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Ultrasonic Inspection and Data Analysis of Glass- and Carbon- Fibre-Reinforced Plastics

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Abstract

Non-destructive testing (NDT) helps to find material defects without having an influence on the material itself. It is applied as a method of quality control, for online structural health monitoring, and for inspection of safety related components. Due to the ability of automation and a simple test setup ultrasonic testing is one major NDT technique next to several existing options. Whereas contact technique allows the use of higher frequencies of some MHz and phased array focusing, air-coupled ultrasonic testing (ACUT) shows different advantages. Most significant for ACUT is the absence of any coupling fluid and an economical test procedure respective time and costs. Both contact technique and ACUT have been improved and enhanced during the past years. One important enhancement is the development of airborne transducers based on ferroelectrets, like charged cellular polypropylene (cpp), which makes the application of any matching layers being mandatory in conventional piezoelectric transducers unnecessary. In this contribution we show ultrasonic inspection results of specimens made of carbon- and glass-fibre-reinforced plastic. These specimens include defects represented by drill holes and artificial delaminations of various size and depth. We compare inspection results achieved by using contact technique to those achieved by ACUT. For ACUT, conventional piezoelectric transducers and transducers based on cpp were used, both focused as well as non-focused types. Contact inspections were performed with a multi-channel matrix array probe. Once the inspection data is recorded it can be analysed in order to detect and evaluate defects in the specimen. We present different analysing strategies and compare these regarding detection rate and sizing of defects.

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1. Non-Destructive Testing of Fibre-Reinforced Plastics

Non-Destructive Testing (NDT) is used for the detection of material defects due to production failure or fatigue. It also may support process and quality control. Various NDT techniques such as radiographic examination, thermography, eddy-current testing or ultrasonic testing represent different ways with distinct advantages and disadvantages depending on actual existing inspection conditions.

Contact ultrasonic technique enables one-sided inspection as it is usually performed in pulse-echo mode. Defects are detected by the occurring reflection of a transmitted ultrasonic pulse. The time of flight provides information about the depth of a detected defect. Furthermore, inspection in contact technique allows the use of frequencies of some megahertz and phased array focusing, which improves the signal-to-noise ratio and the lateral resolution. It may be performed automated or manually but always requires a couplant between probes and inspected material.

In contrast to contact technique, air-coupled ultrasonic testing (ACUT), recently reviewed by Chimenti (2014), is characterized by the absence of any coupling fluid. This makes it suitable for application to porous materials and composite structures, especially those consisting of fibre-reinforced plastics. Most kinds of inspections with ACUT require two-sided access as it is usually performed in transmission mode. Due to high sound attenuation in air, ACUT is limited to frequencies below 500 kHz. Recently developed airborne transducers based on ferroelectrets make the application of matching layers, being mandatory in conventional piezoelectric airborne transducers, unnecessary. For example, cellular polypropylene (cpp) shows excellent properties after a high-voltage corona discharging process, first shown by Paajanen et al. (2000). This material can easily be bent, which enables the production of spherically focussed transducers, as shown by Gaal et al. (2013 and 2016) and Schadow (2016), as well as other forms as reported by Ealo (2008). In a certain range of conditions ACUT represents an economical inspection method respective time and costs.

In this contribution, we compare matrix array testing and ACUT on two specimens made of carbon- and glass-fibre-reinforced polymers including flat bottom holes and artificial delaminations of various sizes.

2. Ultrasonic Inspection of Specimens made of Carbon- and Glass-Fibre-Reinforced Plastic

We inspected two similar specimens of composite material: one made of a carbon-fibre-reinforced plastic (CFRP) and one made of a glass-fibre-reinforced plastic (GFRP). Both CFRP and GFRP are widely used in the field of renewable energy, e.g. in wind energy turbines, in the sector of lightweight transport, e.g. marine and automotive, as well as in oil and gas industries. The thickness of both specimens was 5 mm. A prepreg material consisting of unidirectional glass fibre and epoxy matrix resin was used for the GFRP specimen. Multiple prepreg layers of an orientation of $\pm 55^\circ$ were then oven cured at 120°C , so that the structure was $[\pm 55, -55]_{9S}$. The CFRP was built using a unidirectional carbon fibre prepreg with epoxy matrix resin. In this case a unidirectional fibre layup was applied and the curing process of 120°C was performed in an autoclave, resulting in structure $[0]_{8S}$. The specimens include defects represented by flat bottom holes and artificial delaminations of various sizes between 1 and 40 mm in diameter. These defects were placed in three different depths: close to the upper surface, in the centre, and close to the lower surface of the specimen as shown in Fig. 1 (b). Table 1 contains the exact positioning of flaws. Both specimens were inspected by air-coupled ultrasonic testing (ACUT) and contact technique. For ACUT we performed measurements with conventional piezoelectric transducers and transducers based on cpp. Frequencies were applied in the range from 200 kHz to 330 kHz. This inspection was performed in transmission mode, with the specimen's front and back surfaces in their focal points (Fig. 1 (b)). Defect indication occurs due to alteration of the transmitted amplitude when transducers are passing over a defect.

Measurements in contact technique were performed with a multi-channel matrix array probe consisting of 60 elements of an operating frequency of 2.25 MHz. The use of a matrix array probe allows precise focusing to the appropriate depth of the defect. The inspection was performed in pulse-echo mode where a defect can be detected by the occurring reflection of the ultrasonic wave at the defect interface.

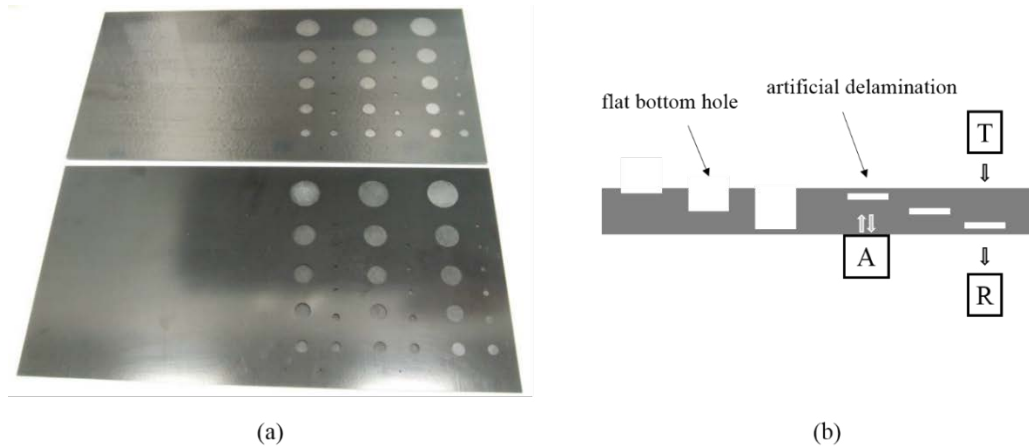


Fig. 1. (a) Specimens AICQ UD SE84 CFRP (above) and AICR 55 MTM28 GFRP (below). (b) Sketch of the specimens with the positioning of air-coupled (T, R) and phased array (A) probes.

Table 1. The depths of flaws in fibre-reinforced specimens.

Specimen	Hole depths	Delamination depths
CFRP [0] _{ss}	0.65 mm	0.625 mm (between plies 2 and 3)
	2.6 mm	2.5 mm (between plies 8 and 9)
	4.55 mm	4.375 mm (between plies 14 and 15)
GFRP [+55, -55] _{9s}	0.54 mm	1.11 mm (between plies 4 and 5)
	2.4 mm	2.5 mm (between plies 18 and 19)
	4.26 mm	3.89 mm (between plies 32 and 33)

3. Detection of defects using the collected inspection data

There is an important difference between the ACUT data and the contact technique data: the collected data for contact technique represents reflected ultrasonic signals, while ACUT provides transmitted ultrasonic signals through the specimen. This means that the detection criteria for an ultrasonic signal collected in contact technique is the occurrence of a sufficiently large echo amplitude so it can be clearly separated from the noise of the received signal. In case of ACUT a noticeable increase or decrease of the transmitted amplitude is required in order to differentiate the region of defect from non-damaged areas.

Fig. 2 compares the transmitted amplitudes of an inspected CFRP specimen for an ACUT transducer based on cellular polypropylene (cpp) with a transducer couple NCG500-D19-P50 available by “Ultran”. Both types are focused transducers with an aperture of 19 mm with a focal size of 2-3 mm and a similar operating frequency: 274 kHz for cpp and 320 kHz for the “Ultran” transducer.

The smallest detectable diameter for flat bottom holes was 2 mm, for delaminations close to the surface or bottom it was 4.7 mm, and for delaminations at the middle of the specimen 3 mm. There was no relevant difference between the cpp and the commercial transducer. Therefore, the diameter of the smallest detectable defect was in the range of the transducers focal size. Furthermore, very small delamination may not be detectable even if a flat bottom hole of the same size can be found.

The air-coupled inspection of the GFRP specimen was performed with the same transducers as applied to CFRP. The GFRP inspection required a 4dB higher amplification of the received signal, because of higher sound attenuation and scattering inside the material. The smallest detectable flat bottom holes and delaminations were 3 mm in diameter, regardless of depth (Fig. 3). The fibre orientation of $\pm 55^\circ$ is visible too. Next to flat bottom holes and artificial delaminations, also multiple smaller unintended natural defects can be seen. We assume this to be porosity in the epoxy matrix as a result of a different production process compared to the previously inspected CFRP

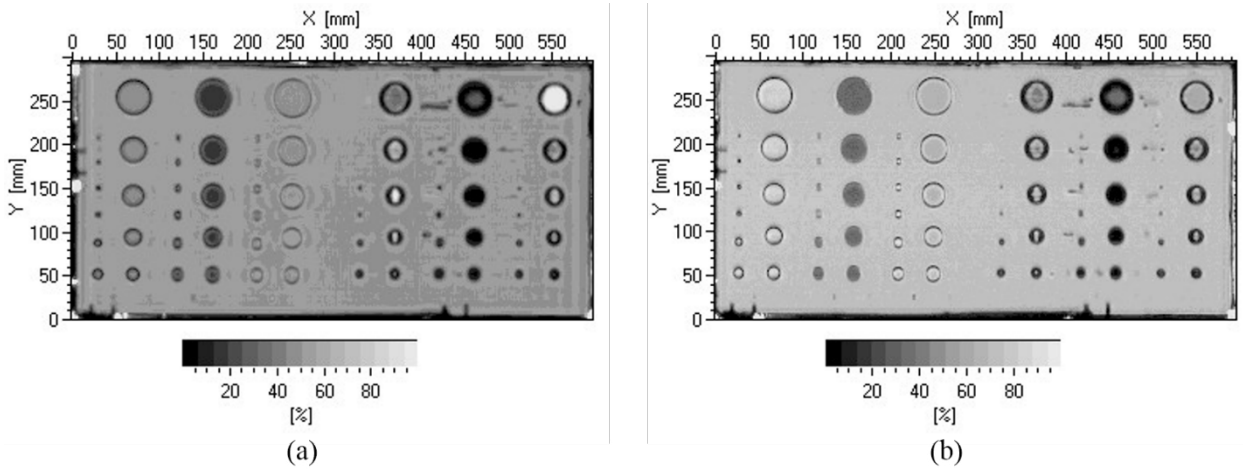


Fig. 2. Transmitted amplitude of air-coupled ultrasonic inspection of a CFRP specimen; (a) BAM-cpp transducer, aperture 19 mm, focused, 274 kHz; (b) NCG500-D19-P50 transducers, aperture 19 mm, focused, 320 kHz. Flat bottom holes are at the left and delaminations at the right side of each specimen.

specimen. Instead of an autoclave process which applies additional pressure to the vacuum-bagged layup, this GFRP specimen was only oven-cured.

Comparing all ACUT inspection results, we see that a defect may result in an increase of transmitted amplitude for one transducer while it results in a decrease for another one. This effect depends on the wavelength, the specimen thickness, the flaw size and the material properties, which makes it difficult to predict the resulting image. Some of the artificial delaminations result in an increase of transmitted amplitude, surrounded by decreased amplitude or the other way around. This leads to the question how such a defect can be measured in size.

Ultrasonic contact technique is presented in Fig. 4, showing the inspection result on flat bottom holes located near the surface in CFRP and GFRP specimens. The depth of the shown defects could be determined to 1.1 mm using the time of flight (TOF) information, as shown in the lower area of the images. Additionally, the specimen thickness can

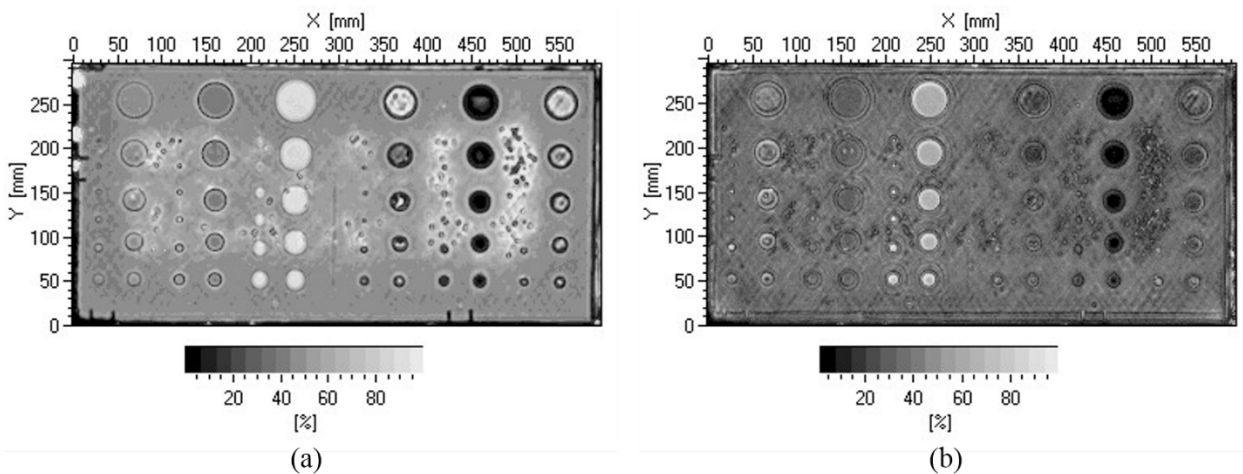


Fig. 3. Transmitted amplitude of air-coupled ultrasonic inspection of a GFRP specimen; (a) BAM-cpp transducer, aperture 19 mm, focused, 274 kHz; (b) NCG500 transducers, aperture 19 mm, focused, 320 kHz. Flat bottom holes are at the left and delaminations at the right side of each specimen.

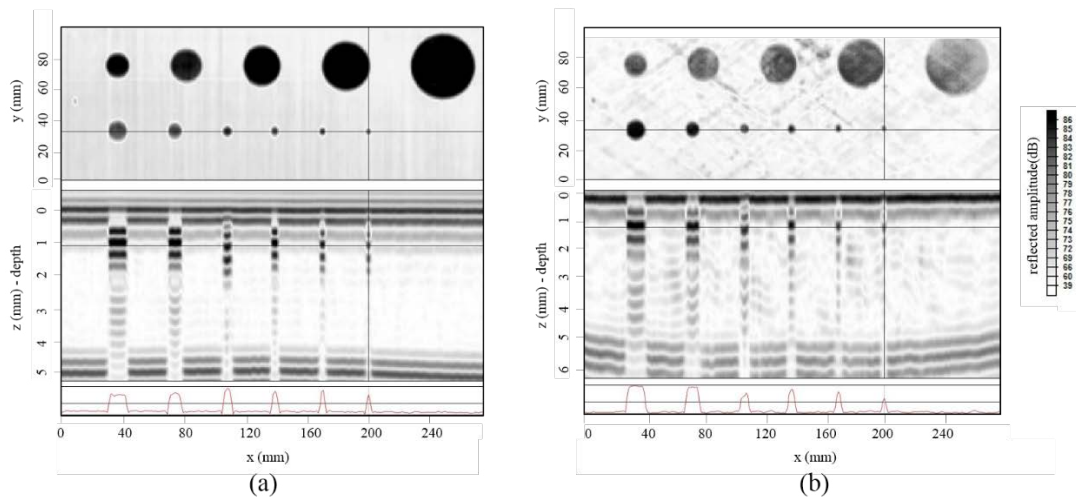


Fig. 4. Reflected amplitude of ultrasonic inspection in contact technique using a matrix array of 2.25 MHz, focused to flat bottom holes at 1 mm depth, (a) in the CFRP specimen and (b) in the GFRP specimen.

be monitored by the entering and back wall echoes at the depth “z” of 0 and 5 mm. The difference of the TOF over the specimen width “x” occurs due to a variation in material thickness. Also a variation in ratio between matrix and fibre, which would also result in a change of the TOF, could result in the shown back wall echo. In CFRP even the smallest flat bottom holes and delamination of 1 mm in diameter could be found using the matrix array probe. Inspections of the GFRP specimen showed the smallest detectable flat bottom hole and delamination of 2 mm in diameter. The inspection GFRP also shows the $\pm 55^\circ$ fibre orientation as previously observed by ACUT.

4. Sizing of detected defects

Most commonly the defect size is used as a criterion to judge the criticality of a defect. For most NDT-techniques there are given sizing methods, e.g. the “full-width-at-half-maximum” (FWHM) of a reflected echo for ultrasonic contact technique. ACUT leads to more complex effects of transmission amplitude at existing defects. As already shown in Fig. 2 and 3, a defect may raise or lower the amplitude of the ultrasonic transmission depending on its size, depth and kind. Even combinations of both – increasing and decreasing amplitudes as plotted in Fig. 5 (a) – has been observed and needs to be considered. All this is a challenge for automated detection and sizing. We investigated various sizing methods and compared these to the known diameter of artificial defects.

A region of interest (ROI) around a found defect can be described as matrix A with n columns and m rows representing the inspection area. A contains all values of transmitted amplitudes at each discrete point within the ROI. The reference amplitude of a non-damaged area is named R . It can easily be determined by calculating the median of all recorded amplitudes $A(i,j)$ during inspection. We used five sizing methods described as follows.

- For sizing method “M1” we calculate the vector $v(j)$ of the dimension $1 \times n$ containing n elements which are the maximum values of the deviation of $A(i,j)$ from the reference R for a given line j . Sizing by method M1 may then be described as the full-width-at-half-maximum (FWHM) in v , which is depicted in Fig. 5 (b).

$$v_j = \max(|A(i, j) - R|) \quad (1)$$

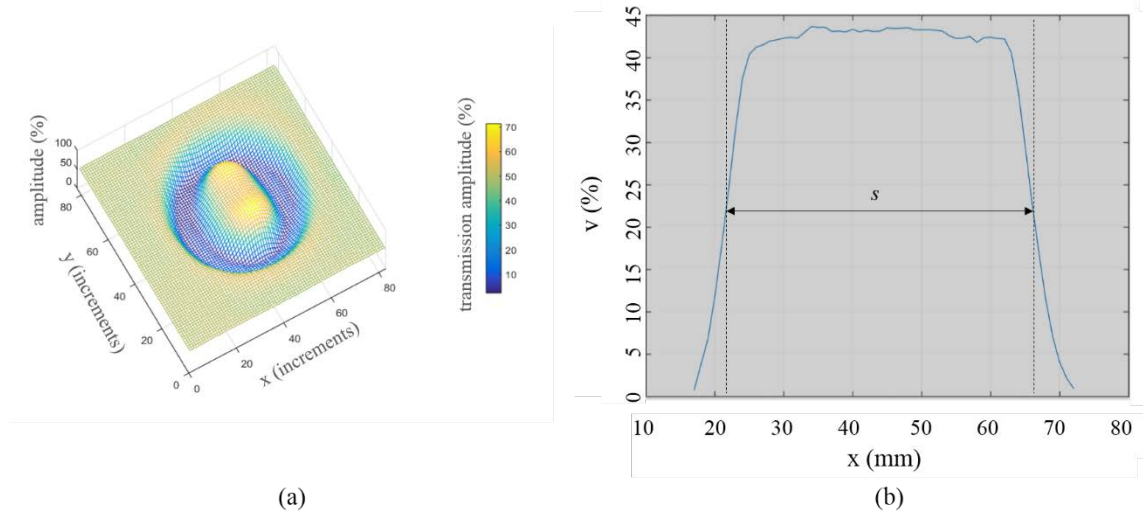


Fig. 5. (a) Transmitted amplitude using ACUT at artificial delamination, diameter 24.7 mm. (b) Sizing method M1 using vector v and full width at half maximum.

- Sizing method “M2” uses the distance between the first and the last peak in vector g , which is defined as the gradient of previously calculated vector v :

$$g = \frac{dv}{dx} \quad (2)$$

- For sizing method “M3” all positions in matrix $|A-R|$ were counted which contain values with a deviation of more than 10% from the reference amplitude R (equation 3) to obtain a defect area. Size s is the diameter of a circle of the same area.

$$|A - R| > 0.1 \times R \quad (3)$$

- For sizing method “M4” all positions in matrix $|A-R|$ were counted which contain values greater than a threshold of 10% of the maximum value in this matrix (equation 4) to obtain a defect area. Again, size s is the diameter of a circle of the same area.

$$|A - R| > 0.1 \times \max(|A - R|) \quad (4)$$

- Sizing method “M5” determines a defect area by counting all points which contain amplitudes below the 10% quantile and above the 90% quantile of all transmission amplitudes in A . Again, size s is the diameter of a circle of the same area.

The graph in Fig. 6 (a) shows calculated defect sizes s versus the known diameter d of artificial defects of flat bottom holes close to the specimen’s surface in CFRP. This analysis was performed by using the inspection data obtained with a focused ferroelectret cpp transducer of an aperture of 27 mm and an operating frequency of 284 kHz.

For defects larger than 8 mm in diameter, all five sizing strategies show a good approximation to linear behavior. Though M1, M3 and M4 overestimate the size of large defects. Defects with a variation of transmission amplitude below 10% are not detected by method M3, which is the case for some of the smallest defects. In contrast, M4 does

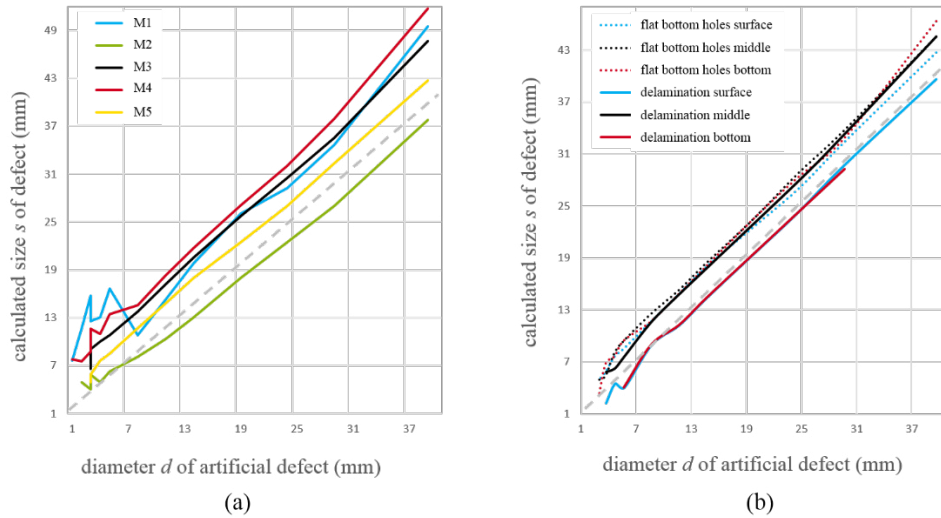


Fig. 6. Comparison of calculated defect size s vs. real size d for (a) flat bottom holes near to surface with different sizing methods and (b) flat bottom holes and artificial delamination in three depths for sizing method M5.

respect smaller variation of transmission amplitudes as it refers to the 10% threshold of the maximum occurring amplitude and thus detects even the smallest defects. Most accurate sizing results for small and large defects were obtained by methods M2 and M5. Method M2 slightly underestimates the size, which might be critical, whereas M5 gives a slightly overestimated result.

Sizing method M5 was used to investigate the influence of the type and depth of a defect to its estimated size. To account for both lower and higher transmission amplitudes than the reference amplitude, the applied quantiles in method M5 were set to the 10% and 90%. Delaminations close to the surface and bottom of the specimen lead to a smaller estimated defect size than flat bottom holes or delaminations in the middle of the specimen, as seen in Fig. 7. The relative error $(s-d)/d$ of sizing decreases with the actual defect size, as shown in Fig. 7 (b). Defects of more than 10 mm in diameter were sized with an error of less than 30%, while the error for small defects reaches up to 80% of their actual diameter.

The same sizing methods were applied to the inspection of the GFRP specimen. Results were very similar to the CFRP results, but the detection of small defects of less than 3 mm was impossible and multiple smaller natural defects included in the specimen disabled data analysis in some areas.

5. Summary

Two composite specimens were inspected by using ultrasonic contact technique and air-coupled ultrasonic testing (ACUT). The specimens made of CFRP and GFRP included artificial defects represented by flat bottom holes and artificial delaminations. The smallest detectable size was between 1 and 4.7 mm, as shown in Table 2.

Table 2. The smallest detectable defects in the inspected fibre-reinforced specimens.

Specimen	Defect type	ACUT	Matrix array
CFRP $[0]_{ss}$	Flat bottom holes	2 mm	1 mm
	Delaminations	4.7 mm near surface 3 mm in the middle	
GFRP $[+55, -55]_{9s}$	Flat bottom holes and delaminations	3 mm	2 mm

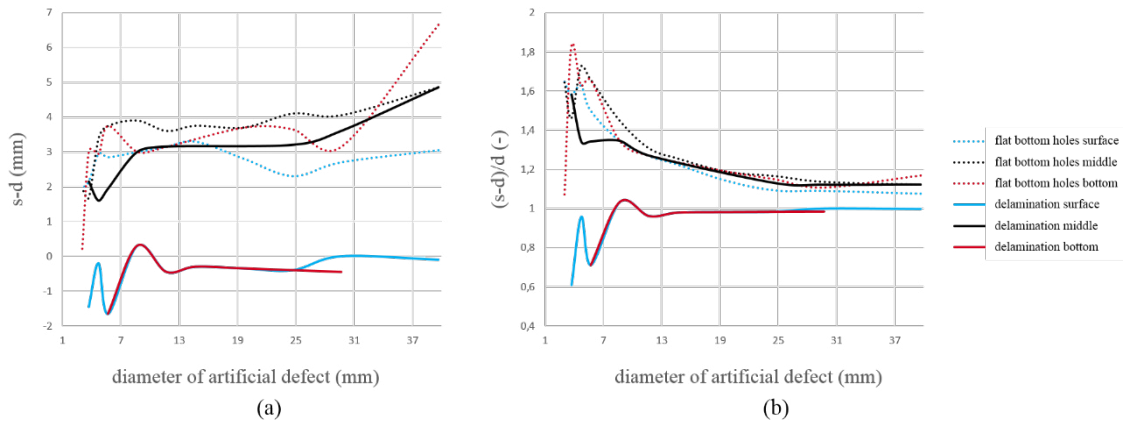


Fig. 7. Difference of calculated defect size s and real defect diameter d of flat bottom holes and delamination in CFRP using the M5 sizing method; (a) absolute difference $s-d$; (b) relative difference $(s-d)/d$.

Depending on the transducers operating frequency, some defects caused increasing and decreasing amplitudes over the defect area. For ACUT five different sizing methods were presented and compared to the actual defect size. Good results could be obtained by one criteria which uses the gradient and one which uses statistic quantiles of transmitted amplitudes. An investigation about the influence of the type and depth of defect to the estimated defect size was carried out. Delamination close to specimen's surface were sized smaller than other defects. The relative error in sizing decreases with the actual diameter of the defect.

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