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Optimization and comparison of ultrasonic techniques for NDT control of composite material elements

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Abstract

This work contains an overview of innovative procedures related to the optimization of non-destructive control ultrasonic techniques for defect investigation on composite plates. The inspection procedure improvement allows developing ideal ultrasonic setup and methods, giving the operator appropriate criteria and guidelines in terms of equipment, material and control procedures. Ultrasonic inspections are conducted on different GFRP laminates with artificial defects; tests are improved using special parts designed for probe positioning and contact conditions on inspected components. The data processing of UT procedures allows comparing detection sensitivity of different probe frequencies and plate material behavior. Contact ultrasonic method presents best results for GFRP plates using 1 MHz Olympus A103S probe, detecting small defects with maximum signal amplitudes. Finally, a statistical study is performed for repeatability demonstration of UT inspections.

Keywords: GFRP; composite material; contact UT; immersion UT; ND controls; Phased Array; ultrasonic technique.

1. Introduction

In engineering applications, structural integrity and mechanical properties verification of component material is determined through destructive controls and non-destructive controls (Mcgonnagle, 1986; Lloyd, 1989).

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Despite recent improved software and inspection procedure solutions, the human factor is still crucial for inspection quality as observed by Bertovic et al. (2009).

Ultrasonic testing is an NDT technique that investigate components and structures to detect internal and surface breaking defects, and measures wall thickness on components and structures (Richter et al., 1991). This method is based on high-frequency acoustic waves introduced into examined material for detecting internal defects, also evaluating defect thickness, distance and size. Example main advantages of UT method are higher depth detection, automated detailed images, minimal required part preparation, instantaneous results (Ben et al., 2012; Djordjevic, 2009).

Therefore, Ultrasonic test operates on the principle of injecting a very short pulse of ultrasound (typically between 0.1 MHz and 100 MHz) into a component and then analyzing any reflected sound pulses. Conventionally, an operator moves a transducer over the surface to inspects all the area that is required to be tested by means of a scanning motion. The inspection relies on the training and integrity of the operator to ensure that he has inspected all that is necessary.

Sound pulses reflected are conventionally displayed on the screen with A-scan or B-scan diagrams and the operator analyses these signals and report if the component is defective or acceptable according to the test specification that he is given (Bernard, 1992).

In this work, execution and optimization of ultrasound scans are carried out in manual mode in order to evaluate the experimental sensitivity of ultrasound probes on different composite plates for defect investigation. Optimization of inspection method is the basic solution for advanced UT process development and for preliminary operator choice of control procedures to be executed. Analysis procedure is performed on GFRP laminate plates with artificial defects and data results allow sensitivity evaluation and performance of various probes and techniques.

2. Materials and methods

Reference specimen can be used in ND experiments to compare ultrasonic methods according to the size, location and depth of detectable defects to guarantee the reproducibility of inspections under same test conditions (Carofalo et al., 2014). As in previous works, composite specimens are assembled with artificial defects in consideration of influence factors as size and defect depth.

2.1. Reference Specimens

Ultrasonic study is here conducted on two composite plates made of GFRP material, denoted Plate-1 and Plate-2. GFRP E-glass fibers in epoxy specimens were laminated by hand lay-up process. The characteristics of materials are reported in Table 1.

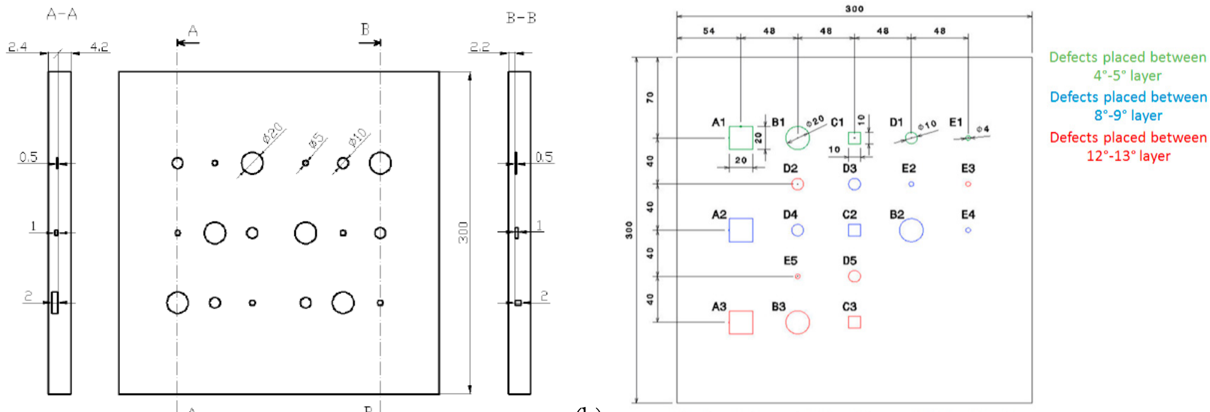
Details of reference defects and location under study are given in Table 2 and different defect configurations are shown in Figure 1. Defects are generated with polystyrene and thin Teflon inserts with different thickness to be glued between layers.

Table 1. Mechanical properties of glass fiber and epoxy resin.

E-glass (produced By Selcom Multiaxial Technology S.r.l.)	
Mean diameter (μm)	14
Young modulus (MPa)	72500
Ultimate stress (MPa)	2150
Ultimate strain (%)	3.75
Epoxy resin EC 130 LV + hardener W340 with ratio 100:31 (produced by Altana Varnish-Compounds)	
Density (g/ml)	1.14÷1.16
Young Modulus (MPa)	2900÷3100
Ultimate stress (MPa)	75÷80
Ultimate strain (%)	8.5÷9

Table 2. Specimen material and geometry.

Specimen	Material	Plate surface area [mm^2]	Plate thickness [mm]	No. of layers	Staking sequence	Artificial Defect material	Defect thickness [mm]
Plate-1	GFRP	300x300	7	12	N/A	Polystyrene inserts	0,5 ÷ 2
Plate-2	GFRP	300x300	14	20	[0, 90, +45, -45, 0, 90, 0, 90, +45, -45]s	Teflon inserts	0,04



(a) (b)

Figure 1. (a) defect configuration of GFRP plate-1; (b) defect configuration of GFRP plate-2 with defect size from 4 to 20 mm.

2.2. Experimental equipment and Ultrasonic Techniques

USIP 40 for conventional UT has been employed in this study for defects investigation on composite plates. The conventional ultrasound probes used in this article are scheduled in Table 3, adopting several techniques resumed in Table 4. During control tests, specific equipment tools in Table 4 are designed to allow us facilitating all probes orientation, easy manipulation, distance control from specimen surface, displacement on component surface and achieve UT inspection improvement. In other works, the authors adopted UT Phased Array technology (Ruiju and Lester, 2009; Xiao et al., 2012) with different tools applied to perform inspection of components with complex shapes.

Table 3. Experimental probes for UT inspections.

Probe Denomination	Type	Model	Frequency [MHz]	Transducer Size
Probe 1	axial	Olympus A103S	1	Ø 12.7 mm
Probe 2.25	axial	Olympus V204	2.25	Ø 6.35 mm
Probe 1-6	axial	DS 12 HB 1-6	1.22÷6.19	Ø 19 mm
Probe 0.5	axial	Olympus M2008	0,5	Ø 25.4mm

Table 4. Experimental tools for UT inspections.

Designed Probe Tool	Quantity	ND technique	Probe model
Probe Scanning Tool-A	4	Contact UT	Probe 1, 2.25, 1-6 and 0.5
Probe Scanning Tool-B	4	Water Stream UT	Probe 1, 2.25, 1-6 and 0.5
Probe Scanning Tool-C	4	Immersion UT	Probe 1, 2.25, 1-6 and 0.5
Probe Scanning Tool-D	1	Single Axis Automated Water Stream UT	Probe 1-6

Contact Ultrasonic Testing is the first implemented technique based on transducer direct contact of component under examination, interposing a direct coupling between transducer and the test surface to provide an appropriate wave passage from transducer to detected material. This UT method is based on capture and quantification of either reflected waves (‘pulse-echo’) or transmitted waves (‘through transmission’).

Each of two types is used in the present work and a thin film of glycerin is coupling employed to facility ultrasonic energy transmission. User performs ultrasound inspection with manual probe positioning adjacent to component. However, the effective use of manual probe is limited by scan variability in the data produced and the inability to monitor a specific defect detail during exercise. These limitations can seriously affect reproducibility of the ultrasound technique, due to movement of the probe between successive analyses; the probe must be maintained in a steady orientation and contact conditions relative to inspected component and for this goal, experimental tools are conceived using CATIA V5R21 software, to minimize errors and reduce variability among obtained UT scans, constructed in thermoplastic polymeric material PLA with Ultimaker2 3D printer (as seen in Figure 2c). Example of designed accessories (denotated Probe Scanning Tool-A for 1 MHz probe) and useful for contact UT inspection is shown in Figure 2a. Similar designed tools are created with specific geometric dimensions for other utilized probes.

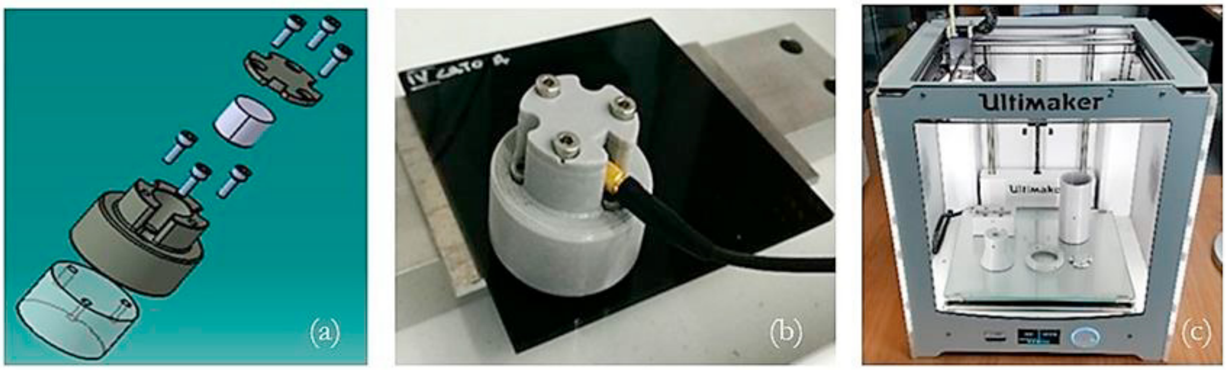


Figure 2. (a) CATIA exploded view of Tool-A; (b) Tool-A for Probe 1 and (c) Ultimaker2 3D printer.

Tool accessory A for 1 MHz probe is aimed at holding probe. The apparatus comprises a body portion having three longitudinal screws allowing positioning both Plexiglas wedge (in the lower part) and the probe (in the upper part). Probe holder, screws, Plexiglas wedge and probe define a sealed chamber to keep good contacting state and allow stable coupling to components. Water Stream Ultrasonic Testing is the second applied inspection methodology using a different base support, which allows raising Plexiglas wedge surface from specimen surface for few millimeters, to create a thin film layer between the parts. This creates a coupling medium layer, generally water filled, allowing optimal coupling and avoiding friction damage and sticking due to Plexiglas contact on inspected part. This technique maximizes sonic transmission even in cases the transducer could not homogeneously enter in contact with inspection surface (and specimens' borders for example) and avoiding manual control subjectivity, because the pressure exercised by user on probe influences echo amplitude of ultrasonic signal. These tests are carried out realizing a base support in PLA material to be applied on Tool-A creating the Scanning Tool-B (Figure 3a); holes created on base support allow the connection conveying water pipes.

Another way better transmits the UT signal from transducer to a test object is transfer the sound wave with water. This third solution can be done with squirters where the sound is transmitted through a jet of water or using transducer immersion in a tank of water; this method is denominated Immersion Ultrasonic Testing. In this UT testing technique, the transducer is placed in the water, above the test object and the graph of pulses using the immersion method is slightly different, because between the initial pulse and the back-wall echo there is an additional peak caused by the sound wave passing from water to test material interface and called 'front wall peak'. Different probe holder accessory are needs (denominated Tool-C) and was designed for immersion UT applications, partially submerging specific probe base in water tank at a distance D (near field area) from monitored plate surface as shown in Figure 3b and 3c. The minimum distance D_{min} of circular shape A103S probe, is for example estimated as:

$$D_{min} = \frac{d^2}{4 \cdot \lambda} = \frac{d^2}{4 \cdot \frac{c_m}{f}} = 27{,}24 \approx 30 \text{ [mm]} \quad (1)$$

Where: d is probe diameter, λ beam wavelength, c_m is sound speed in considered medium (sound speed of medium water is equal to 1480 m/s) and f is the frequency (1 MHz for the A103S probe).

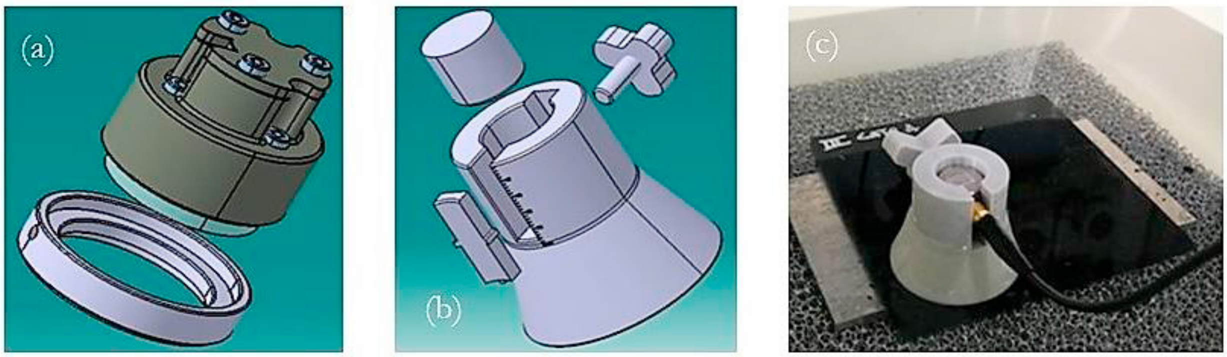
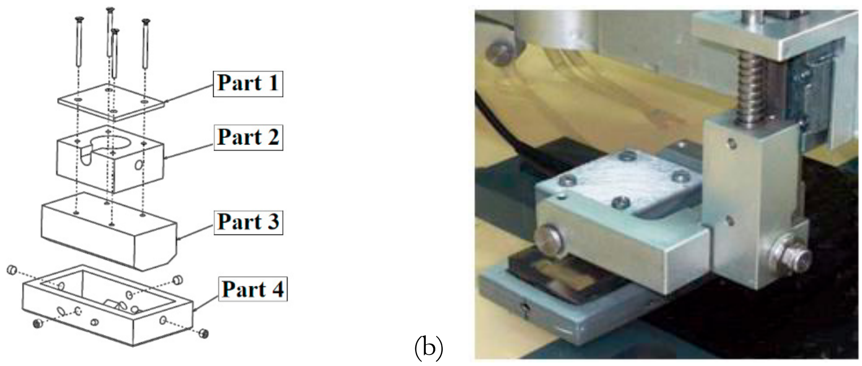


Figure 3. (a) CATIA exploded view of Tool-B (Tool-A plus ring); (b) CATIA exploded view and (c) Tool-C for Probe 1.

Finally, for the use of the ultrasound handling structure with DS12HB 1-6 axial type cylindrical probe, two PLA experimental tools were designed and 3D printed, in particular the probe holder support (part 1 and part 2) that allows fixing the probe to the relative bracket of probe holder and the integral coupling with the already mentioned Plexiglas wedge and the base support (part 4) that makes it possible to create a water stream film between the wedge and the surface to be scanned and thus avoid any friction and contact state variations.

Part 3 in exploded view (Figure 4a) is the Plexiglas wedge, while the screws and the grains are used to fix the probe support (and therefore the probe) to the base and the shoe. It was decided to prepare this last support for the use of water stream method, as a coupling means to avoid complete immersion of the product, using the water transfer system already integrated in the tank.



(a) (b)

Figure 4. (a) CATIA exploded view of tool D; (b) Probe 1-6 mounted into automatic Water Stream scanning equipment.

3. Results and discussion

Inspection results are improved for each experimental test methods and data results are managed to analyze influence of defect size and depth. The obtained amplitudes were analyzed to evaluate the defect characteristic size and depth. Table 5 shows three different defect depth ranges for GFRP plates.

The following Figures show most interesting signal amplitude (AMP [%]) diagrams obtained with the four used probes in the UT inspections. Figure 5 presents example results for contact UT test analyzing average and high defect depth.

Table 5. Scheduled defect depth classification.

Specimen Material	Low Depth [mm]	Average Depth [mm]	High Depth [mm]
GFRP -Plates	1,4 ÷ 2,8	3,4 ÷ 4,2	5,6 ÷ 8,4

Among the different probes, Probe 1 seems to be the best effective for the Contact UT method (with special regards to Probe 0,5) especially for low/average depth, detecting small defects with higher signal amplitude than other transducers. Probe with large frequency range 1 ÷ 6 gives also satisfactory results even better that fixed frequency probe 2,25 on GFRP material for defect of any size. The signal amplitude presents a linear trend respect to defect dimension. Probe 0,5 shows not suitable sensitivity for small investigated defects (Figure 5a), not releveled at lower-middle depth. An optimal view is in general guaranteed by Probe 1 for contact UT technique.

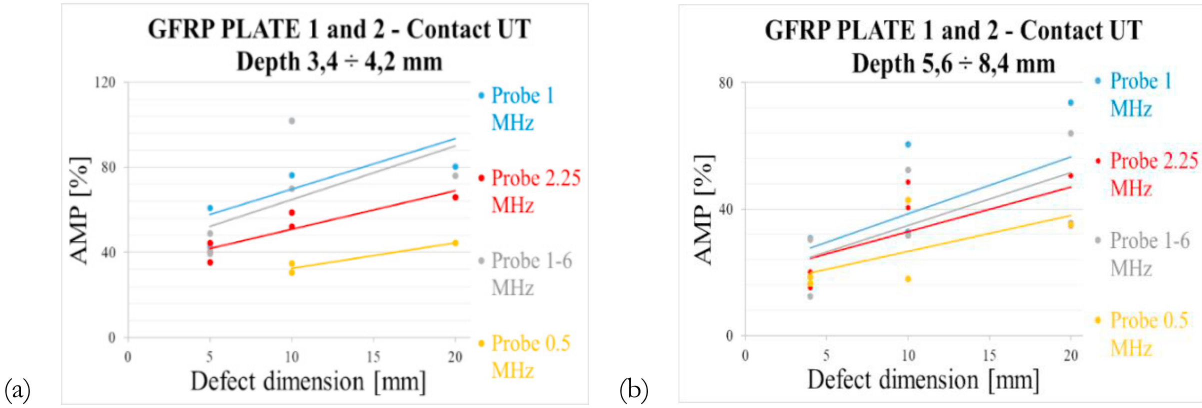


Figure 5. (a) – (b) Influence of defect dimension on signal amplitude for different depths using Contact UT method in GFRP plates.

In Figure 6 and 7, the data dispersion and a relevant result variability is evident for the two Immersion and Water Stream UT methods, due to the influence of defect size and optimal probe is more difficult to be identified for all size defect at high depth (Figure 6b and 7b). For lower and average depth analyzed (Figure 6a and 7a), data show for small defects higher amplitudes achieved with both Probes 1 and 2,25 but the probe 1-6 shows considerably lower amplitudes (Figure 7a); only for larger defects, all probes seem to offer elevated and similar signal.

In addition, it is observed in case of deep defects the influence of probe choice appears to be less important for both techniques (Fig. 6b and 7b), whilst for defects at 1,4-2,8 depth the probe choice is critical in particular in case of small defect.

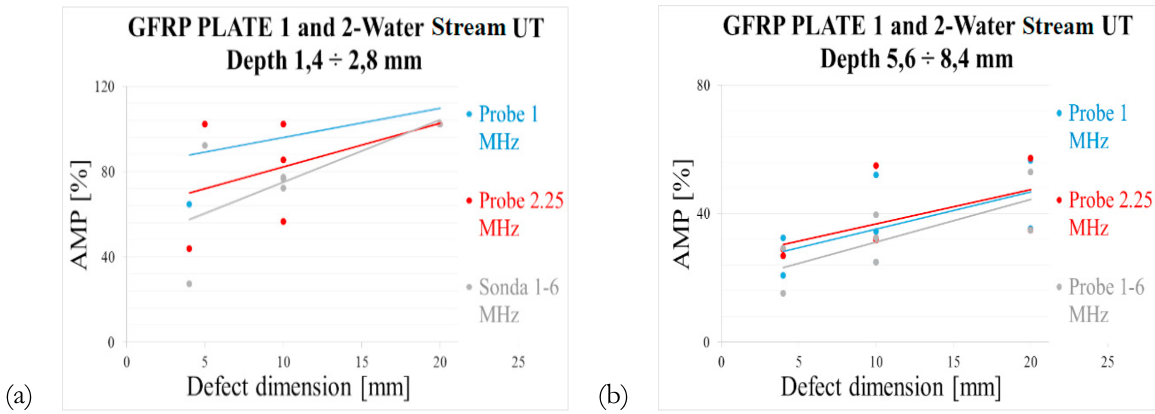


Figure 6. (a) – (b) Influence of defect dimension on signal amplitude in different depths using Water Stream UT method in GFRP plates.

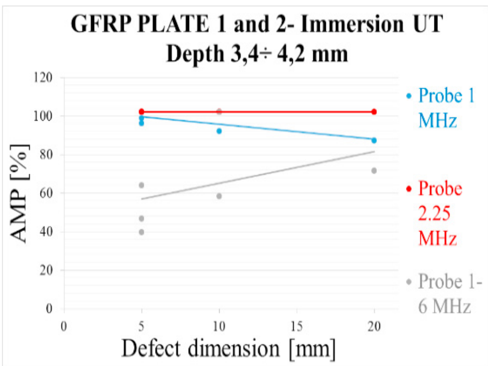
Table 6 and 7 summarizes the signal UT amplitude data detected with the various techniques and probes employed in this study.

Table 6. Principal defects results of Plate-1.

		CONTACT UT			WATER STREAM UT			IMMERSION UT		
Defect Dimension [mm]	Defect Depth [mm]	Probe 1 [%]	Probe 2,25 [%]	Probe 1÷ 6 [%]	Probe 1 [%]	Probe 2,25 [%]	Probe 1÷ 6 [%]	Probe 1 [%]	Probe 2,25 [%]	Probe 1÷ 6 [%]
5	1,9	102	102	98	102	102	92	102	102	102
5	3,4	44	35,2	40,8	60,8	73,2	55,6	102	102	64
5	4,2	42,4	40	39,2	92,4	77,6	45,2	96	102	39,6
5	4,2	60,8	44,4	48,8	61,2	68,4	39,2	98,8	102	46,8
10	1,4	102	102	102	102	102	76,4	102	102	102
10	2,4	102	102	87,2	102	85,2	72	102	102	102
10	3,4	102	52	102	102	86	61,2	102	102	102
10	4,2	76,4	58,8	69,9	67,2	81,2	46	92	102	58,4
20	1,9	102	102	102	102	102	102	102	102	102
20	4,2	80,4	66	76	74	76,8	48,4	87,2	102	71,6

Table 7. Principal defects results of Plate-2.

		CONTACT UT			WATER STREAM UT			IMMERSION UT		
Defect Dimension [mm]	Defect Depth [mm]	Probe 1 [%]	Probe 2,25 [%]	Probe 1÷ 6 [%]	Probe 1 [%]	Probe 2,25 [%]	Probe 1÷ 6 [%]	Probe 1 [%]	Probe 2,25 [%]	Probe 1÷ 6 [%]
4	2,8	76,4	65,2	50	64,4	43,6	27,2	102	102	102
4	5,6	30,8	34,4	30,4	32,4	28,8	29,2	38	36,8	30
4	8,4	18,4	29,2	12,4	20,8	26,8	15,2	19,6	26	25,2
10	2,8	102	92,8	102	102	56,4	77,2	102	102	102
10	8,4	32,8	40,4	31,6	34,4	32,4	32,4	29,2	26	38,8
10	8,4	32,8	32	31,6	24,8	31,6	24,8	23,6	25,2	30
10	5,6	60,4	48,4	52,4	52	54,8	39,6	60	49,6	78,4
20	5,6	73,6	50,4	64	56,4	57,2	52,8	54,8	87,6	72,8
20	8,4	35,6	35,2	34,8	35,2	34,8	34,8	34,8	34,8	35,2

(a)


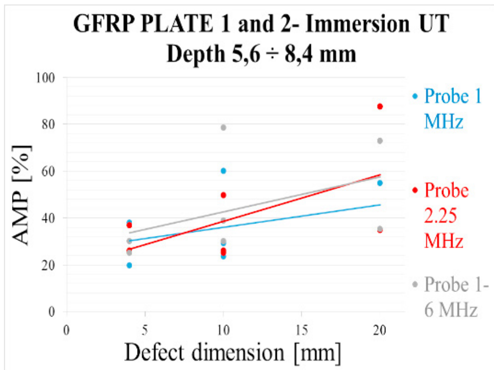
(b)


Figure 7. (a) – (b) Influence of defect dimension on signal amplitude in different depths using Immersion UT method in GFRP plates.

Analyzing the following diagram (Figure 8), the UT signal presents a linear behavior decreasing respect to defect depth and highlighting data dispersion due to defect depth. Data analysis shows the better sensitivity of probe 1 MHz in the Contact UT tests for various detected defects in GFRP laminate plates, as in Figure 8. For smaller defects (Figure 8a) with Contact UT technique, the Probe 0,5 also seems unsuitable for all depths. Probes 1 and 1-6 are the highest performing, especially for low depths. The depth influence is negligible on the probe choice for larger defects (Figure 8b) because of the irrelevant signal variability.

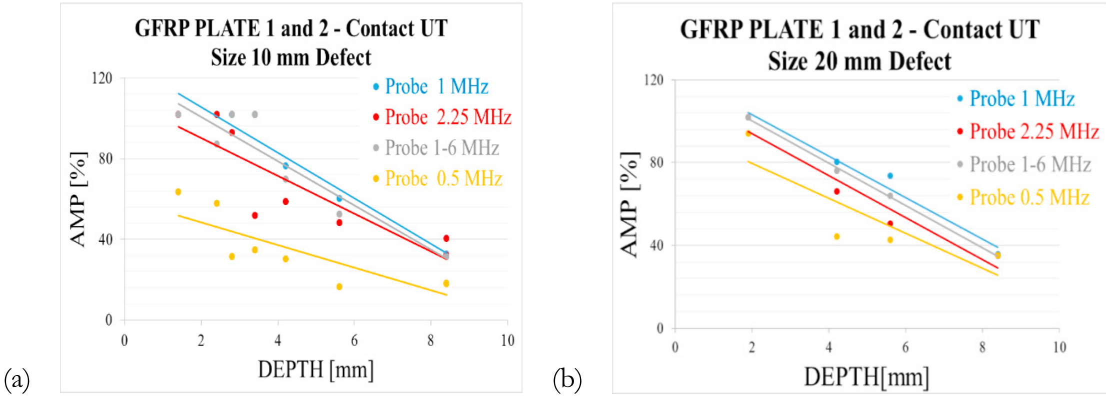


Figure 8. (a) – (b) Influence of depth on signal amplitude for different defect sizes using Contact UT method in GFRP plates.

For the Immersion and Water Stream UT methods (Figure 9), a similar sensitivity of probes is observed for 10 mm and 20 mm defects and this phenomenon avoids a unique choice of the optimal UT probe; in fact, the Probe 2,25 and Probe 1-6 present similar data results. Comparing the Figures 8a, 9a, the signal level is very similar with different techniques because of standardization and optimization of control procedures by means of the new employed tools designed for the various UT methods and available probes. In all cases some scattering of data is still observed even that trend lines appear to be coherent in slope and position as function of defect depth; in particular, for water stream technique in Figure 9b all the probes seem to have similar performance even that sparse single measurement points are positioned away from the average levels presumably because the reference artificial defect may not be glued perfectly and also because defects are not with some thickness. Also in Figure 9a is possible to assert the water stream and immersion technique applied to detect large defects at any depth with proper inspection tools make the probe choice nearly not influent on final results.

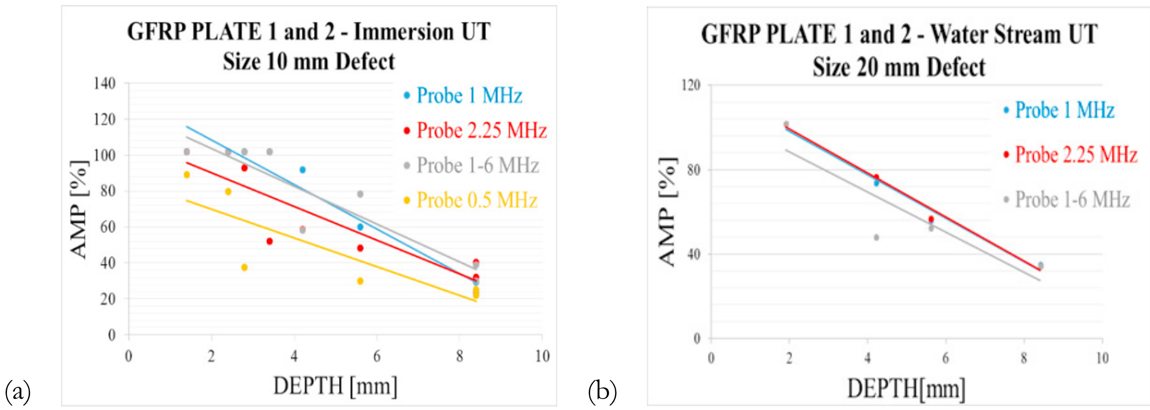


Figure 9. Influence of depth on signal amplitude for different defect sizes using Immersion (a) and Water Stream UT (b) in GFRP plates.

Figures 10 show, as an example, the amplitude trends of the UT signal as a function of depth, for the smaller defect of 5 mm diameter. From Figure 9b, it is noted that the 1MHz and 2.25MHz probes have a similar behavior with the best sensitivity in terms of signal amplitude detected, even for high depths. Similar behavior was also observed for the other two techniques analyzed; contact and immersion as illustrated in Figure 10a-c.

Figure 11 shows an example the different UT inspection methods behavior, examining the signal amplitude variation versus depth of 10 mm diameter defects with 1 MHz and 2,25 MHz probes. In particular, Figures 11a and 12a show a similar behavior, using probe 1 at any depths, with the different methods; however, the Immersion method presents better performance. On the contrary, examining the Figures 12a-b, relating to the 20 mm defects, the

Immersion method seems to offer best results, with the 2.25MHz probe. From the graphs it showed that the 1MHz probe is slightly better than 2.25MHz in contact technique.

Figure 11c shows the amplitude trend versus defect thickness for low range depth to 10 mm defect diameter; the general trend of all Probes is similar for two analyzed techniques. Probe 1÷6 in Contact UT and Probe 2.25 in Water Stream UT present different behavior.

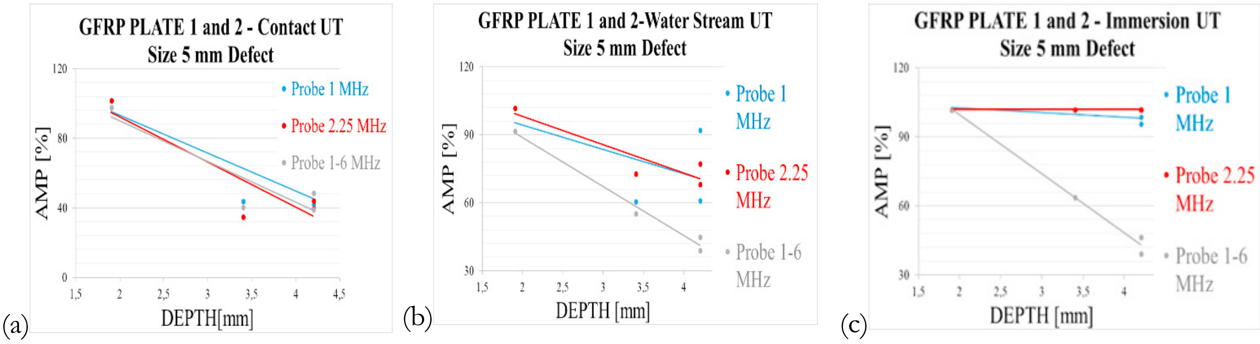


Figure 10. (a) – (b) – (c) Influence of depth on signal amplitude for 5 mm defect size using different UT methods in GFRP plates.

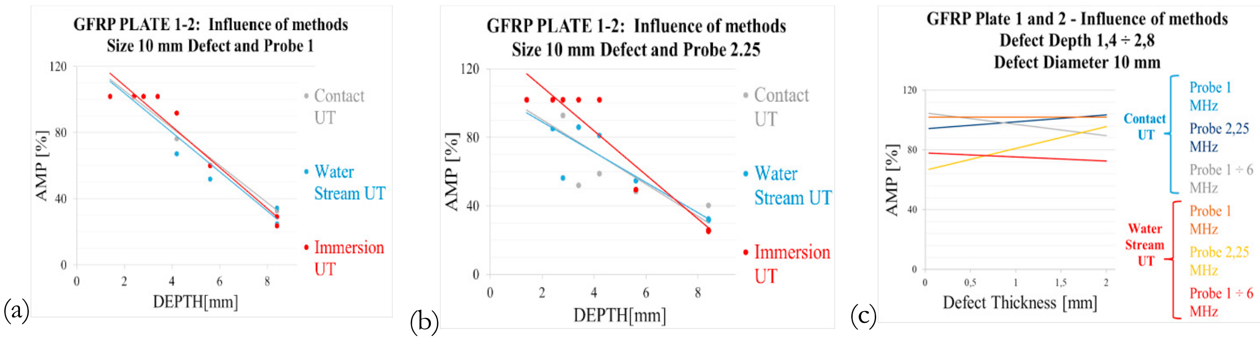


Figure 11. (a) – (b) – (c) Influence of depth and defect thickness on signal amplitude for different UT methods for 10 mm defects.

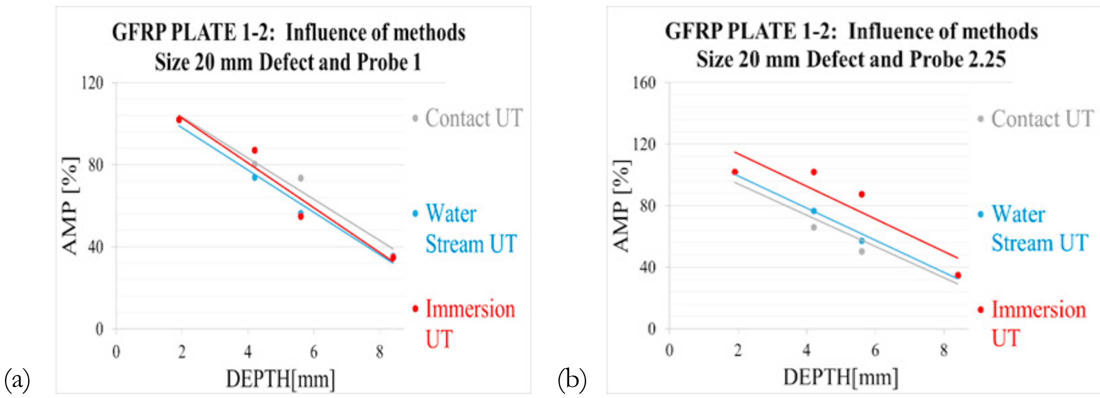


Figure 12. (a) – (b) Influence of depth on signal amplitude for different UT methods for 20 mm defects in GFRP plates.

A statistical analysis is also performed in order to verify the repeatability and validity of the acquired values for automated UT scans using special tool D. Several ultrasonic inspections are recorded for example as associated to linear B-scan on Ø 10 mm on plate 1. Repeated acquisition of signal amplitude are recorded along two orthogonal X and Y directions using 0.5, 1 and 2 mm / s scan velocity and inspection diagrams are shown in Figure 13a and 13b, both for the defect and Back Wall echo. Scanning gain of 50 dB value is fixed for each amplitude detection.

Amplitude error detectable present data dispersion value around +/- 5% and this result guarantees acceptable repeatability and reliability of base support optimized in case of Water Stream UT technique and automatic detection software. Similar results are achieved in direct contact repeated A-Scans with probe applied using tool A.

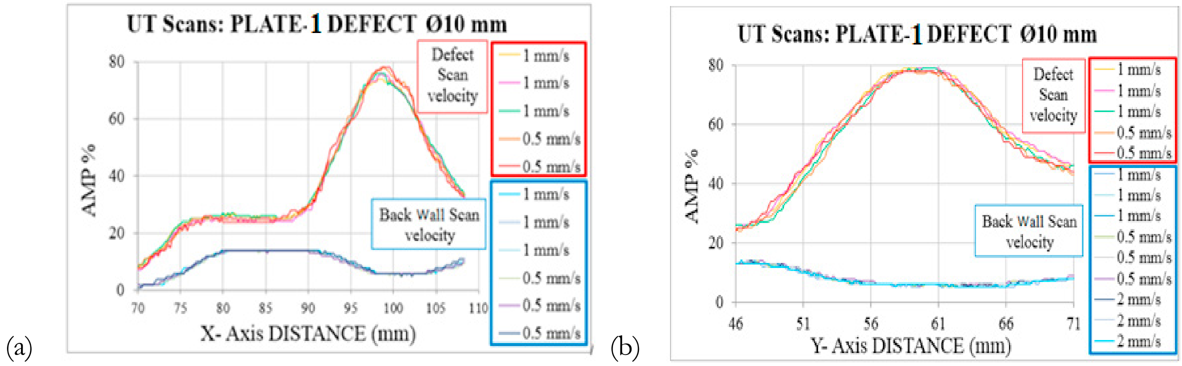


Figure 13. (a)-(b) Amplitude of UT scans for Ø 10 mm defect on GFRP plate 1 and Mean Amplitude along X and Y-axis direction.

4. Conclusions

The purpose of this document is to create and optimize procedural tools for ultrasonic scans of GFRP plates for various types of probe. The choice of the correct scanning procedures with aid of specially designed tools has been carefully improved during the numerous inspections which have contributed to obtain reduced standard deviation values in experiment repetitions.

Several inspections were done on defects at different depth and size for both materials and Olympus A103S probe with a 1 MHz frequency results the better choice for GFRP plate inspections with contact technique, especially for small defects than other probes and techniques. For immersion and water stream technique all probes offer good results when proper tools are used. When water immersion method is used the 2.25 probe is generally more precise at any defect depth, whilst Contact UT method with aid of special tools seems to be a valid technique for small defects detection with higher peak amplitudes.

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