Development of Reference Test CFRP Specimens for the Standardisation of Active Thermography with Flash Excitation

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Abstract. In this contribution, the authors present the results of a project which involves the development of a testing standard for flash thermography. In addition to the standardization of the selection of appropriate equipment and procedures for testing and data analysis, the new standard will provide suitable reference test specimens for several materials, including CFRP as used in aerospace applications with typical flaws. We will particularly consider these test specimens which should enable qualification of the equipment as well as the validation of the flash thermography method for CFRP in general.

1. Introduction

With increasing use of carbon fiber reinforced polymers (CFRP) in civil aviation, the need for nondestructive testing (NDT) techniques has gained significance. One of the very promising methods is active thermography with flashlight excitation (*flash thermography)*. It is also highly customizable and has an attractive price performance. Flash thermography is already exploited to detect faults in CFRP laminates, however it is not yet recognized as test method for the very reason user standard is still missing.

Existing thermography standards describe the general principles, equipment, and terms [1-4] or relate to a very limited area of applications [5,6]. Currently, for each area of application flash thermography has to be validated by extensive individual tests and calibration procedures. Comprehensive testing instructions have to be developed for each implementation individually. Regarding the present development in material employments for a reliable and reproducible use of active thermography with flash excitation, also a practical testing standard is urgently required. Thus a new national standard, which is intended as an European standard in the near future, shall support device manufacturers and service providers to perform standardized testing. A consistent use of NDT methods for quality assurance may accelerate the enhancement process in CFRP usage ensuring safety, efficiency and reliability. BAM and further subcontractors are working on a project entitled *Development of standards for active thermography with flash excitation*. This project is supported by the *Deutsches Institut für Normung e. V.* (DIN) and is funded the *Federal Ministry of Economics and Technology* (BMWi) and administratetd by the *German Aerospace Center* (DLR).

Flash excitation is very well suited for the detection and quantification of defects close to the surface and with an orientation parallel to the surface like delamination. With the short optical impulse, a very thin layer close to the surface is heated up. Afterwards, the heat is transported into the structure by thermal conductance. The total penetration depth and thus the detectability of defects, of course, depend on the absorbed heat, the material system, its thermal properties and defect geometry. These factors lead to the decisive contribution when applying them to CFRPs.

Appropriate test specimens are needed for systematic investigations concerning the limits of application, detectability and measuring accuracy. The development of standards for flash thermography includes the characterisation of suited equipment, as well as the considerations of user demands. Therefore typical testing problems have been specified in collaboration with industrial partners. Considering these aspects the authors investigated various types of CFRP specimens with artificial delaminations, impact damages and deviations in fibre orientation. Test specimens have been developed and are still under optimisation. These might be used as reference test specimen in the near future. The most suitable ones as well as their thermographic testing results will be presented in this contribution.

2. Reference test specimens

Considering the standards mentioned above, only in ASTM E 2582-07 [6] the application of reference test specimen is advised with a rough description of its design. Here, first a detectability standard including five known flaws representing the range of aspect ratio to be expected for testing in the composite material shall be provided. These flaws can also be replaced by flat bottom holes which represent the state of art for standardised reference specimens made of CFRP.

However, the field of application for fibre reinforced composites is manifold and ranges from simple technical applications to high-performance structures in aerospace. Defects and inhomogeneities already occur during production or during use due to external damage, load or fatigue. These include:

- Ondulations of fibres
- Inhomogeneous distribution of fibres and fibre orientation
- Pores, larger voids, or variations in matrix density
- Detachment of the matrix and delaminations
- Fibre cracks

The thermal properties are mainly determined by the anisotropic structure of the carbon fibres. Thus, the distribution of heat inside the CFRP-structures depends very much on the used orientation and combination of fibres. Nevertheless, flash thermography has already been proven to be very well suited for investigating these structures. As already described above, for testing of thin plates and of repair patches of CFRP, an ASTM standard has been issued [6]. Within the project, different test specimens with artificial delaminations as well as defined impact damages and fibre direction derivates have been developed.

2.1 Stepbar specimens with artificial delaminations in CFRP

In order to investigate the detectability of flash thermography, the spatial and depth resolution have to be analysed as a function of defect size and depth. Therefore, CFRP specimens with double layered PTFE platelets of well known size, location and depth had been constructed and investigated. Even if this kind of artificial defects cannot comprehensively simulate real delaminations, there is still the advantage of having well defined information on size and position. First of all we can get fundamental data about the thermal processes in the given laminate structure.

Furthermore, these specimens are suitable for testing and comparing various setup configurations as well as data analysis prozedures.

Artificial delaminations with different sizes have been included into two stepbar specimen at different depth (see figure 1). The delaminations have been realised with double-laid sheets of Polytetrafluoroethylene (PTFE) with a thickness of 0.1 mm each and with sizes between 20 x 20 and 2 x 2 mm^2. Each of the stepbar specimen consists of 5 steps. Thus the covering of the delaminations varied between 0.5 and 5 mm with increments of 0.5 mm. The specimens are made of aviation approved epoxy resin impregnated carbon filamentary materials (prepregs) with a layer thickness of 0.13 mm have been used.

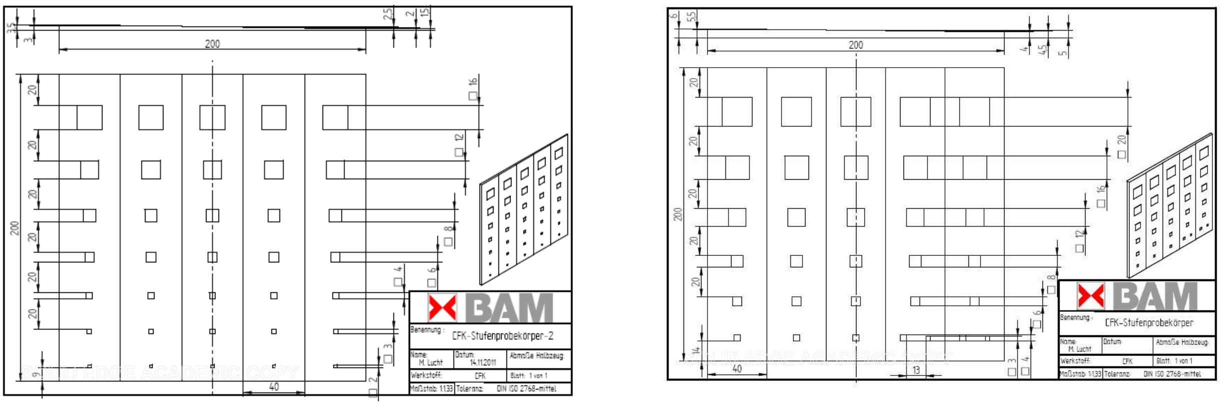


Figure 1: Sketches of CFRP step test specimen with artificial delaminations having different sizes and depth. Left: Variation of depth between 0.5 and 3 mm, and of sizes between 16 x 16 and 2 x 2 mm^2. Right: Variation of depth between 3.5 and 5 mm, and of sizes between 20 x 20 and 3 x 3 mm^2. Dimensions are given in mm.

2.2 Specimens with impact damages

For the samples with impact damages plates has been constructed according to DIN 65561 [7] containing 24 or 36 layers ordered symmetrically to the mid layer. The size of each plate was 15 x 10 x 0.3 cm^3. Impact damages have been introduced by a falling weight with two different impactors with a radius of 8 and 10 mm and weights of 58.6 and 61.9 g, respectively. These have been mounted onto two different slides. In total, impact energies between 4 and 25 J could be realized. As a reference method, the samples with impact damage have been investigated with Computer Tomography (CT) and Ultrasonic Testing (UT).

2.3 Specimens with incorrect fiber orientation

Specimens with incorrect fibre alignment have also been designed. They include undulations due to the production process as well as intentionally arranged defects like laminate layers under specific angular deviations. Figure 2 shows the side view of a sample with $[0/90°]_S$-laminate with deviating fibre layers under 30° in 1 mm depth and 45° in 2.5 mm depth.

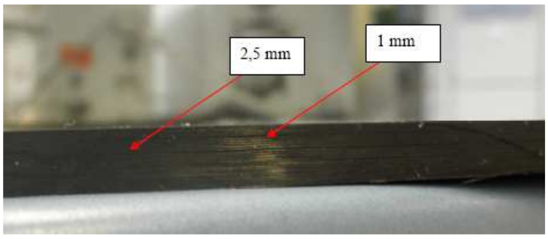


Figure 2: Lateral view of [0/90°]-sample with one layer of laminate under 30°-angle in 1 mm depth and one layer under 45°-angle in 2.5 mm depth.

3. Experimental Design

The thermal data of the above described test specimen have been generated with a SMWIR infrared (IR) camera with a cooled InSb FPA detector with 512 x 640 pixels, sensitive between 1.2 and 5.4 µm. The frames have been recorded in the integrate-then-read snapshot modus with a frame rate of 93 to100 Hz. A SMWIR lens with a field of view of 15.1° x 18.8° was used together with a temperature controlled band pass filter being transparent between 3.7 and 5.3 µm.

The thermal excitation was performed using two or four flash lamps with an energy consumption of 6 kJ each, mounted in optimum distance to the test samples realising a homogeneous and efficient heating, but not disturbing data recording with the camera. A comparison of four different flash lamps showed that although the radiated intensity slightly varies, the shape of the impulse is similar. Measurements have been performed both with a reflection set-up, see figure 3 left, and a transmission set-up, see figure 3 right. In the visible range, the duration of the flash is about 2.6 ms (FWHM). For reducing sample heating from residual heat of the lamps, Plexiglas sheets have been mounted in front of the lamps.

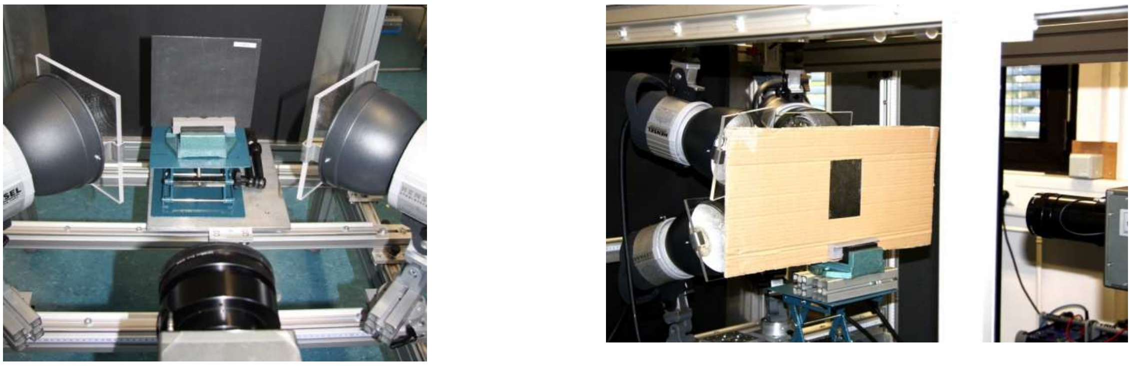


Figure 3: Experimental set-up for performing measurements with flash excitation with two flash lamps and reflection configuration (left) and four flash lamps and transmission configuration (right).

4. Data analysis

For the analysis of recorded data, several methods were implemented and applied either only single thermograms or complete sequences of thermal images, sometimes including also the thermal flash excitation. The main aim of these methods is to get as far as possible quantitative information about the structure and the defects under investigation from the thermal and temporal response after thermal excitation. Depending on the testing problems and recorded data, each method has its advantages and disadvantages.

The principle of PPT (pulse phase thermography) is to pixelwise transform the temperature-time curve into the frequency range by fast Fourier Transformation (FFT). Thus, a series of amplitude and phase images can be displayed, which are related to different frequencies[8]. Depending on material properties and defect depth, in some cases the phases images show an enhanced detectability of defects related to contrast images. This is due to suppression of disturbing signals that belong to other frequencies than the excitation signal. Therefore, effects due to inhomogeneous surfaces, inhomogeneous heating or surface reflections can be reduced.

The principle of TSR (thermal signal reconstruction) is based a double logarithmic plot of the temperature-time curve. Polynomal fits of these curves are used to reduce noise in the signal. Subsequently the 1st and 2nd derivative of these curves is calculated. Hereby peaks in the second derivative usually mark the time of defects appearance, which can be used to calculate the depth of defects or layer thickness (or, if the thickness is known, the thermal properties can be estimated) [9]. Further on, the visualisation of the resulting images along all pixels of the first or second derivatives at this time usually gives a considerably good contrast for the respective defect.

5. Results

5.1 Artificial delaminations in CFRP

Here, only experimental data recorded at the thinner reference test specimen with steps are shown (maximum thickness: 3.5 mm). Four flash lamps have been used for thermal excitation. In figure 4, the thermogram with the maximum thermal contrast (left), the best phase image (middle) as well as the second derivative of TSR (right) are shown. In the thermogram, the delaminations can be detected only for coverage of 0.5 and 1 mm. In the phase image and in the second derivative, also for 2mm coverage defects down to a size of 8 x 8 mm can be clearly recognized. The image of the second derivative has a slightly better SNR as that of the phase image.

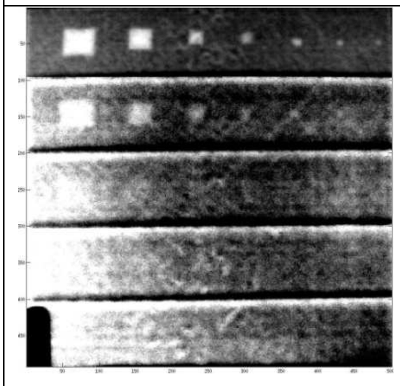
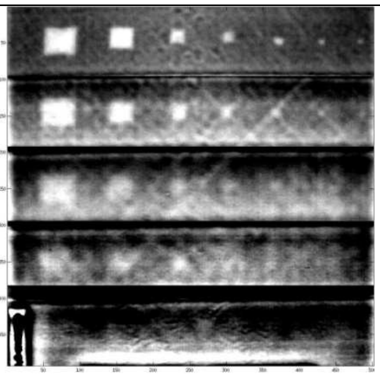
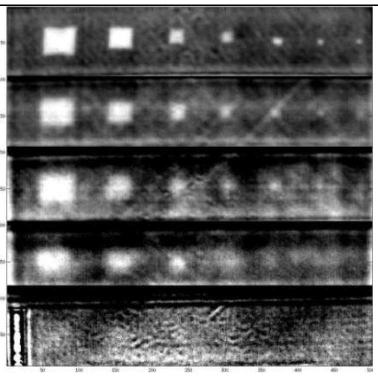
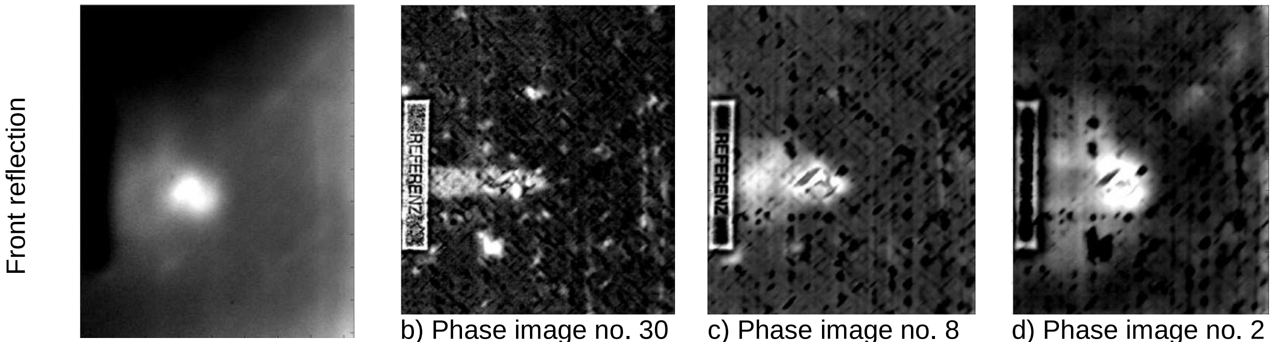
Thermogram	**Phase image**	**2nd derivative TSR**	**Depth in mm**
			0.5 1.0 1.5 2.0 2.5

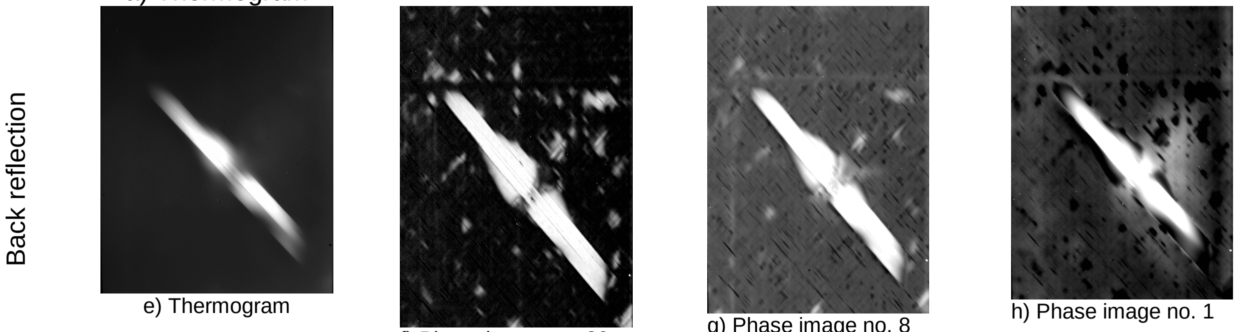
Figure 4: Thermogram (left), phase image (middle) and image of 2nd derivative (TSR), right) of thermal data recorded with 4 flash lamps at the reference test specimen with a total thickness of 3.5 mm. For each step of the specimen, the data in the images have been scaled to minimum and maximum. Sizes of the defects from left to right: 16 x 16, 12 x 12, 8 x 8, 6 x 6, 4 x 4, 3 x 3, 2 x 2 mm^2. The depths of the delaminations are shown on the right. Type of fiber: Carbon/UTS50F13-12K,800tex

5.2 CFRP structures with impact damages

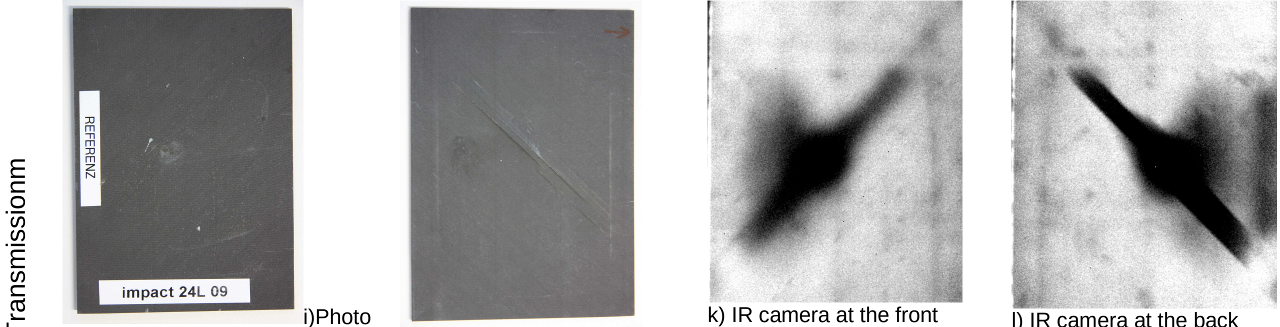
The results of one of the test specimens with 24 layers and thus a thickness of 3.2 mm with an impact damage resulting from an impact with 14.42 J are displayed in figure 4. Here, two flash lamps have been applied for the reflection measurements and four flash lamps for the transmission measurements. Reflection and transmission measurements have been performed from both sides of the specimen. A sequence consisting of 1050 frames and at a frame rate of 93 Hz has been recorded each.



a) Thermogram b) Phase image no. 30 c) Phase image no. 8 d) Phase image no. 2



e) Thermogram f) Phase image no. 30 g) Phase image no. 8 h) Phase image no. 1



i)Photo from the front j) Photo from the back k) IR camera at the front l) IR camera at the back

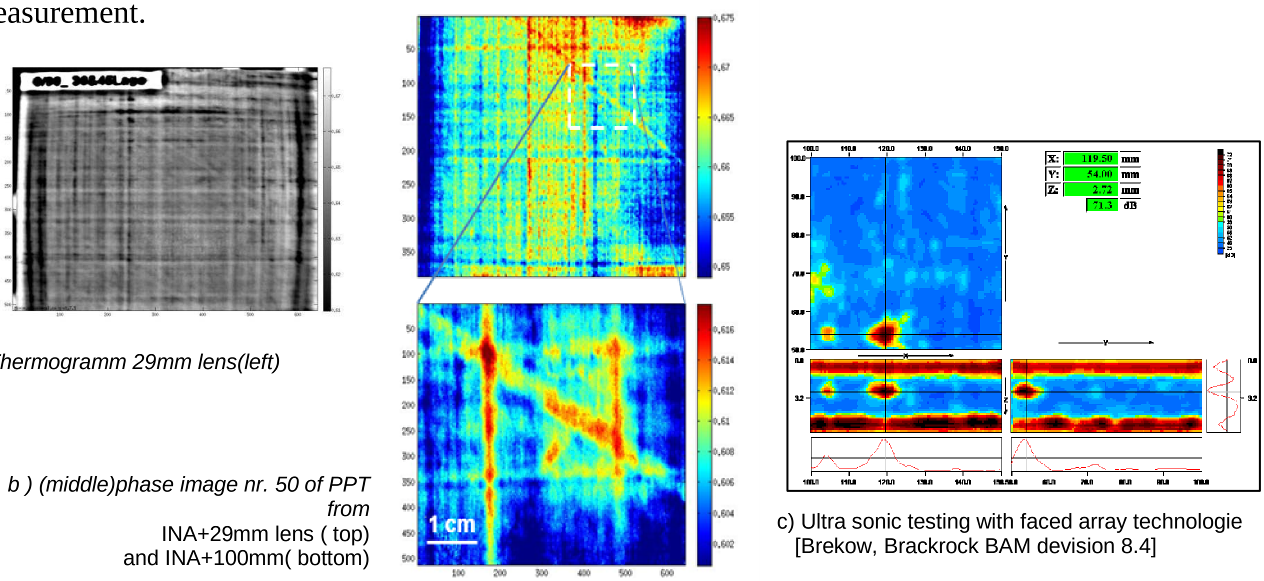
Figure 5: Results of investigations at a test specimen with 24 layers and with an impact damage of 14.42 J. a) to d) Thermograms recorded in reflection configuration at the front side 2.43 s after the flash and phase images no. 30, no. 8, no. 2. e) to h) Thermogram recorded in reflection configuration at the back side 2.43 s after the flash and phase images no. 30, no. 8, no. 1. i, j) Photos of the front and back side of the specimen. k, l) Thermograms recorded in relfection configuration. The size of the area shown here is always 10 x 12 cm^2.

Figure 5 a) shows a thermogram, which was taken 2.43 s after the flash in reflection configuration, where the front surface (surface from which side the impact was introduced) was heated. Although at the surface only a small dent is visible, the thermogram shows a much larger area with increased temperature indicating a lager delamination. The phase images no. 30, no. 8 and no. 2, shown in figure 5 b) to 5 d), can be attributed to different depths. Here, the phase image with the largest number corresponds to the highest frequency and thus to a low information depth. In phase image no. 30, a sharply bounded vertical area is related to a delamination of one of the top most layers of the structure. In phase image no. 8, the position of the impact can be located clearly with a further damaged area on its left side. Phase image no. 2 shows a larger area corresponding to even larger delaminations between deeper layers. Thus, the size of the delaminations increases with increasing depth corresponding to the theoretical model of crack mechanism [10]. In figure 5 e) to 5 h), thermogram and phase images of the reflection measurements performed from the back side of the specimen are shown. Here, a much larger delamination becomes visible, which can also be seen in the photo in figure 5 j). It has to be noticed that this large delamination could not be detected in the reflection measurements performed from the front side (a week but not distinct signal of this delamination can however be seen in the phase image no. 2 in figure 5d)). Again, it is shown that the detectability depth of flash thermography in CFRP is limited approx. 2 mm.

Thermograms of the transmission measurements from both sides are shown in figure 5 k) and 5 l). Especially in the thermogram in figure 5 l), where the flash lamps were heating from the front side and the thermal data were recorded from the back side, the whole damaged area can be visualised as a colder region.

5.3 CFRP laminates with Undulations and other deviations of fibre direction

Investigations of specimens with undulations and other deviations of fibre direction showed the detected orientation in thermograms became more obvious in phase images after PPT. Figure 6 shows the thermogram (left) and the phase images after PPT (middle) from investigations with a 29mm lens and a 100mm lens of the test sample [0/90°]$_S$ laminate with derivating fibre layers in 30°angle in 1mm depth and 45° angle in 2,5mm depth (see also figure 2). The ultrasonic reference measurement showed a signal that implies an imperfection like a delamination or an excessive resin buildup in the specimen, the fiber orientation was not obvious in that kind of phased array measurement.



a)Thermogramm 29mm lens(left)

b) (middle)phase image nr. 50 of PPT from
INA+29mm lens (top)
and INA+100mm(bottom)

c) Ultra sonic testing with faced array technologie
[Brekow, Brackrock BAM devision 8.4]

Figure 6: Results of investigations at the [0/90°]$_S$ laminate with derivating fibre layers in 30°angle i n 1mm depth and 45°angle in 2,5mm depth

6. Summary

For the development of a testing standard defining the application of flash thermography, several reference test specimens of different CFRP laminates have been designed and tested consisting artificial delaminations, delaminations induced by impact damages and deviations from the fibre direction. These reference test specimens enable the quantification of the detection limits of a given experimental set-up concerning the maximum detectability depth and the spatial resolution. The given experimental set-up here consisted of the excitation sources (here: two and four flash lamps) and the IR camera in reflection and transmission configuration. Further on, the experimental data recorded at these test specimens can be used to evaluate different methods of data processing. Here, thermograms with the highest thermal contrast have been compared to phase images obtained by pulse phase thermography and to the second derivative in double logarithmic scaling. The following results have been obtained concerning the detection limits and assessment of data analysis methods:

- The smallest defects investigated here had a size of 2 x 2 mm^2. These could be detected down to a depth (coverage) of 1 mm in CFRP for the reflection configuration. With the application of PPT or TSR data analysis, defects at a maximum depth of 2 mm could be detected.
- The large impact damage at the back side of the specimen with a thickness of > 2 mm could only be detected by reflection measurements from the back side or by transmission measurements.
- Undulations and angular deviations of fibre orientation were detectable up to a depth of 2.5 mm; application of PPT enhanced the spatial resolution.

In summary, flash thermography is well suited for testing CFRP materials, but has a maximum detectability depth of 2 mm for delaminations. And at this depth, only defects could be detected which are much larger as their coverage, which might be explained by the anisotropic thermal conductivity being much larger in fibre direction as in transverse direction. An increased detectability depth is expected from lock-in thermography. Investigations with this method of further reference test specimens are planned.

Acknowledgement

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