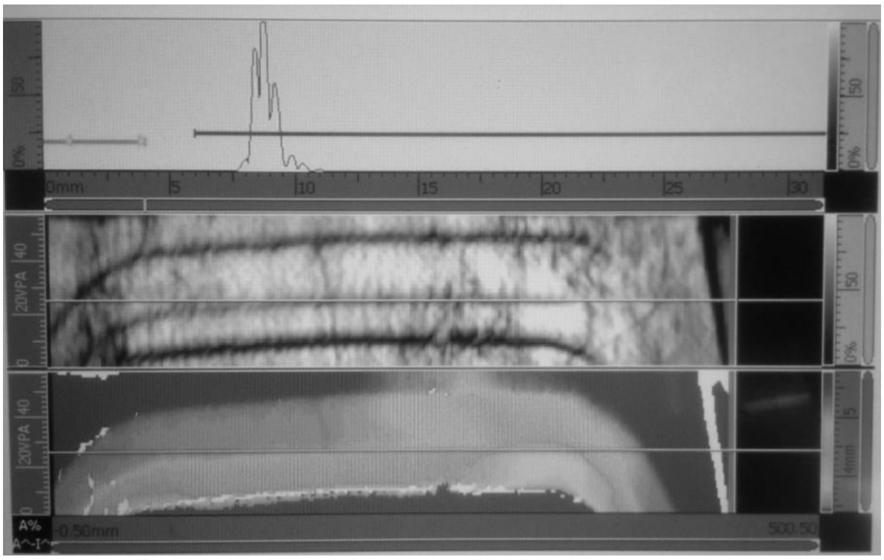

Fig. 3. A-C-C-scan views of the inspected sample

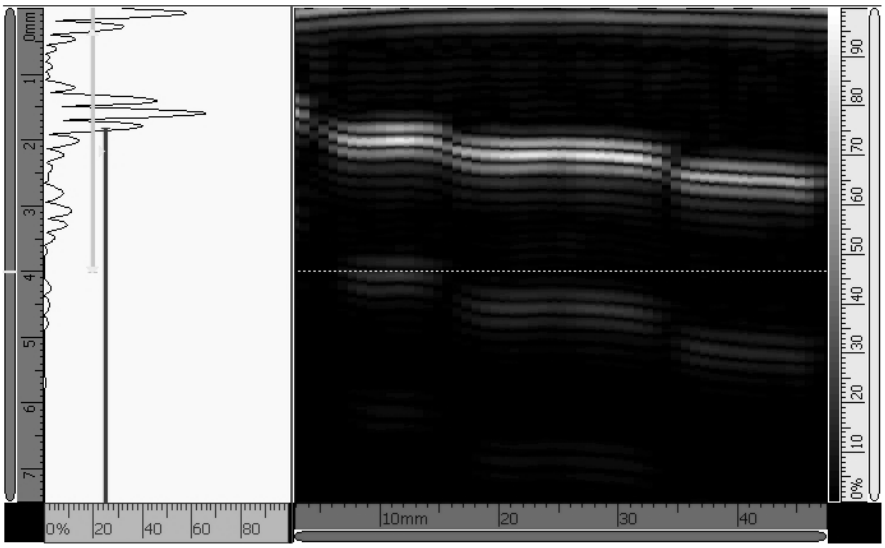

Fig. 4. A-S-scan images of the examined part of the aileron

In order to have the opportunity to compare the results received through PAUT, additional measurements were made with a traditional UT probe CLF-4 and Olympus Panametric 35DL meter. The instrument has been calibrated as a given in the aircraft's NDT manual, with the speed of sound propagation in CFRP structures manually selected. Again, as in the case of PAUT, measurement reference standards were not available to check the calibration. However, thickness values read during the measurement matched the ones obtained during the phased array scan. This measurement was done using 10x10 [mm] grid mapping. The results of this measurement are presented in the table below. This table contains thickness values measured in the grid, as seen in Figure 2. These values represent the depth at which the back-wall echo has been received. If the value is lower than in the surrounding cells of the same material thickness, this can be interpreted as a flaw or defect in the inspected component. Such dependence can be seen in cells E3-E6, F3-F5 and G3-G5 of the outboard grid.

Table 1

Results of UT measurement involving 10x10mm grid mapping over areas of the suspected production flaw

INBD	1	2	3	4	5	6	7	8	9
A	2.54	2.51	2.56	2.55	2.54	2.56	2.53	2.53	2.54
B	2.56	2.56	2.57	2.59	2.57	2.49	2.52	2.52	2.57
C	2.56	2.57	2.57	2.48	2.41	2.29	2.29	2.29	2.27
D	2.56	2.57	2.45	2.24	2.30	2.29	2.27	2.27	2.17
E	2.57	2.40	2.27	2.30	2.23	1.98	2.03	2.03	1.95
F	2.42	2.28	2.21	1.98	1.94	1.37	1.35	1.35	1.38
G	2.30	2.21	1.94	1.62	1.17	1.23	1.18	1.18	1.34
H	2.26	2.01	1.62	1.48	1.27	1.25	1.22	1.22	1.34
I	2.10	1.91	1.52	1.47	1.42	1.50	1.39	1.39	1.42
OUTBD	1	2	3	4	5	6	7	8	9
A	2.40	2.44	2.42	2.45	2.48	2.52	2.54	2.57	2.57
B	2.61	2.41	2.40	2.42	2.48	2.50	2.56	2.52	2.58
C	2.02	2.05	2.06	2.09	2.13	2.14	2.28	2.50	2.57
D	2.06	2.01	2.02	2.01	2.06	2.16	2.22	2.25	2.54
E	1.92	1.83	1.77	1.75	1.74	1.81	1.93	2.20	2.25
F	1.43	1.39	1.31	1.27	1.33	1.88	1.96	2.01	2.28
G	1.43	1.39	1.35	1.33	1.37	1.42	1.46	2.21	2.05
H	1.42	1.41	1.42	1.42	1.43	1.47	1.50	1.53	2.17
I	1.46	1.47	1.46	1.49	1.51	1.53	1.54	1.54	1.55
Note: all dimensions in [mm]									

5. CONCLUSIONS

The phased array method allowed us to thoroughly check the affected specimen and confirm the presence of a production flaw in the form of epoxy resin build-up. The major advantage of this method over traditional UT testing is that the array covers a much larger area. The software facilitates grid mapping over the scanned image and automatically fills it with measured thickness values. Thus, this inspection is much quicker and easier to perform. Additionally, PAUT equipment is capable of performing all four types of scans and saving the images, which makes analysis of the results a lot easier. Additionally, it is possible to transfer an entire scan file into a PC or a laptop and work with it in the same way as on the scanner. The presentation of results is clearer and does not require drawing grids on inspected components. By using a range of colours, PAUT equipment makes it easier to spot irregularities compared to tables with thickness values. In the case of this investigation, it is much easier to spot the production flaw in the A-C-C-scan image (Figure 3) than to find it based on material thickness values, as given in Table 1. It is possible to view the measured thickness of any point within the scan range by manually selecting the focus point. This is very useful when measurements are made in close proximity to thickness steps, as was the case in this experiment. The PAUT method produced the clearest indication of all the methods used to investigate whether the defect was a production flaw.

The PAUT method can be used in a variety of situations and on different materials such as aluminium alloys, CFRP, GFRP and GLARE. Additionally, this method can be used on both monolithic composites and honeycomb structures (depending on their thickness). Most of the major aircraft manufacturers, such as Airbus or Boeing, approve this method for aircraft maintenance. While the equipment and training of personnel can be quite costly, this method is much more time-efficient than traditional UT measurements and capable of lowering NDT man hours required for aircraft maintenance. Phased array measurement, as described in this article, took approximately 15 min, including the hardware set-up. The ability to use water as a couplant makes the phased array method more universal (as water is widely available) compared to conventional ultrasonic measurements, which often require the use of gels or pastes for coupling purposes.

Last, but not least, PAUT examinations of composite structures are going to be used more widely in the very near future, as new aircraft, such as the Boeing 787 and the Airbus A350, use many more composites compared to the previous generation of airplanes. Indeed, both the Boeing 787 and the Airbus A350 have bonded skin stiffeners and solid carbon laminate fuselages, which can be easily inspected for possible damage by using this method.

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