Quantifying Drilling Induced Delamination in Carbon-Fibre-Reinforced Epoxy Laminates Using a Fast, Manual and Mobile Ultrasonic-Based Procedure as Compared to Low-Magnification Microscopy

Silvia SCHUHMACHER [1], Kai DAUBERT [1], Georgeta SCHOEN [1], Andreas HAEGER [1], Fabian LISSEK [2], Gerhard SCHNEIDER [1]

[1] University of Applied Sciences Aalen, Beethovenstr. 1, 73430 Aalen, Germany
[2] University of Applied Sciences Ulm, Prittwitzstr. 10, 89075 Ulm, Germany

Contact e-mail: Silvia.Schuhmacher@hs-aalen.de

Abstract. In aircraft as well as in other industrial fields, Carbon composites are of steadily increasing importance. But, due to their inhomogeneous structure and strong anisotropy, drilling of carbon composites is difficult. Within the cooperation project “ZAFH Spantec light”, different series of 6 mm diameter drilling holes using drills with different geometries, coatings and abrasion were produced in carbon-fibre reinforced epoxy laminates. An important part of the project deals with the characterization of drilling induced delamination.

When analyzing the drilling-hole series, the X-ray-CT-technique supplied a large and detailed catalogue with high-resolution three-dimensional damage-pattern. Combining the CT-slices of the relevant layers of a sample to a resulting overlay-image allowed the quantification of the delamination-factors. Due to the high resolution required, the samples had to be cut into small pieces of approximately 20 mm width. So in this context, the X-ray-CT-method cannot be considered as non-destructive, but it is very important to provide reference results.

Starting from the detailed knowledge supplied by the X-ray-CT-damage-catalogue, a fast, mobile and manual Ultrasonic-based testing procedure was adapted to the special type of damage. This allows the measurement of the delamination of a drilling hole within 5-7 seconds with scanning resolution of 0.1 mm. Comparing the US-C-Scan and the CT-Overlay image of the same drilling-hole demonstrates the high resolution of the ultrasonic method even for small delamination. To receive quantitative results, the US-data were segmented by a global, normalized threshold. The image analyzing software AxioVision or Avizo offered a fully automated segmentation and calculation of the delamination-factors. Thus, for numerous samples of different delamination, the diameter-weighted delamination-factor was quantified. The results correspond well with those received by the X-ray-CT reference method, even for small delamination with diameter-weighted delamination-factors of approximately 10%

In a further study, the delamination-factors were determined by Low-Magnification Microscopy. A comparison of the results of the three methods will be discussed finally in the presentation.

1 Introduction and state of the art

The steadily increasing demand for energy efficiency requires for light-weight-materials such as carbon fibre reinforced plastics (CFRPs). To assemble the CFRP parts with fasteners like rivets, bolts and nuts, post processing machining operations such as drilling is often necessary. Due to the inhomogeneity and anisotropy of the composites, the drilling process induces different kinds of damage, such as fibre pull-out, fibre-matrix debonding and delamination [1–3]. Especially the damage type of delamination causes a strong reduction in structural integrity and long-term performance deterioration [4].

Drilling induced delamination consist of two different types: peel-up and push-down delamination. Peel-up delamination area result of the peeling force induced by the drill at the entry side. This causes debonding of single fibres or of the whole upper ply. However the major damage happens on the exit side. The drill pushes the last remaining uncut plies down, causing a separation between two plies of the laminate [5]. Numerous research work has been done to investigate the influence of drill geometry and cutting parameters (feed rate and spindle speed) on drilling induced delamination [6–13].

Due to their negative impact on the structural integrity of the laminates, the nondestructive detection and characterization of the drilling induced delamination is of great industrial interest. Various methods such as scanning electron microscopy (SEM), optical microscopy, digital photograph, X-ray computed tomography (X-ray CT) and ultrasonic (US) methods have been used to characterize the delamination in size, shape and location. J. Babu et al. gave an overview of the authors and the formula for calculating the delamination factor [14].

Tsao et al. [12, 15, 16] used ultrasonic C-scans to examine the drilling induced delamination of woven CFRP laminate. The tested laminates were immersed in a water box and the testing device consisted of a 0.025 mm scanning bridge moving a conventional 5 MHz focused ultrasonic transducer (9.5 mm means). The diameter weighted delamination factor was determinate from the US C-scans and compared to the corresponding ones from the X-ray CT measurements. A good agreement was found [15].

Lopez-Arraiza et al. [17] examined drilling induced delamination in bidirectional thermoplastic laminates by SEM, low magnification microscopy, X-ray CT inspection and ultrasonic B- and C-scans. The testing device consisted of a two axes encoder scanner (0.1 mm) moving a 5 MHz linear phased array, the coupling was carried out by a gel. Each hole was scanned twice with relative orientation of 90° and the signals were averaged to improve the resolution. X-ray CT and US C-scan were compared based on the diameter weighted delamination factor. The results show ultrasonic testing being an accurate non-destructive method for detecting and quantifying drilling induced delamination [17].

Due to the immersion tank and/or scanning bridges, the US-methods described above are rather to be used in laboratory environment.

The purpose of this work is to provide a basis for an ultrasonic-procedure, which might be used as a mobile, manual and fast NDT-tool on a production line for the quantification of drilling induced delamination in common autoclaved epoxy CFRP laminates of unidirectional plies. The results of the method will be compared to those received by X-ray CT and low magnification microscopy (LM).

2 Materials and Methods

2.1 Samples and drilling tests

Within the project “Spantec light - Drilling Technology of Light Weight Materials - Quantifying the comprehension of material and application properties”, a cooperation of the Universities of Applied Sciences Aalen, Ulm and Mannheim, numerous different series of samples were produced.

Quasiisotropic, symmetric CFRP laminates were layed up using the carbon/epoxy prepreg HexPly® UD/M21/35%/194/T800S (short: T800S/M21) from Hexcel. The even sheets were cured in an autoclave under the conditions recommended by the manufacturer. The stacking of sequence of the laminates is $[0,45,90,-45]_{3s}$, resulting in a final thickness of about 4.6 mm.

Wear series were carried out using the above described CFRP laminate and several modified [18] step drills from Klenk GmbH (Germany) with a diameter of 5.9 mm. The used point angles of the drilling tools are 70°, 85°, 100° and 130°. The corresponding wear series are referred to as K70, K85, K100 and K130 respectively. The experiments were performed in a CNC machine DMC 64 V from DMG (Germany) without using of a cooling agent. Each wear series was driven up to 305 holes, respectively to a total feed length of 1.4 m. Five investigation points over the wear path of the drill were chosen after 25, 75, 150, 225 and 300 drilled holes. The state of the drills was evaluated at this investigation points and subsequently five samples were prepared with dimensions of 200 mm x 15 mm. The holes were drilled in the centre of these samples whereby the samples were solidly clamped in order to avoid any influence of vibrations. The drilled holes were investigated using three different non-destructive methods. The samples were subsequently tested in open hole bending experiments in order to figure out the impact of delamination on static strength. The results of these experiments are the subject of another paper [19].

2.2 X-ray computed tomography

The experiments were performed using the computer tomograph phoenix X-ray v tome X with a nanofocus X-ray tube. Several samples with a wide range of typical delamination were investigated with a voxel size of 15 μm. One scan was necessary to measure one hole and their surrounding area where damage occurs. Up to 1100 X-ray projections were taken while the sample was turned 360° around its axis. Finally a 3 D volume was computed containing the fully three dimensional extension of the damaged area around the drilled hole.

2.3 Ultrasonic inspection

The ultrasonic experiments were performed using the portable ultrasonic flaw detector OmniScan MX2 with a linear array probe having 64 elements and a center frequency of 5 MHz. The distance between the centres of two adjacent elements of the array is 0.6 mm. In order to decrease its divergence angle, the ultrasonic beam was electronically focussed. For the electronic scanning inside the linear array an active group of 16 elements was used to generate a single beam. The focus distance was set to a value of 3 mm.

The ultrasonic measurements were performed at normal incidence in pulse-echo mode. The CFRP samples with the drilled holes were manually scanned using of a gel couplant and a manual wheel encoder in a single axis with a scanning resolution of 0.1 mm like shown in Fig. 1. The linear phased array provides electronical scanning in the array axis, the scanning resolution of this axis was kept at 0.6 mm. The linear array was located during the measurement on the entry side of the sample in order to detect the push-down delamination on the exit side. The recording of a US C-Scan took about 5-7 seconds.

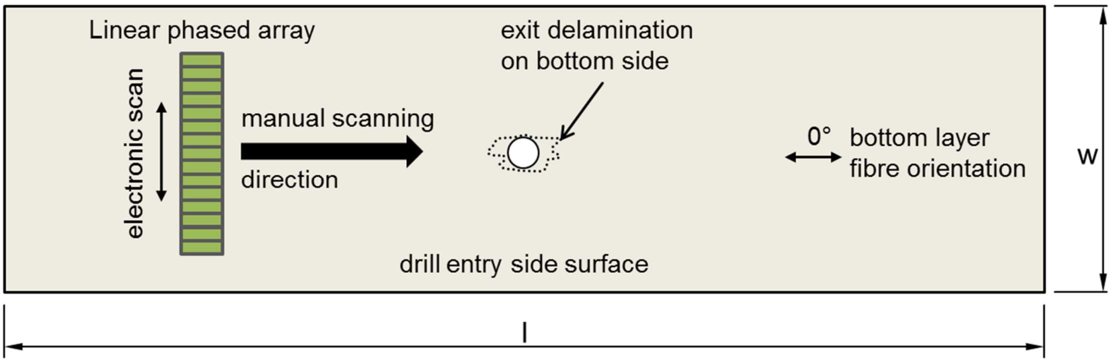

Fig. 1. Schematic of the experimental setup for the ultrasonic inspection.

3 Experimental Results

3.1 Typical CT-patterns of the delaminated area and CT-overlay-images

Several CFRP samples were selected from different investigation points (see section 2.1) and investigated by means of X-ray computed tomography (X-ray CT). X-ray CT provides the reference method for this study. The results of X-ray CT show that the major damage happens on the exit side of the drilled sample. Fig. 2 shows CT images of three different holes with the numbers 22, 155 and 301 performed using of a twist drill with a point angle of 100°. The CT slices in the upper part of the Fig. 2 show the plane of the top layer (exit side) with the largest delamination. The damage happens especially within the top layer itself. The second layer of the CFRP laminate is also affected in a few samples whenever a worn-off drilling tool is used (see the lower part of Fig. 2).

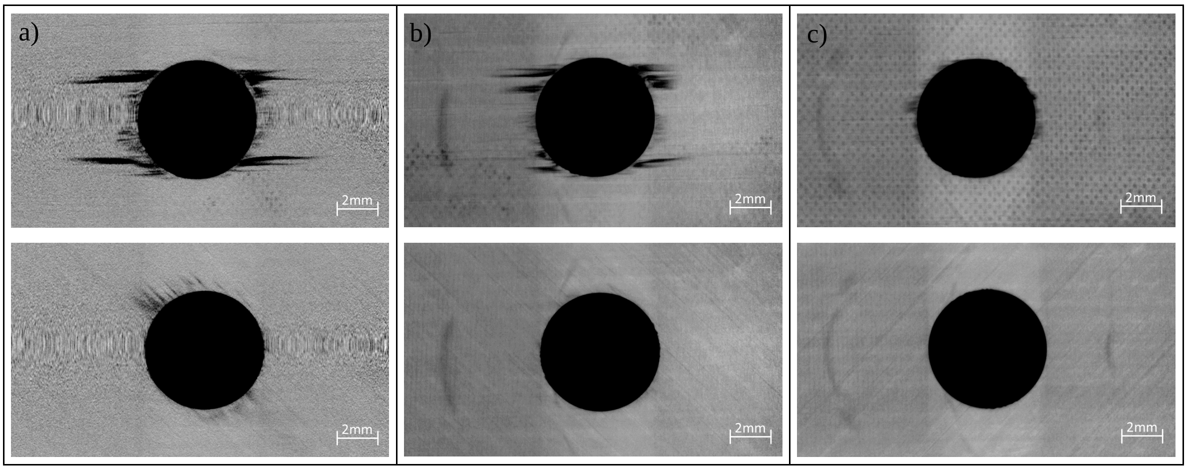

Fig. 2. CT slices showing the largest delamination of the exit side top layer (upper images) and second layer (lower images) of the CFRP laminates (drill point angle 100°). a) Hole No. 301; b) Hole No. 155; c) Hole No. 22.

In order to obtain two dimensional images containing information about the extension of the delamination from deeper plies, the so called CT overlay images were generated. An image stack, containing single CT slices like shown in Fig. 3a, was thus extracted from the reconstructed volume. The CT slices of the image stack were added in one image using the image processing software GIMP 2.6. Two-dimensional images, containing the whole three-dimensional information were thus generated (see Fig. 3b).

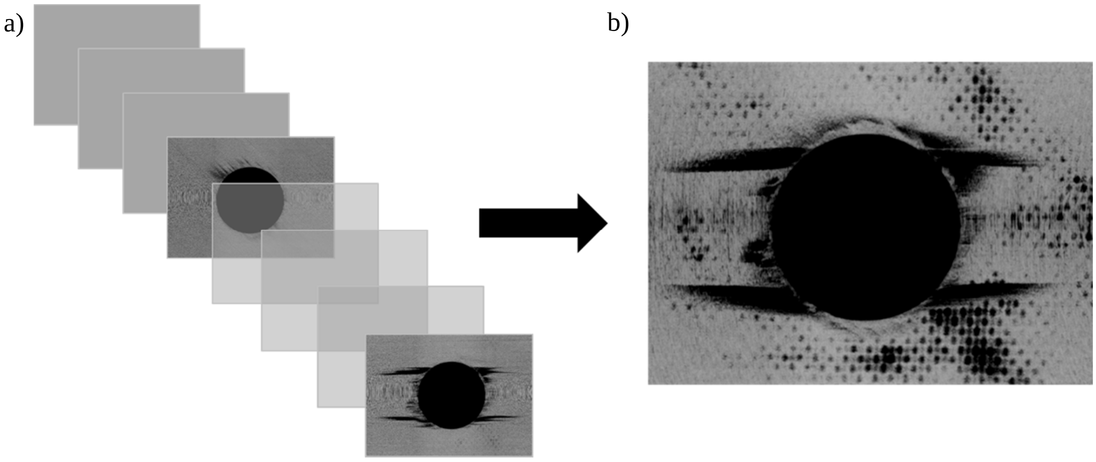

Fig. 3. Additive overlaying of the image stack to a CT overlay image.

Fig. 4a show CT overlay images of the holes with the numbers 22, 155 and 301 from series K100. The damaged area around the drilled holes is more pronounced in Fig. 4a compared to Fig. 2 due to the additional information gained from the deeper plies. The damage is larger for drilling tools of a higher wear state. The extension of the delamination around the holes 155 and 301 in Fig. 4a is much higher in the fibre direction of the laminate compared to the other direction resulting in a non-symmetric shape of the delamination. This shape of the delamination is typical for the used CFRP laminates consisting of unidirectional plies. The delaminated area is also very irregular because there are single fibre bundles which are lifted over a longer extension than others in direct neighbourhood. This effect is smaller for the holes of the series K70 (see Fig. 4b).

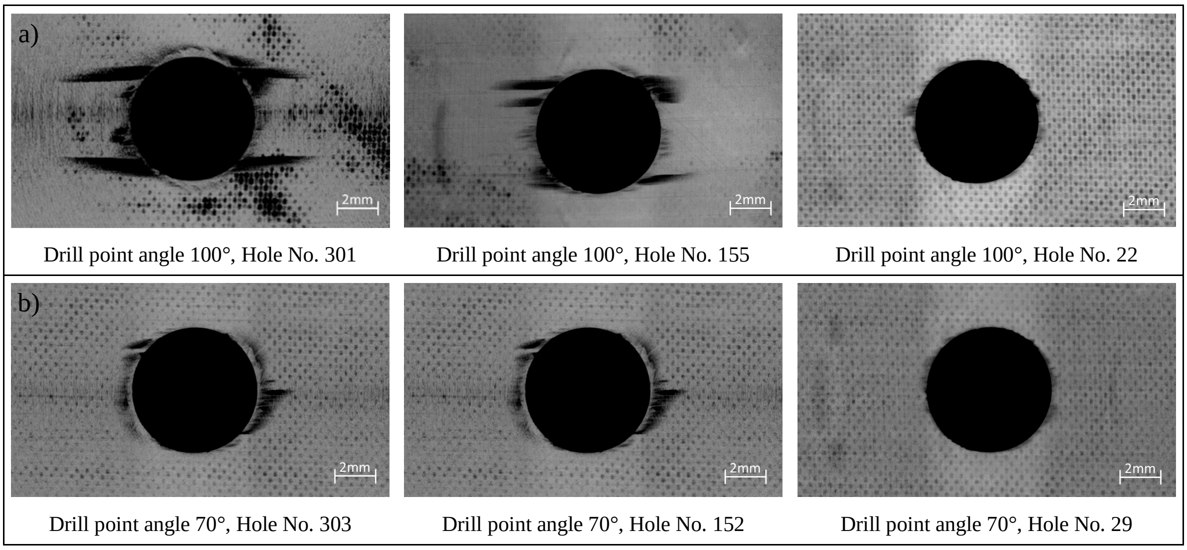

Fig. 4. CT overlay images of holes performed using drills of different wear states. The damage is larger for drilling tools of a higher wear state. a) drill point angle 100°; b) drill point angle 70°.

3.2 Ultrasonic C-scan patterns

The CT results in the previous section were used as reference for developing the experimental setup of the ultrasonic testing The CT overlay images in Fig. 4 are typical for the used material and all drill series. The spread direction of the delamination in the anisotropic composite was thus chosen to be the scan axis having the highest resolution (0.1 mm) by the ultrasonic inspection. The extension of the delamination is thus with the highest resolution detected. By adapting the ultrasonic testing procedure to the special type of damage, a simple and mobile ultrasonic testing procedure results which allows the manual measurement of the delamination quickly and with high resolution.

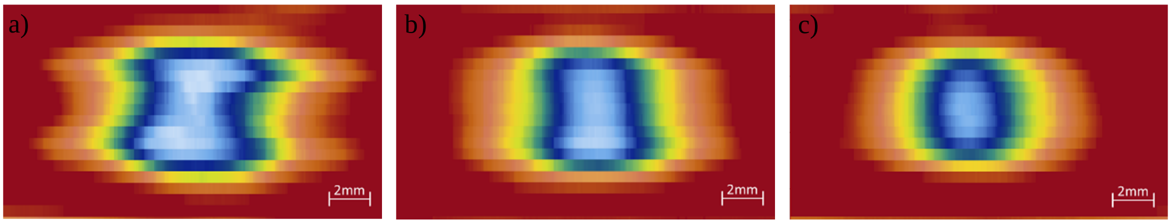

Fig. 5. Ultrasonic C-scans of holes drilled with tools in different wear states corresponding to the CT overlay images in Fig. 4a. (drill point angle 100°): a) Hole No. 301; b) Hole No. 155; c) Hole No. 22.

Fig. 5 shows US C-scans of the three drilled holes having the damage pattern shown in Fig. 4a. A clear difference in the profile of the ultrasonic back reflection intensity can be recognized between the different holes. Fig. 5a shows the US C-scan of the hole 301 (corresponding to the CT overlay image in the left side of Fig. 4a). The non-symmetric shape of the delamination is easy to be recognized in US C-scan in Fig. 5a. Furthermore, the non-symmetry of the delamination extenuate from left to right in Fig. 5 accordingly with the CT results in Fig. 4a. One can thus conclude that qualitatively the ultrasonic results correspond to the CT ones. A further comparison of the US C-scans and the corresponding CT overlay images is shown in Fig. 6.
The left column of Fig. 6 contains US C-scans of three different holes having a small, medium and large delamination. The corresponding CT overlay images are shown in the middle column of Fig. 6. The images in the right column of Fig. 6 are obtained superposing the transparently illustrated US C-scans over the corresponding CT overlay images. A detailed analysis of the images in the right column of Fig. 6 shows that the boundary of the damage area in the CT overlay image corresponds to a certain threshold of the intensity of the ultrasonic back reflection in the US C-scans. This threshold was later used for segmentation in order to quantify the US C-scans (see section 3.3.1).

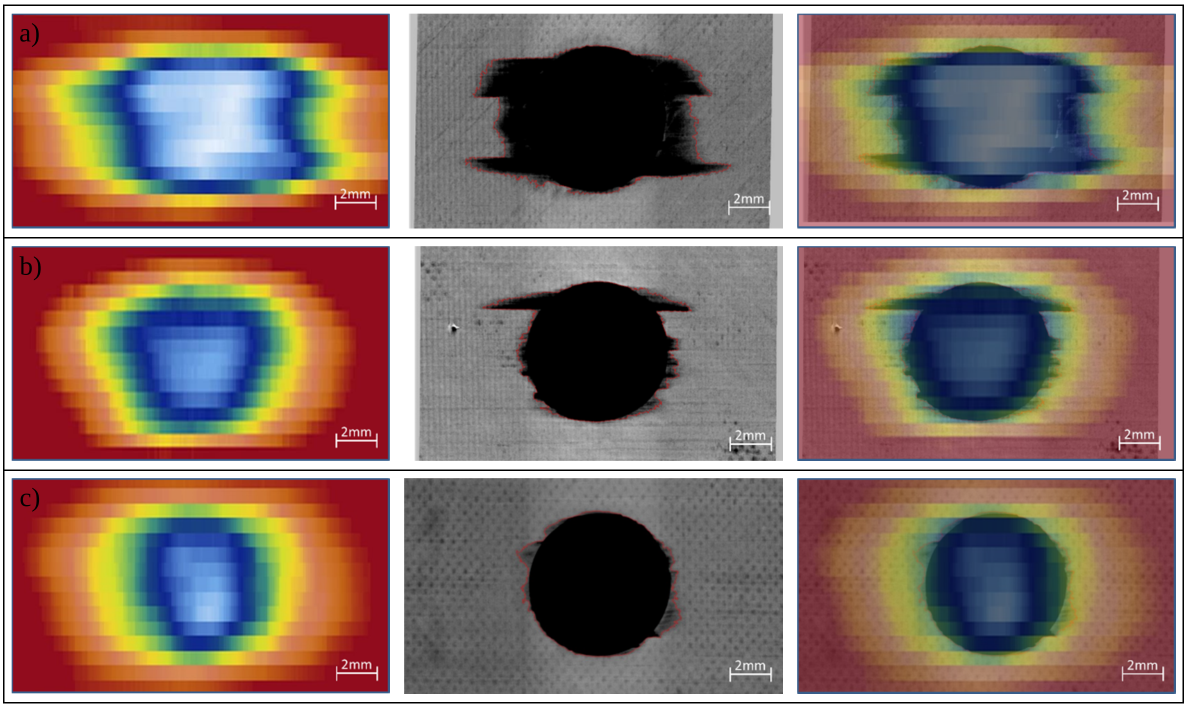

Fig. 6. Qualitative comparison between US C-scans and CT overlay images for three different holes having a large, medium and small delamination. Right column consists of a superposition of the transparently illustrated US C-scans (left column) and the corresponding CT overlay images (middle column). a) drill point angle 130°, Hole No. 230; b) drill point angle 130°, Hole No. 24; c) drill point angle 100°, Hole No. 23.

3.3 Determination of the delamination factors and comparison of the three methods

The diameter weighted delamination factor on the basis of the one first introduced by Chen et al. [7] was calculated as follow:

$$F_d = \left(\frac{D_{\max} - D}{D}\right)\% \text{, where D is the hole diameter.} \tag{1}$$

3.3.1 Delamination factor by Ultrasonic inspection

In order to quantify the US C-scans, a threshold of 50% of the maximum ultrasonic back reflection intensity was used to mark the boundary of the damaged area. The 50% threshold was manually marked using dark dots in Fig. 7a.

An automatic segmentation of the US C-scans by using image processing is presently under progress. The delamination factors are subsequently computed based on a binary image like in Fig. 7b. The automated method allows a fast and quantitative analysis of the US C-scans.

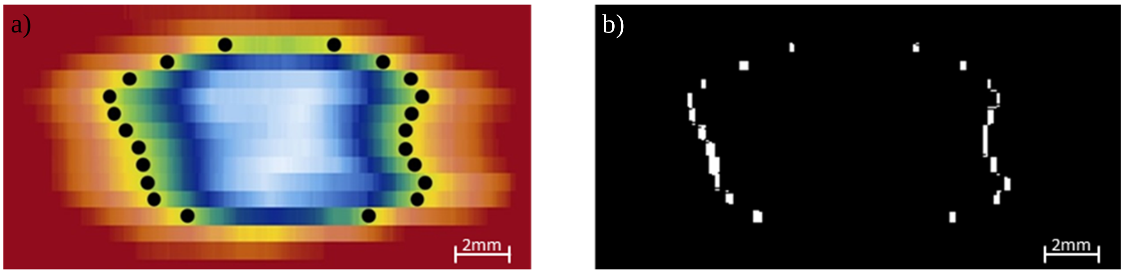

Fig. 7. Segmentation of a US C-scan: a) 50 % threshold manually marked; b) binary US C-scan.

In Fig. 8c the maximum extinction of the delamination is green encircled. The corresponding delamination factor was determined using equation (1).

3.3.2 Delamination factor by computed tomography

In order to compute the delamination factor F_d, a digital analysis of the CT overlay images was done using the software Carl Zeiss AxioVision (rel. 4.9). The CT overlay images were therefore imported into AxioVision and the delaminated area around the hole was segmented by setting a threshold value (see Fig. 8b). The red line in Fig. 8b marks the damaged area and the diameter of the green circle having the centre in the middle of the hole corresponds to the maximum diameter of the damaged area. The delamination factor based on the CT overlay image was determined similarly to the optical one using equation (1).

3.3.3 Delamination factor by low magnification microscopy (LM)

The surface of the exit side of the drilled holes was analysed with a light optical microscope Carl Zeiss AxioZoom V.16 equipped with a high resolution digital camera of type AxioCam 506 color. Grey value images showing the extension of the delamination at the surface of the sample were captured using dark field illumination. The maximum diameter of the damaged area D_{max} was measured using the software Carl Zeiss AxioVision (rel. 4.9) as shown in Fig. 8a. An automatic segmentation based of a threshold value is for this material not possible because of the low contrast of the images [19].

3.3.4 Comparison of the three methods

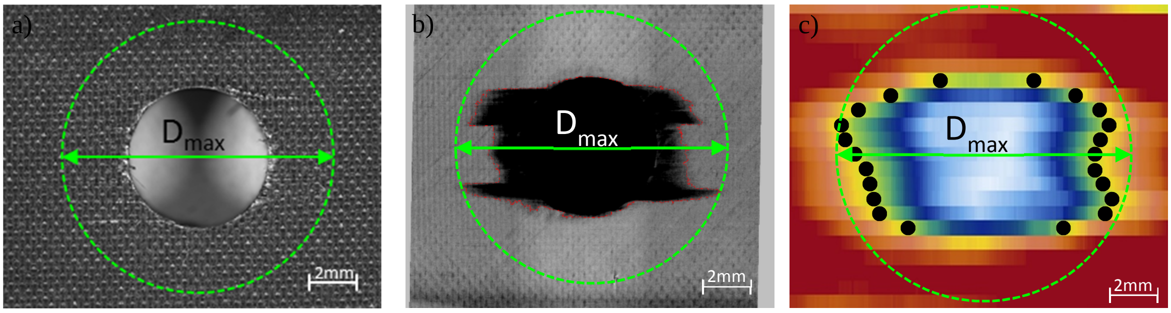

Fig. 8. Calculation of the diameter weighted delamination factor from LM (a) and CT overlay images (b) and from the US C-scans (c).

Computed tomography is the reference method in this study. Therefore, the delamination factors determined from the US C-scans and LM images are directly compared with the delamination factors based on the CT overlay images. The procedure to determine the delamination factor from the US C-scans as described in section 3.3.1 is quite time expensive. For this reason a limited number of the US C-scans were quantitatively analysed. The delamination factor determined from the US C-scans is plotted against the one based on the CT overlay images in Fig. 9a. The diagram in Fig. 9a shows that the two methods are quantitatively also in good agreement. The experimental points are distributed around the diagonal line which corresponds to identical delamination factors. A good agreement between LM and CT is clearly shown by Fig. 9b.

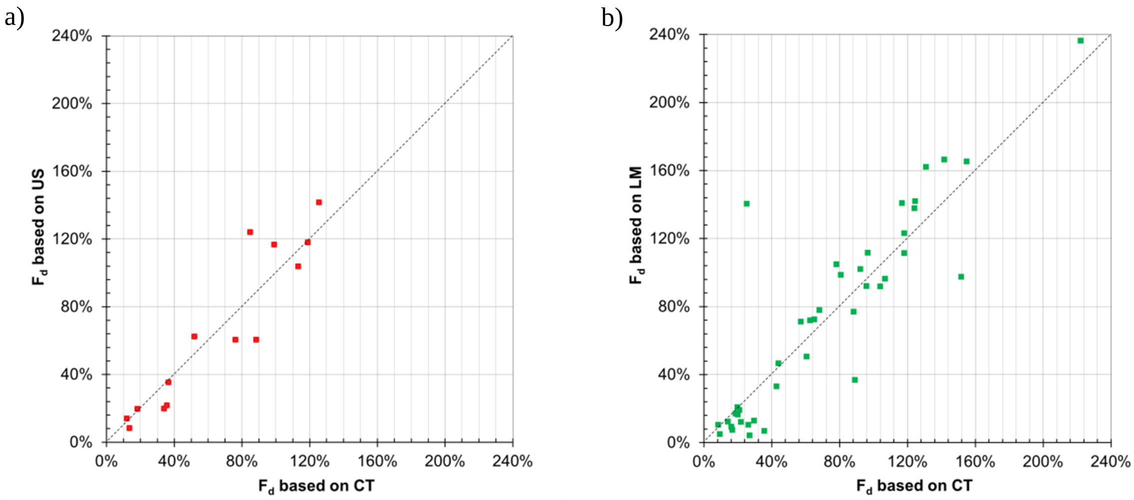

Fig. 9. Comparison between diameter weighted delamination factors based on US and LM with CT.

Despite the overall good accordance between the three non-destructive testing methods, there are still some differences. Fig. 10 shows a bar diagram comparing the determined delamination factors F_d based on the ultrasonic tests (red), computed tomography (blue) and low magnification microscopy (green). The delamination factors for 14 drilled holes over all drill series were used for this plot. The variation of the three delamination factors to each other could be quite small (for example hole 29 from series K100) but also larger like for example for the hole 48 of the series K100. At this point has to be mentioned that the delamination around the drilled hole is measured in different ways by the three methods. The whole three-dimensional information is contained only in the CT images. The method is however time and costs intensive and limited available. Contrary, using the light optical method only damage visible direct on the surface but not inside the material can be detected. Especially for weakly damaged holes, this leads to underestimation by the optical method (see Fig. 9b). Sometimes a small delamination only appears as a small crack on the surface which can hardly be seen. This is especially difficult, if the CFRP surface is rough and structured like the one of the material used in this study formed by a peel ply [19]. Computed tomography as well as low magnification microscopy allows the analysis of the entry and exit sides of the drilled hole separately. The probe of the ultrasonic device is located on the entry side of the sample. The existing results show that the US C-scans corresponds mostly to the exit delamination. The influence of the entry delamination is in focus of a further study. Furthermore, defects in the near of the drilled hole located inside of the sample can also affect the US C-Scan. A long but thin delamination like in the left image of the Fig. 4a, appear smaller in the US C-scans. The thin end of the delamination causes no measurable changes in the ultrasonic back reflection intensity.

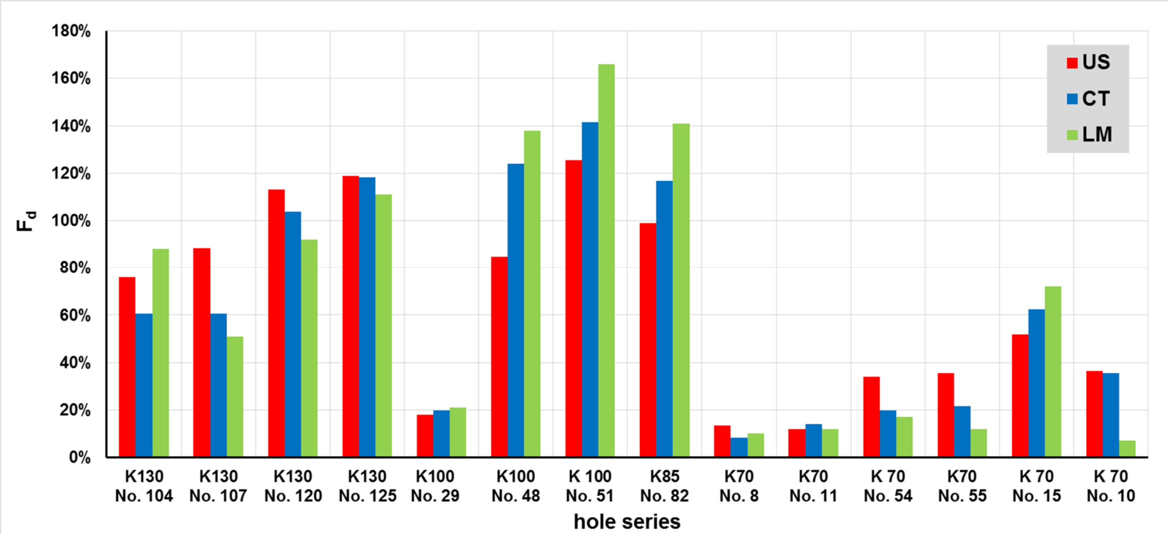

Fig. 10. Quantitative comparison between ultrasonic testing (red), computed tomography (blue) and low magnification microscopy (green).

4 Conclusions

This paper presents a fast, mobile and manually driven non-destructive ultrasonic inspection procedure for drilling induced delamination obtained by adapting the experimental setup to the special type of damage in common autoclaved epoxy CFRP. The basis for this adaption was provided by a detailed catalogue of high-resolution three-dimensional damage-pattern supplied by X-ray CT. The X-ray CT results show that the spread direction of the delamination in the CFRP laminates consisting of unidirectional plies is identical with the fibre direction of its top layer on drill exit side. The scanning axis having the highest resolution (0.1 mm) in the ultrasonic equipment was chosen in accordance with the fibre orientation of the top layer, thus enabling the highest possible resolution of the delamination spread. A subsequent image analysis allows an automatic segmentation of the US C-scans by using a threshold value of the ultrasonic back reflection intensity and, based on that, a quantitative calculation of the diameter weighted delamination factor.

The results of the presented ultrasonic testing procedure correspond qualitatively and quantitatively well with those received by X-ray computed tomography and low magnification microscopy even for small delamination.

Computed tomography offers the entire three dimensional information of the damaged volume around the drilled hole. But due to the high resolution required, it is limited to small samples (of a width about 20 mm). So in this context, the X-ray-CT-method cannot be considered as non-destructive. In addition, the method is time and cost intensive as well as limited in availability.

The low magnification microscopy (LM) provides reasonable results for significantly damaged holes. But it is very sensitive with regard to the surface structure. Because of the low contrast of the images, an automatic segmentation based on a threshold value was not possible for the material considered in this work.

The presented results show that the US C-scans corresponds well to the exit delamination. The detection of the entry delamination as well as of other defects located around the drilled hole should be the subject of further studies.

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