



## **Quantitative comparison of different non-destructive techniques for the detection of artificial defects in GFRP**

Krankenhagen R<sup>1</sup>, Maierhofer C<sup>1</sup>, Heckel T<sup>1</sup>, Brackrock D<sup>1</sup>, Gower M<sup>2</sup>, Lodeiro M<sup>2</sup>, Baker G<sup>2</sup>

<sup>1</sup>Department Non-destructive Testing, Bundesanstalt für Materialforschung und -prüfung (BAM), Germany, Rainer.krankenhagen@bam.de

<sup>2</sup>Materials Division, National Physical Laboratory (NPL), GB, maria.lodeiro@npl.co.uk

### **Abstract**

In order to test their suitability different non-destructive methods were performed to inspect a GFRP plate with artificial defects. These defects were manufactured by means of thin PTFE sheets inserted between two plies in three different depth. The inspection methods were microwave reflection, flash thermography and phased array ultrasonics, all applied to the same specimen. Selected results are shown for all methods demonstrating opportunities and limits of the particular inspection methods. The achieved detection limits and further application aspects are compared directly to provide a useful information for the planning of inspection tasks.

### **1. Introduction**

For assuring the safety and reliability of components and constructions in energy applications made of fiber reinforced composites (e. g. blades of wind turbines and tidal power plants, engine chassis, flexible oil and gas pipelines), innovative non-destructive testing methods are required. In the past a series of different methods has been evaluated to be suited for certain defects in certain materials i.e. ultrasonics, thermography, shearography, Terahertz inspection, acoustic emission or digital radiography. However, only few groups investigated different inspections methods comparatively(1) (2). Within the EMRP project VITCEA (3) four different methods (laser shearography, microwave, phased array ultrasonics and active thermography) have been further developed and evaluated. Together with input from industry partners, a series of test specimens were designed and manufactured from various composite materials. Different kinds of artefacts were produced: reference defect artefacts (RDAs) containing artificial defects with well-defined geometries and natural defect artefacts (NDAs) with naturally occurring defects caused by overloading and impact. NDAs represent more realistic defects but their real extent and geometry is a priori unknown. Thus, additional reference methods are required to define these defects when used to evaluate the detectability of different non-destructive testing methods. Finally, the results of the project could be structured as a simple table with typical materials and their corresponding defects against the particular measurement methods. This contribution is focused at only a small subset of the defect/materials investigated corresponding to an artificial circular delamination created by the insertion of encapsulated PTFE sheet placed between composite plies (4).

## 2. Experimental details

### 2.1 Sample preparation

The results to be presented here were obtained from a GFRP specimen, which was built up as a plate of 300 mm \* 600 mm and 5 mm thickness. It was manufactured with 36 plies MTM28 UD glass fibre prepregs. This material includes black pigments. The plies were alternating orientated in  $+55^\circ$  and  $-55^\circ$  direction. The circular artificial delaminations were located at three different depths of 0.53 mm, 2.4 mm and 4.36 mm from the front surface with diameters between 1 mm and 40 mm (5).

### 2.2 Microwave reflection

Microwave inspections were conducted using an Evisive Inc. microwave flat-bed scanning system. Here, the microwave transducer is fixed to a scanning system to enable the inspection of larger surfaces. The equipment is shown in figure 1; note, the sample shown in this figure is a GFRP-Nomex® sandwich panel and not the RDA inspected in this study. The transducer includes two separate sensor diodes to record the complex reflection signal. For these investigations a probe frequency of 34 GHz was selected corresponding to a wavelength in the order of 9 mm. Conducting the scan with an increment of only 0.5 mm, a good spatial resolution, certainly below the wavelength, could be obtained as can be seen in figure 2. This image is only the intensity distribution from one sensor diode. Most of the artificial delaminations can clearly be recognised. More details about the setup and data processing are described in (5).

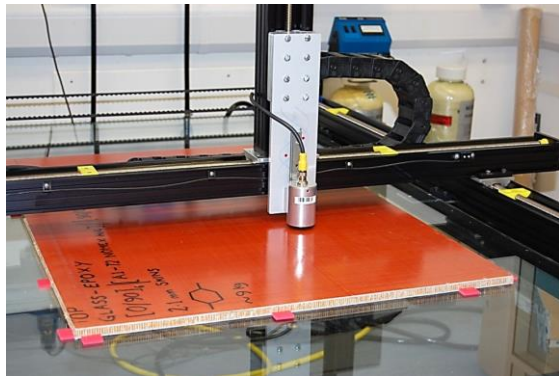


Figure 1. Evisive microwave inspection system, here shown with another sample (orange)

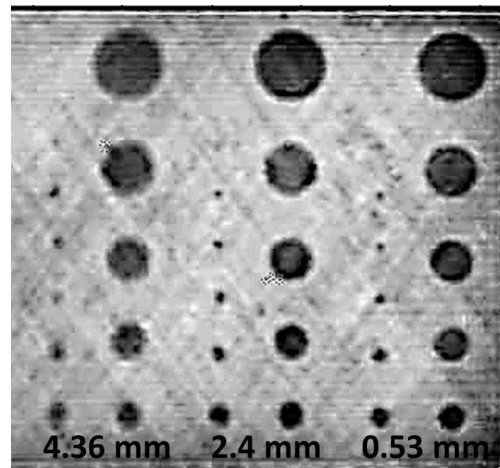
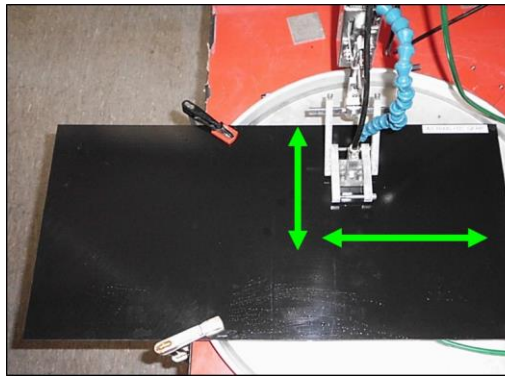


Figure 2. Inspection result of a GFRP specimen with artificial delaminations from channel B output, the frequency was 34 GHz and the scanning increment 0.5 mm

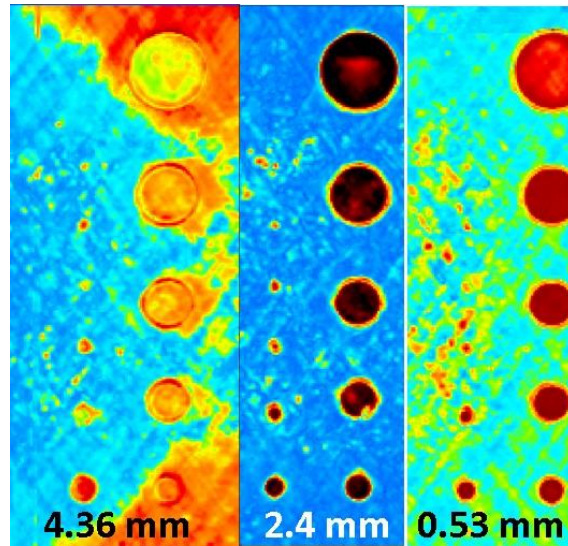
### 2.3 Phased array ultrasonics (US)

Ultrasonic investigations were realised in contact technique in reflection configuration. A matrix array of 10x6 elements with 1.3 mm pitch is mounted on a scanning unit. The

scanning was carried out with 0.5 mm or 1 mm increment in both directions with variable focus point. The ultrasonic frequency of the elements was 2.25 MHz. Figure 3 shows the used setup and figure 4 contains a compilation of three different scans of the GFRP specimen including all investigated defects. At a first glance it can be seen that, besides the designed defects, a number of unintentional defects also occur. A detailed discussion of these results follows below in the *Experimental results* section.



**Figure 3.** GFRP specimen and the scanning unit with US matrix array, the arrows show the scanning directions



**Figure 4.** Compilation of three different US images obtained at the GFRP specimen, the numbers indicate the intended depth of the respective delaminations

## 2.5 Thermography

Thermographic inspections were realised with an array of 4 flash lamps and a cooled IR camera with an InSb detector of 640 x 512 pixels, both located at the same side of the specimen i.e. in reflection configuration. The lamps had 45 cm distance to the specimen surface generating an energy density of about 0.5 Ws/cm<sup>2</sup> at the surface. The arrangement of lamps, IR camera and specimen is illustrated in figure 5. The spatial resolution was about 0.5 mm per pixel. The thermal resolution characterised by the NETD (noise equivalent temperature difference) at 30°C is about 25 mK. Here, thermal sequences of 3100 frames were recorded with a frame rate of 50 Hz, including some frames before the flash heating and at least 60 s during cooling down.

In order to reduce influences from inhomogeneous heating and to enhance the depth range phase images at suited frequencies were considered. Here, standard tools integrated in the camera manufacturer's software were used. Figure 6 contains phase images with respect to 20 mHz (2.4 mm part) and 100 mHz (0.53 mm part) frequency. Both phase images indicate, as well as the ultrasonic results, smaller unintended defects. Much more details about experimental results and data analysis will be published soon (6).

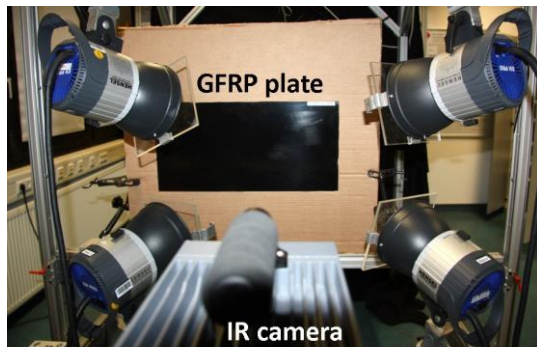


Figure 5. Thermography setup with four flash lamps and the GFRP specimen (from a view point at the IR camera), the GFRP is black due to black pigments within the material

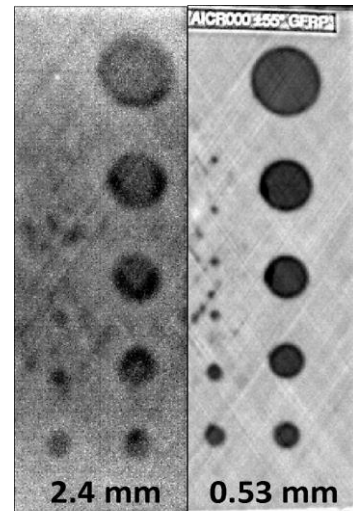


Figure 6. Compilation of two different phase images obtained at the GFRP specimen, the numbers indicate the intended depth of the respective delaminations, the delaminations at 4.36 mm depth could not be detected

### 3. Experimental results

Faced with a large amount of data, limited results are presented for every measurement method demonstrating a typical clear result and one demonstrating the detection limit.

#### 3.1 Microwave reflection

In the presented case the single channel signal was sufficient to detect most of the artificial delaminations. The following figures show the data obtained at delaminations of 25 mm and 20 mm diameter in 2.4 mm depth (clear result) and at 3, 4 and 5 mm diameter in 4.36 mm depth. The cause of the chequered pattern at 5 o' clock position from the left delamination is still unknown. The detection limit is reached at 4 mm, probably caused by material inhomogenities. Please note the appearance of the surface which results from the orientation of the plies in the  $\pm 55^\circ$  lay-up.

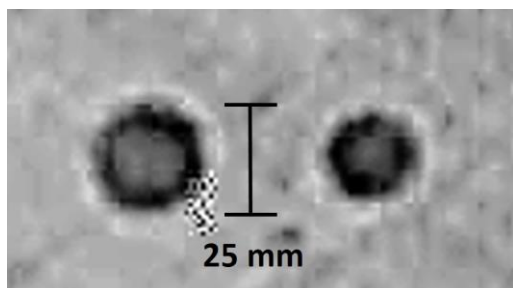


Figure 7. Intensity image obtained by single channel microwave reflection at artificial delaminations of 25 mm size (left) and 20mm size (right) in an intended depth of 2.4 mm in GFRP (clear result)

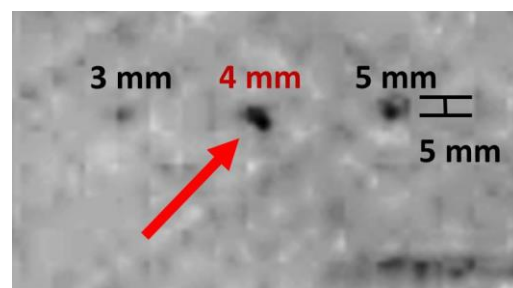
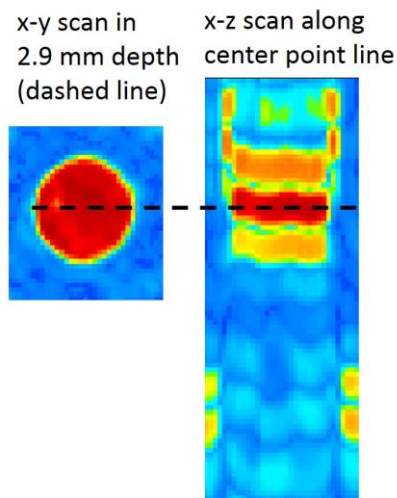


Figure 8. Intensity image obtained by single channel microwave reflection at artificial delaminations of different sizes in an intended depth of 4.36 mm in CFRP, the detection limit is 4 mm

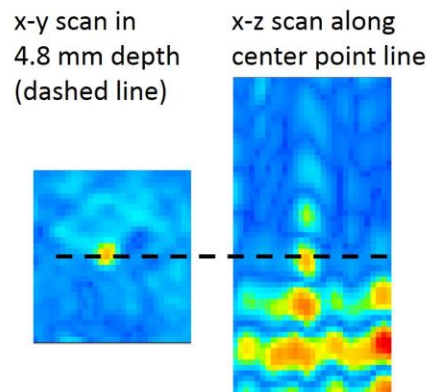
It has to be investigated if enhanced data processing using the second channel enables a further improvement of these findings.

### 3.2 Phased array ultrasonics

The following figures show the data obtained at a delamination of 25 mm diameter in 2.4 mm depth (clear result) and at 3 mm diameter in 4.36 mm depth. A sound velocity of 3600 m/s was determined in a range without known failure based on the known thickness. Comparing the estimated thickness values with the intended depths of the delaminations an offset of about 0.5 mm occurred.



**Figure 9.** Ultrasonic scan result obtained with a matrix array at an artificial delamination of 25 mm size in an intended depth of 2.4 mm in GFRP (clear result)



**Figure 10.** Ultrasonic scan results obtained with a matrix array at an artificial delamination of 3 mm size in an intended depth of 4.26 mm in GFRP (detection limit)

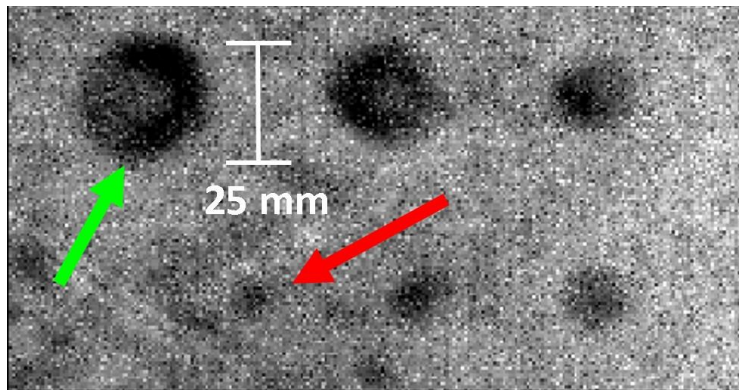
In figure 9 the shown image of the x-z-scan includes also part of the back-wall signals. Here, the reflections are shielded in the range below the delaminations. That means there are two indications for inner delaminations. However, this effect could not be observed in case of small delaminations (x-z scan in figure 10)

The x-y-scan indicates the 3 mm small delamination in 4.25 mm depth clearly. However, further signals with similar magnitude, probably caused by unintended manufacturing defects, were also recorded (not shown here). Thus, the used specimen is not suitable for evaluating even lower detection limits.

The reason for the observed thickness offset is yet not clear. Thickness variations of the specimen as well as spatial variations of physical material properties (density, internal stress) are possible explanations. Both phenomena influence the correct determination of the sound velocity and thus the thickness calibration directly.

### 3.3 Thermography

The next figure shows the data obtained at the delaminations in 2.4 mm depth. It is a magnified part of the phase image in figure 6 (rotated by 90°).



**Figure 11. Phase image obtained after flash excitation at 20 mHz, clear result: delamination of 25 mm size in an intended depth of 2.4 mm in GFRP (green arrow)  
Detection limit: delamination of 6 mm size in an intended depth of 2.4 mm in CFRP (red arrow)**

Similar to the other methods, the evaluation of the detection limit is affected by further unintended manufacturing defects. In addition, it had to be established that the deep delaminations in 4.36 mm depth could not be detected for no diameter at all.

### 3.4 Comparison

After the presentation of the individual results, the results are compared directly with each other. In addition to the measuring accuracy achieved, further criteria concerning onsite applications must be regarded.

**Table 1. comparison of the different inspection methods applied to artificial delamination in GFRP**

critierion	Microwave reflection	US (matrix array)	TG (flash excitation)
Detection depth (for large diameters > 15 mm)	> 4.25 mm	> 4.25 mm	>=2.4 mm
Detection depth (for small diameters 3 ... 12 mm)	>=4.25 mm (at 4 mm)	>=4.25 m (at 3 mm)	2.4 mm (at 6 mm)
Depth determination (for large diameters > 15 mm)	N/A	4.25 ±0.1 mm	N/A
Depth determination (for small diameters 3...12 mm))	N/A	4.25 ±0.1 mm	N/A
Size determination (25 mm diameter in 2.4 mm depth)	25 ±1 mm	24.7 ±0.3 mm	26 ±2.5 mm
Size determination (for small diameters 3...12 mm)	5 ± 1 mm (4 mm diameter) depth: 4.36 mm	3 ±0.3 mm (3 mm diameter) depth: 4.36 mm	7.5 ±3 mm (6 mm diameter) depth: 2.4 mm
Onsite installation effort	medium	high	medium
Required measurement time (area 30x30 cm²)	20 min	90 min	5 min
Required qualification for data evaluation	medium	high	medium

For microwave inspection and thermography, the ability to determine the depth of the delaminations will be evaluated later.

The suitability of an inspection method for a specific measurement task depends strongly on the weighting of the individual criteria. Thus, it is not useful to give a general recommendation, even for the considered specific kind of damage. However, the user can evaluate his specific inspection task by means of table 1.

## 4. Conclusions

For non-destructive testing of fibre reinforced composites, a series of different measurement methods is available. The suitability of the respective inspection method depends strongly on the material as well as from the nature of the expected defects. Within the VITCEA-project two imaging methods (shearography and thermography) and two scanning methods (ultrasonics and microwave reflection) were specified and compared for different kinds of defects. This presentation has been focused on one specific defect: a PTFE insert located between two plies of a GFRP-plate made from MTM28. The results are compiled in a table considering various aspects of onsite application. Phased array ultrasonics and microwave inspections (both scanning techniques) are found to be similar suited for this kind of artificial delamination. For shallow defects until 2.5 mm depth flash thermography provides a fast opportunity for inspections with lower technical effort. To complete this comparison the ability to determine the depth of the delaminations as well as the inspection method Laser shearography should be included.

Further systematically comparisons are planned concerning natural defects like impacts and delaminations due to overloads.

## Acknowledgements

This study was funded by EURAMET within ENG57 EMRP (European Metrology Program) as a part of the EMRP-project VITCEA (Validated Inspection Technologies for Composites in Energy Applications).

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